Spring 5-1-2012

Tribes, States, and Landscapes: The Ecological Impacts of Changing Land Use During the Islamic Period in Southern Portugal

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DISSERTATION

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

Anthropology

The University of New Mexico
Albuquerque, New Mexico

May, 2012

DEDICATION

For Erin and Perrin. You bring love, joy, and wonder to my world, and you provided the motivation and support I needed to finish this project.

And for my parents, my first and best teachers. More than anybody else you nurtured my curiosity, taught me to reason and to write, and showed me how to be in the world.

ACKNOWLEDGMENTS

I happily offer my heartfelt thanks for the help given by many, many people during this journey. Jim Boone fed my early interest in archaeology and started encouraging and supporting me even before I entered the graduate program. He has been a wonderful teacher, mentor, colleague, and friend. Thank you, Jim, for introducing me to Mértola and the Campo Arqueológico, for guiding my research and writing, for all of those letters of support, and for everything else you've done for me over the years.

Each member of my dissertation committee deserves thanks for important contributions to this work. Grant Meyer helped me start to see the amazing complexities of the landscapes around us, and then patiently tolerated my near-endless questions about geomorphic systems, research design, and even Excel. Lawrence Straus has been a model scholar, sharing his knowledge of Old World archaeology and reading drafts and returning comments faster than I would have thought humanly possible. Chip Wills provided insightful critiques and key references that helped sharpen my thinking, particularly about production systems and residential mobility. Thank you all.

Thanks to Erin Hudson for help with fieldwork over three seasons. Thanks also to Sue Ruth, Oskar Burger, Pat Mullen, and Burl Carpenter for coming to Portugal for the 2004-05 survey, and for digging soil test pits with minimal complaining. We'll all miss you, Pat. This work would have been impossible without the resources and help provided by our colleagues at the Campo Arqueológico de Mértola. I am indebted especially to Cláudio Torres, Susana Gomez, Santiago Macias, and Virgilio Lopes for their advice and hospitality. They and the Campo are a big part of what makes Mértola a special place.

In addition to my dissertation committee, many people on the anthropology faculty at UNM shaped my thinking and helped me in one way or another. Ann Ramenofsky has been a friend and mentor since I participated in her field school. She, Jim Boone, Garth Bawden, and Jane Buikstra fostered my interest in archaeological theory. Bruce Huckell and Arianne Pinson sparked my interest in geoarchaeology. Thank you, Bruce and Lisa Huckell, for being mentors and friends over the years. Patty Crown is an outstanding scholar and researcher; thank you Patty for your classes, and for being a role model and mentor. And thank you Patty and Chip for the seasons with the Chaco field school. Thank you also to Lynne Sebastian for opening my eyes to the

possibilities of the CRM world. Even though we never had classes together, Frances Hayashida, Ozzy Pearson, Keith Prufer, and Sylvia Rodriguez offered guidance and support. I have also greatly enjoyed friendship with and mentoring from Joe Watkins and Carol Ellick.

Faculty members in UNM's Earth and Planetary Sciences department have been incredibly generous with lab space, supplies, equipment, training, advice, and most importantly, their time. Les McFadden and Grant Meyer have been outstanding mentors and they literally changed the way I see the world. Thanks also to John Geissman and Tim Wawrzniec for the training and resources I needed for my magnetic susceptibility studies. Thanks to Amy Ellwein and Tim Wawrzniec for friendship and help along the way, and to Lou Scuderi and Gary Smith for helpful conversations and guidance.

Colleagues at the Office of Contract Archeology kept me employed during much of this journey, and they taught me more about how to actually *do* archaeology than anyone else. I have benefitted enormously from working with Patrick Hogan and Dick Chapman; they showed me how to design and carry out contract funded research. Peggy Gerow taught me the nuts and bolts of running a project, and Bill Doleman helped me pursue my early interest in geoarchaeology. Thanks also to Robin Cordero and Alex Kurota for being great colleagues and friends, to Donna Lasusky for keeping grounded in the "real" (non-archaeology) world, and to the many techs, students, volunteers, and other co-workers who made OCA a great place to work.

Fellow students at UNM contributed enormously to my graduate career and to this dissertation. In particular the cohort of 2000 and our proposal writing group constantly challenged me to explore new ideas and to clarify my thinking and writing. Thank you Roberto, Hannah, Luke, Sue, Marcus, Connie, Gwen, Kelly, Audrey, Jo, and Kristy for being good friends and colleagues. I was also fortunate to share a few classes with the cohort of 1998, another outstanding group. Thanks also to Oskar Burger and Michael Church for conversations that influenced my thinking, and to Lee Drake for sharing his enthusiasm as well as unpublished manuscripts and data. Adam Sullins and Lilly Greenawald have been great friends over the years. Thanks, Lilly, for catching more than a few typos in this manuscript.

Finally, and most importantly, thank you to my family and friends for encouragement and support of all kinds. Erin Hudson's contributions are beyond measure. Thank you, Erin, for fieldwork in Portugal, for help with GIS and maps, for being a sounding board for ideas, for believing in me, for putting up with me while I was writing, and for pushing me when I needed it. Thank you to my parents for helping me out and cheering me on, and to my brother and sister, Chris and April, for being there for me over the years. And thank you also to Travis and Patty Hudson. I'm lucky that Erin came into my life with such a kind and loving family. Earl and Laura Nesbitt, Adam Sullins and Lilly Greenawald, Luke and Nicole Coffey-Kellett, and Roberto Herrera and Vicky Eng have been there for me at key times, good and bad. Thank you all, I couldn't have done this without you.

This research was made possible by funding from many sources. The National Science Foundation provided a Doctoral Dissertation Improvement Grant (Award ID # 0715321) that supported fieldwork and analyses. The National Science Foundation also provided funding for the UNM Dean's Dissertation Fellowship (2006 – 2007), which supported further analyses and writing. I received substantial support through Research, Project and Travel Grants and a Graduate Research and Development Grant from UNM's Office of Graduate Studies, as well as a Field Research Grant from the Latin America and Iberia Institute. These and a series of smaller Student Resource Allocation Committee grants from the UNM Graduate and Professional Student Association supported the research and allowed me to present the results at national conferences.

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ABSTRACT

This dissertation concerns human-environment interactions in southeastern Portugal during the centuries following the dissolution of the Western Roman Empire. In contrast to the feudal systems that developed across Western Europe outside Iberia, the Islamic polities that controlled the study area from 711 to 1248 C.E. allowed agrarian producers a great deal of political and economic independence. As a result, rural areas were more densely populated and the residents were wealthier than in earlier or later periods or contemporary feudal Christian kingdoms. The archaeological, geological, and historical investigations reported in this volume illuminate the timing, nature, and causes of past ecological change in the study area, its relationship to population growth and changing land use patterns, and the role of social organization in mediating relationships between people and the environment.

Large scale pedestrian surveys documented dramatic increases in both site numbers and total occupied area during the Islamic period. They also identified locations within the study area that were densely populated and others that were more sparsely occupied in the past. Soil-stratigraphic studies of floodplain sediments exposed along incised streams suggested erosion and arroyo formation in densely populated areas during

the Islamic period. Complimentary studies completed in soil test pits excavated along hillslopes, coupled with laboratory determinations of bulk magnetic susceptibility of sediments, showed that past erosion was severe and widespread throughout the densely populated areas. A program of optically stimulated luminescence dating and radiocarbon dating demonstrated that severe erosion and arroyo formation occurred rapidly during the later Islamic period. Additional evidence indicates that there was no significant erosion prior to the 20th century in areas that were sparsely occupied during the Islamic period, which strongly suggests that people caused degradation in the densely occupied areas.

Dramatic population growth through the early Islamic period coincided with moderate soil erosion and progressive deforestation. Despite these ecological transformations agro-pastoralism remained productive during the first four centuries after 711 C.E., suggesting that production was sustainable at the scale of human lifetimes. As the Islamic state deteriorated and Christian armies advanced south in the 11th century, urban elites increased demands for taxes from independent rural communities. Facing taxation and diminished security, rural populations chose to augment production even though signs of degradation must have become increasingly apparent. Enlarging the area devoted to wheat cultivation in particular made the landscape highly susceptible to erosion. Widespread plowing combined with a minor climate change to trigger severe erosion and arroyo formation in the mid-12th century, dramatically reducing agricultural potential. The agrarian economy collapsed. Rural areas were abandoned a century before the Christian r*econquista* and not reoccupied for four centuries.

This study of long-term human-environment interactions illuminates previously unexamined aspects of the growth and decline of the Islamic state in Iberia. It makes methodological contributions to the fields of geoarchaeology and environmental archaeology, particularly by adopting a landscape-scale approach to geoarchaeological research and by using optically stimulated luminescence assays to date past soil erosion directly. The results illustrate the processes of ecological degradation and rebound and the types of production that are sustainable at different spatial and temporal scales on a Mediterranean landscape threatened by desertification. Finally, the research begins to clarify how different socio-economic systems mediate human impacts on the environment at the scale of centuries.

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Chapter 1:
Introduction

This dissertation concerns human-environment interactions in a study area in southeastern Portugal during the centuries following the dissolution of the Western Roman Empire. Post-Roman Iberia, with its centuries of Islamic rule, provides an excellent setting for investigating diachronic interactions between state-level polities, primary producers, and the landscape. The Islamic state presents a structural alternative to the feudal systems that developed at the time in the rest of Western Europe, entailing different relationships between agrarian producers and elites. Changes in political and economic systems at the beginning, during, and at the end of the Islamic era provide other points of contrast. In addition, the landscape in the study area is sensitive to anthropogenic degradation and the climate has been relatively stable for the past two millennia; conditions are favorable for identifying and measuring past human impacts on the environment. This study uses that landscape as a natural laboratory to investigate the timing and causes of past ecological change and the role of social organization in mediating long-term recursive relationships between people and the environment.

Methodologically, the research combines archaeological and geological techniques to generate data about the past that are interpreted alongside information gleaned from written histories. Building on a previous site survey and a series of excavations undertaken by Dr. Boone during the 1990's (Boone 1992a, 1993, 1994, 1996, 2002, 2009; Boone and Worman 2007; see also Dinsmore 1994), Boone and Worman completed a second pedestrian survey covering 64 km^2 in the study area. These archaeological investigations documented changes in the organization and intensity of agrarian land use through time and showed that rural populations were wealthier and more numerous during the Islamic period than they were during earlier or later periods. The archaeological research also generated data pertinent to reconstructing rural social organization and patterns of rural – urban interaction. Finally, an archaeobotanical study

of samples recovered during the excavations provides some insight into anthropogenic impacts on plant communities in the study area during the Islamic period (Carrión 2006).

In the next stage of the study, Worman used geological techniques to investigate the history of environmental change in the surveyed areas, specifically by examining evidence of past soil erosion. These investigations were undertaken in order to address a series of related questions: Have there been significant ecological changes in the study area during approximately the past two millennia? If so, when did those changes occur, how extensive were they, and were they detrimental to agrarian productivity? Finally, can ecological changes during the post-Roman era be attributed to human actions?

In order to explore in detail the links between human activities and landscape change, chronometric methods including radiocarbon dating and Optically Stimulated Luminescence (OSL) dating were used in concert with the data generated by detailed in-field pedostratigraphic recording and laboratory measurements of bulk magnetic susceptibility of sediments to determine as closely as possible the trajectory and timing of landscape change. A controlled comparison of geological data from the two surveyed areas, each with a different history of settlement and land use, provides one important line of evidence that significant erosion since the mid-Holocene can be attributed to human activities. Finally, the combined geological, archaeological, and historical data are used to evaluate alternative models of anthropogenic environmental degradation in order to address the more difficult – and ultimately more interesting – question of why people caused detrimental landscape change in this particular instance.

This research adds to ongoing academic debates concerning human-landscape interactions in the Mediterranean region and it provides a new perspective on the growth and eventual decline of *al-Andalus,* the Islamic state in Iberia. The techniques used have the potential for broad application in interdisciplinary studies of socio-ecological systems. More generally, the investigation provides a case study that clarifies how social organization can mediate anthropogenic impacts on the environment at the scale of centuries. The investigation should be of interest to colleagues working in Iberia and the Mediterranean region and to researchers concerned with methodological advances in geoarchaeology and environmental archaeology. Hopefully, the results also will be

relevant for those seeking to use archaeology to provide an expanded temporal perspective on current problems of environmental degradation.

Geographic and Environmental Context

As shown in figure 1.1, the study area is located in the *Baixo Alentejo* region of Portugal. With a landscape of rolling hills covered by cultivated fields, tall scrub, and oak savanna vegetation, the study area around Mértola is situated between the agriculturally productive *plano dourado* ("golden plane") around the town of Beja, to the north, and the low mountains of the Algarve to the south. The area is drained by the Rio Guadiana, one of the largest rivers of the Iberian Peninsula. Although the majority of Portugal has been oriented to the Atlantic world at least since the early modern period, the Alentejo and Algarve historically have been more closely aligned with the Mediterranean sphere, both ecologically and culturally (e.g., Macias 2007).

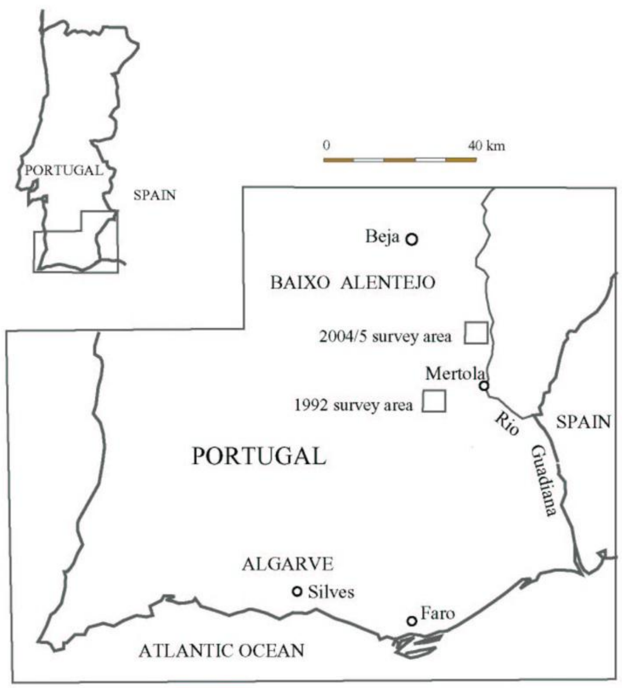

Figure 1.1: Map showing the locations of the surveyed areas in relation to modern towns, political boundaries and the Rio Guadiana.

The landscape and biotic communities in the region have been deeply altered by millennia of human activity (Chester and James 1991, 1999; Grove and Rackham 2001; Stevenson and Harrison 1992; Vis *et al.* 2008). Evidence for significant impacts during the Pleistocene is scant in Iberia, although anthropogenic fire regimes may have been important (Barton *et al.* 2004; Grove and Rackham 2001: 229). Domesticated plants and herd animals were present in southeastern Iberia by approximately 5600 B.C.E. (Barton *et al.* 2004; Gilman and Thornes 1985: 17), and Grove and Rackham (2001: 166) suggest that humans played a role in the colonization of the vast majority of the circum-Mediterranean landscape by the modern suite of plants by ca. 3000 to 1000 B.C.E. Pollen data indicate cultivation of

cereals and grazing by domesticated animals in the *Serra da Estrela*, north of the study area, by approximately 5000 B.C.E. (Van den Brink and Janssen 1985; Van der Knapp and Van Leeuwen 1995). The same pollen data reflect large-scale deforestation by 1200 B.C.E. in the *Serra da Estrela*, part of a pattern of steadily increasing anthropogenic landscape alteration that continued through the Roman era. Similarly, Stevenson and Harrison (1992) use pollen data to infer significant anthropogenic alteration of the forests of what is now southwest Spain, east of the study area, by ca. 4000 B.C.E. Their data indicate increasing anthropogenic impacts through time, leading to widespread deforestation between 1600 and 500 B.C.E. and, eventually, to active management of forests beginning in the Roman era. Archaeological remains in the study area indicate that it saw a trajectory of settlement and land use from the Neolithic through the Roman era similar to that seen across southern Iberia. Clearly the region, including the study area, has witnessed millennia of farming and herding; Barton *et al.*'s (2004: 253) assertion that "ecology has discovered a past; and in many cases this has turned out to be a human past" is particularly apt in this setting.

Unsurprisingly, the composition and distribution of modern plant communities in the study area largely reflects human activities. Outside of villages and small walled gardens sustained by groundwater irrigation, traditional land use practices include extensive wheat farming and the maintenance of *montados* (called *dehesas* in Spain), managed woodlands modified by grazing, light pruning, and manuring to improve the productivity of the landscape for animal husbandry (Stevenson and Harrison 1992). Grove and Rackham (2001: 194) refer to this as an "agro-silvo-pastoral" system to emphasize that it produces a wide range of crop, forest, and herd animal products. Dryland cultivation of wheat is characterized by low inputs of labor and low yields per hectare as well as a relatively long fallowing cycle; individual fields are planted roughly every seven years, depending on the decisions of landowners. Large herds of sheep and the occasional goat, and in some places smaller herds of pigs or cattle, graze fallow and harvested fields or fields in which grain production was too low to warrant harvesting. In the *montados* and many cultivated fields, larger trees (mostly different varieties of oak [*Quercus* spp.], including cork oak [*Quercus suber*]) are left standing, creating a parkland

appearance[1]. Areas left fallow for longer periods revert to a tall brush, dominated by a plant locally known as *esteva* (*Cistus ladanifer*; gum rockrose in English). The result is a patchwork agrarian landscape that is, in general, aesthetically pleasing.

The climate in the *Baixo Alentejo* is Mediterranean, with cool, wet winters and hot, dry summers that are the longest average dry season in the Mediterranean region (Grove and Rackham 2001: Fig. 2.2). Instrumental climate data with significant historical time depth are not available for Mértola but they have been recorded in the town of Beja, located approximately 45 km to the northwest, at least since the early 20th century; data from Beja can be taken as representative of climate patterns in the study area. The instrumental meteorological data covering the 1925 – 1994 water years show an average annual rainfall of 567 mm, slightly below average potential evapotranspiration rates. Rainfall is highly variable from year to year, with a range of 207 mm to 972 mm/ year and a standard deviation of 164.3 mm for the same years (data on file). These data are presented graphically in figure 1.2.

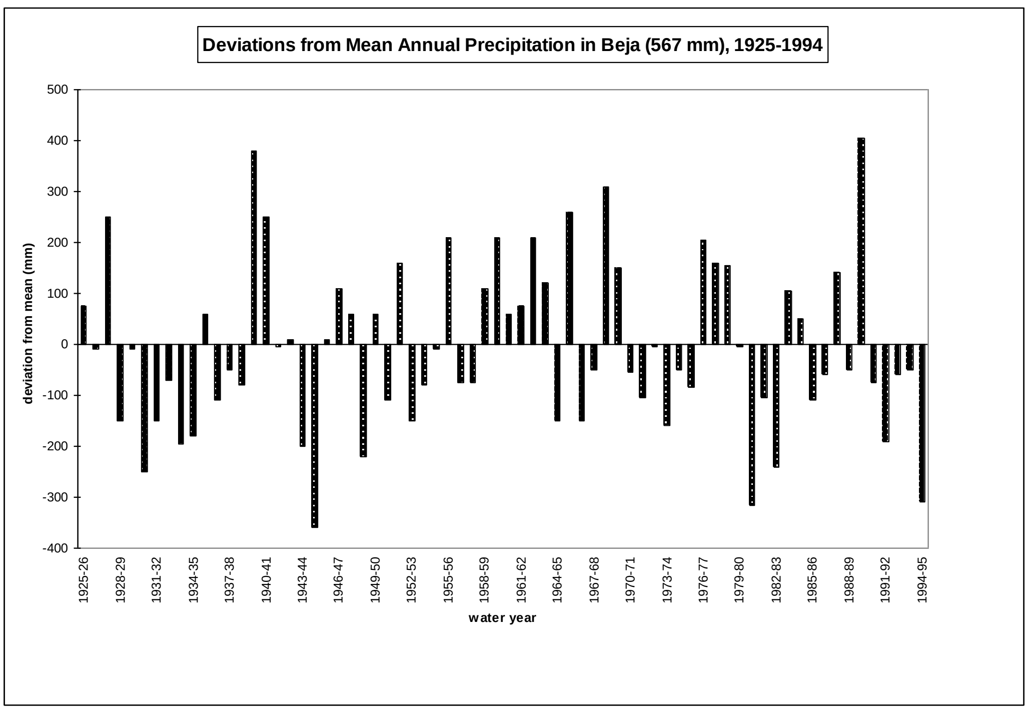

Figure 1.2 Annual rainfall data for Beja, presented as deviations from the mean.

[1] Technically this is a savanna. The English term parkland denotes a walled or fenced area (Grove and Rackham 2001: 190)

The primary environmental determinants of agricultural productivity in the study area are water availability and the quality and depth of soil. Perennial rivers, including the Guadiana and its major tributaries, are deeply entrenched in bedrock-dominated channels in narrow valleys at elevations tens of meters below the surrounding countryside. Smaller streams at higher elevations are dry four to five months each summer. The seasonal lack of surface water and the elevation of permanent water sources relative to the surrounding landscape severely limit irrigation potential. In the absence of irrigation, wheat, the primary cereal crop, requires substantial late winter and spring rainfall for maturation. Instrumental data show that a large proportion of the interannual variability in rainfall in the Alentejo is due to variation in spring rainfall (Grove and Rackham 2001: 125, figure 7.9)

Soils across the study area generally are thin, rocky, and deficient in nutrients, and they are classified as unsuitable for agriculture (SRAO 1959). They are among the poorest soils in the Mediterranean region (Grove and Rackham 2001: 47). Pockets of thicker soil occur in some topographically low areas. These hold winter moisture better than thinner soils, often allowing the crops there to mature in years of poor precipitation. The combination of variable soil depths and unpredictable late winter and spring moisture engenders high variability in agricultural productivity, both across space and from year to year. Localized crop failures are a recurrent problem and domestic animals, dependent on grasses and forage that rely on the same rainfall as agricultural crops, provide only a partial hedge against shortfalls.

Previous investigations of long-term landscape evolution in the adjacent Algarve region demonstrate that the area is particularly sensitive to the impacts of human activities due to thin soils, the xeric/ arid Mediterranean climate, and the high erosion potential caused by hilly topography and erodible bedrock (Chester and James 1991, 1999). The climate and topography in the study area are similar to those of the Algarve. In addition, the bedrock in both areas is highly erodible, consisting primarily of uplifted deep-sea sediments modified by low grade metamorphism (Oliveira 1989). As in the Algarve, extensive farming during the 20th century has caused widespread soil erosion and arroyo formation in the study area. In sum, the study area is a Mediterranean landscape, heavily modified by millennia of human activities. It also is prone to

anthropogenic degradation. Recent degradation may provide a reasonable analog for processes in the past, and episodes of degradation in the past may provide some insight into ecological challenges currently confronting the Mediterranean region and other Mediterraneanoid ecoregions around the world.

Culture-Historic Context

The outlines of the history of Iberia after the decline of the Western Roman Empire are relatively well known from documentary sources and a few archeological investigations and they have been synthesized in several publications (e.g., Boone 2009 chapter 2; Collins 1983; Glick 1995; Lewis 2008; see also Lopes 2003 for a detailed discussion of the late Roman era in the *Baixo Alentejo*). Table 1.1 summarizes the chronology of the post-Roman era, including period designations, dates, major historic events and characterizations of general processes.

Written records provide numerous details including the names of historic figures and calendar dates of significant events, but they generally fail to address broader issues directly. Their apparent precision, often questionable in itself, poses the danger that scholars will continue to accept personality- and event-driven explanations of historic processes. These explanations are, on closer inspection, often facile and incomplete (see Braudel 1976 [1949] for the classic statement of this position; Morris 2000 offers a narrower and more recent discussion that emphasizes the relevance of archaeology). Scholarly debates regarding how to understand historic events and conceptualize processes during the Islamic period in Iberia clearly demonstrate the shortcomings of the documentary record, prompting Glick (1995) to conclude that a social history of Islamic Iberia is virtually impossible without the contributions of archaeology.

As one example, the success of the Islamic invasion led by Tariq ibn Ziyad in 711 C.E. is difficult to understand based solely on written records. Documentary sources recount a truly astounding series of events: despite broadly similar military technologies and tactics, a raiding party of roughly 1,700 to a few thousand Berbers and Arabs from North Africa routed the Visigothic army led by king Rodrigo, purported to number as many as 100,000 men in eyewitness accounts (Collins 1983; Lewis 2008: 123). The invaders pressed on to capture Toledo, the Visigoth capitol, and most other population centers across Iberia fell to them within the year. Resistance to the invasion crumbled,

Table 1.1: Chronology of the Late Roman and Islamic periods in the Iberian Peninsula[2]

Major Period	Minor Period	Calendar Dates C.E.	Characterization/ Major Processes and Events
Late Roman	Late Roman (also Hispano-Roman, Visigothic, Paleo-Christian)	450 – 711	*5th century:* Roman imperial system crumbles; Vandals, Sueves, Franks, Visigoths and renegade Roman Legions invade Iberia. *6th century:* Peninsula divided between Byzantine outpost on Southeast coast and Visigothic and Suevic kingdoms. Visigothic and Suevic kingdoms united in 585 by King Leovigild. King Recarred converts from Arian to Catholic Christianity in 587. *7th century:* Visigoths conquer Byzantine outpost in 624. Ongoing conflict with Basques. Endemic conflicts within Visigoth nobility over leadership and succession to the throne. *General:* Roman cultural traditions and rural settlement patterns continue. Urban centers and long-distance trade decline significantly.
Islamic	Paleo-Andalusí	711 – 929	711: Tariq ibn Ziyad leads Islamic invasion of Iberia, defeats Visigoth king Rodrigo (Roderick) in Guadalquivir valley and captures Toledo (Visigoth capital). 711 – 756: Islamic occupation. 756: ‘Abd al Rahman I enters Iberia. 756 – 929: Umayyad Emirate; consolidation of Muslim political and cultural dominance; independence from Damascus (‘Abassid) Caliphate marks first major rift in Islamic Empire.
	Califal	929 – 1009/ 1031	929: Umayyad Caliphate established, centered in Córdoba. Political and economic unification of *al-Andalus*.
	Taifal *	1009 – 1086/ 1140’s	Internal conflicts cause Caliphate to break apart into a series of independent small states (city-states) called *taifas*. Advance of the Christian *reconquista*; Toledo falls to Christians in 1085. Independent *taifas* persist in parts of the peninsula until the mid-12th century.
	North African *	1086 – 1250	North African armies (mostly Berber) invited to Iberia to fight the Christians. North African Almoravid Dynasty seizes control of much of *al-Andalus* 1086 – 1106. North African Almohad Dynasty controls *al-Andalus* 1145 – 1250. Center of power shifts to Seville. Christian *reconquista* continues to advance; Córdoba falls to Christians in 1236, Seville falls in 1246.
	Nasrid *	1230 – 1492	Nasrid kingdom in Granada becomes the only remaining Islamic political presence on the Iberian peninsula. Nasrid king Boabdil yields to Fernando (Ferdinand) and Isabella, January 1, 1492.

***** periods overlap chronologically because they refer specifically to political configurations that varied at different times in different parts of Iberia.

reinforcements arrived from North Africa, and the Muslim *jihad* overcame all significant remaining opposition within the following few years and pressed on into parts of modern-day France. Contemporary accounts written by observers from both sides take on apocalyptic overtones; unless one believes it was the will of Allah, the historical

[2] Table 1.1 is based on information presented in: Boone 2002, 2009; Collins 1983, 1989; Glick 1995; Guichard 1998; Gutierrez-Lloret 1988; Hernández 1998; Lewis 2008.

documents do not satisfactorily explain how a small raiding party was able to topple the Visigothic kingdom that had ruled the peninsula for generations.

Research focused on the late Roman period has produced several important clues. Cultural traditions and rural settlement patterns established during the Roman period persisted through the late Roman period, with Visigothic and Hispano-Roman aristocrats controlling large rural *villae*, often worked by slaves. At the same time, urban centers and long distance trade declined significantly, reflecting a decline in extra-local economic integration (Boone 2002, 2009; Glick 1995; Gutierrez-Lloret 1988; Lewis 2008: 105 – 117). Independent peasant communities appeared in some parts of Iberia, perhaps indicating that the nobility had lost control of the rural economy, and the Visigothic state may have been weakened further by extended drought (Glick 1995).

Beyond the economic fragmentation, King Rodrigo was elected by the Visigothic nobility in 710 after major disputes concerning succession, and he spent most of the first year of his reign campaigning against the ever-recalcitrant Basques and attempting to consolidate his power in the face of continued resistance by rivals (Collins 1983, 1989; Lewis 2008: 119 – 120). Finally, the Visigoth "state", such as it was, was composed primarily of a relatively small population of ethnically distinct Visigoth elites. They ruled over a disarmed and disenfranchised population, including a relatively large and severely persecuted urban Jewish minority. Outside the Visigoth nobility, the population of Iberia had few military resources to contribute to – and almost no vested interest in contributing to – maintaining the extant order (e.g., Lewis 2008: 111 – 117).

Taken together, these broader archaeological and documentary data suggest that the Visigothic kingdom was poorly integrated economically and politically, and that the King's army likely was far smaller than reported, in addition to being battle-weary and internally divided. David Lewis (2008: 106, 123 – 4) suggests that Rodrigo led a host of perhaps 30,000 men at most against Tariq's few thousand when they met in the Guadalete valley in early July of 711 C. E. Moreover, he presents evidence that at least one wing of Rodrigo's cavalry, loyal to a different aspirant to the Visigothic throne, betrayed him during the final battle. In this context, the astonishing success of the invaders is not as much of a conundrum.

A related and more extensive scholarly debate focuses on how to conceptualize the Islamization of Iberia following the invasion (see Boone 2009, chapters 1 and 5 for overviews of this debate). Written records convey information about the literate classes: the urban Arab elites and the clergy in the surviving Christian churches. They are virtually silent on the issues of rural social and economic organization, population movements, and urban – rural interactions, allowing scholars to argue for widely varying views of the extent, nature, and processes of cultural change during the Islamic period. Pierre Guichard (1976), a historian, has forcefully challenged the traditionalist view of the Islamic period as an ephemeral occupation with limited cultural significance. Instead, he proposed a dramatic cultural disjunction between the late Roman and Islamic periods, with demographic replacement of indigenous populations by Arabs and Berbers whose segmentary lineage organization facilitated defense and expansion in Iberia. Guichard's work stimulated archaeological and historical research through the 1980's and beyond and is undoubtedly among the most significant contributions to the literature concerning the Islamic period in Iberia.

In his seminal work, Guichard was strongly influenced by structural-functionalist theory in social anthropology and he consequently viewed the Islamic and Latin Christian civilizations as founded on conflicting structural principles of domestic organization. These principles dictated different systems of descent, marriage, organization of kinship, roles of women, and notions of honor (see Goody 1984 for a critical discussion). Boone (2002; see also 2009: 16 - 19) observes that the depth of the opposition portrayed by Guichard obscures the complex processes of transition from the Late Roman to the Islamic period. Specifically, it requires wholesale population replacement and, apparently, the disappearance of millions of Hispano-Romans; it virtually rules out intermarriage and syncretization, both of which are well documented in the historical record; and it conceptualizes the contrast between Islamic and Latin Christian cultures in terms of culturally specific mental structures.

During the past two decades, the focus of archaeological and historical research has shifted from documenting the dramatic implantation of North African culture into Iberia, as envisioned by Guichard, to investigating the processes of transition from the Hispano-Roman to the Islamic world (Boone 1994, 2002, 2009, with references). Among

other things, this body of scholarship examines regional variation (Guichard 1998) and the dynamics of interaction between different factions, especially Arab and Berber, within the immigrant populations (Hernández 1998). Current research considers the possibility of syncretism between indigenous and North African populations (Boone 1994; 2002). It also investigates the interplay between the urban and rural spheres, particularly as exemplified by the rural revolts led by *muwalladun* (singular: *muwallad*), early converts to Islam who became clients of the urban Arab elites (Fierro 1998). More general synthetic works (e.g. Acién Almansa 1998; Boone 2009; Boone and Benco 1999; Glick 1995) attempt to place the Iberian case within the context of macro-regional processes such as the resurgence of rural autonomy in the post-Roman world, the fortification of the countryside during the Early Medieval period (Toubert's "*incastellamento*" [1990; see also Hodges 2003]), the development of trade-based Islamic empires in northwest Africa, and the growth of feudal political and economic systems across Christian Western Europe.

Despite – or perhaps because of – this ongoing and lively academic debate, a consensus appears to be emerging among scholars concerning some of the fundamental aspects of the economic, social, and political organization of *al-Andalus.* Immigration from North Africa and the eastern Mediterranean probably was minimal during the first decades following the conquest of 711. In approximately 750, however, the population of Iberia began a trajectory of dramatic increase that lasted for several centuries. Population estimates for the early 8th century are somewhere between 3 and 5 million persons, and taxation records suggest approximately 7 million in 822 and 10.2 million by 947 (Boone 2009: 87). The population increase was due in no small part to immigration beginning in the 8th century, including the arrival of Arab military divisions originally from Syria (*junds*) as well as large numbers of Berbers from North Africa.

During the Islamic period Arabs were a cultural and economic elite class in Iberia like the Visigoths had been before them, despite a significantly more lenient view of intermarriage with women of other ethnicities (Lewis 2008). The Arabs settled primarily along the coastal plains and major river valleys and in established urban centers, loci with the potential for intensive irrigation agriculture and/ or control of trade and commerce (Butzer *et al.* 1985; Collins 1983; Glick 1995; Hernández 1998). Berbers from North

Africa colonized less productive land, often in hilly or mountainous regions (Butzer *et al.* 1985; Guichard 1998) and, with the *muwalladun,* they made up the majority of the population in the marches, the contested areas bordering the Christian kingdoms to the north (Boone 2009: 83 – 84; Lewis 2008: 184 – 208). Immigrant Berbers in particular may have merged to a significant degree, both culturally and genetically, with Hispano-Roman populations (Boone 2002).

The area around Mértola presents a microcosm of the peninsula-wide cultural and ecological interactions of the Islamic period, particularly for the marches. The study area is located at the southern periphery of the lower march (Boone 2009: 65). The high variability and generally low productivity of agrarian production in the study area, as throughout most of the marches, created a situation in which the Arab state appears to have invested little in maintaining direct economic or political control of the hinterland because surplus was too unreliable to be extracted regularly (Dinsmore 1995). In fact, the region probably had maintained some degree of independence throughout the Visigoth period (Boone 2009: 52 – 60) and powerful political rivals were tolerated there, for a time, during the struggles to establish a centralized Umayyad polity in *al-Andalus* (Lewis 2008: 200 – 202). Rural populations during the Islamic period were most likely descended from both Hispano-Romans and Berbers from North Africa (Boone 2002). The area is drained by the Guadiana River which, prior to the twentieth century, was navigable by oceangoing vessels as far north as the town of Mértola. Mértola, as a port and a regional center, was an Arab enclave and a point of articulation between the state and rural agrarian populations. It also was the center of at least one major rebellion by rural populations against the Arab polity (Goulart 1992). The past presence of Arabs, Hispano-Romans, and Berbers, the low modern population density, the recent downcutting of ephemeral streams, and the physical environment make the study area an ideal location to conduct the research reported here.

To summarize, the Islamic state allowed the persistence and even growth of independent rural communities initially established during the period of reduced centralized control following the dissolution of the Western Roman Empire, especially in agriculturally marginal areas. During the Islamic period, rural populations were

organized tribally[3], with local leaders forming unstable alliances with rulers or representatives of the state. Despite the generally low agricultural potential of the tribally controlled areas, land use strategies apparently favored relatively high population densities (Boone and Worman 2007).

General Model and Research Questions

Building on the historical and archaeological research conducted in recent decades, and in contrast to Guichard's concept of competing deep mental structures ("*mentalités*"), the issue of Islamization can be reframed productively by contrasting economy and behavior in the Late Roman, Islamic, and Christian medieval periods. Instead of being viewed as competing mental structures, the Islamic and Latin Christian systems can be characterized as alternative ways of organizing access to and using land, controlling surplus, and mitigating shortfalls. Table 1.2 summarizes this comparison.

Table 1.2: Comparison of past land use strategies in the study area.

Strategy:	**Segmentary Society**	**Latifundia**
Access to land	Acephalous kin groups ("tribes"); broad expanses of land are more or less communally controlled; access and use regulated by genealogical relationships, marriage, political alliances.	Very large expanses of land controlled by single landowning families to compensate for local production failures. Access regulated by inheritance, primogeniture.
Land use	Intensive land use, high population densities.	Extensive land use; underemployment; seasonal labor only. Low population densities.
Control of surplus	Local autonomy with respect to use of majority of surplus. The state, if present, is urban-based and exerts little direct control over hinterlands.	Surplus controlled by landowners, extracted as rent or through slavery or sharecropping. System is dependent on strong central state as "enforcer".
Mitigation of shortfalls	Local production failures ameliorated through kinship links, access to land in multiple ecological niches; common use of fallow for grazing.	Local famine relief (if any) provided by central state. Livestock controlled by landowners.
Time periods	Iron Age, Islamic period, some recent attempts at land reform.	Roman period, Late Roman period, Christian medieval and modern periods.

[3] Following usage common in European scholarship, "tribal" here refers to a form of economic and political organization based on shared territory, language, and identity. Tribes typically are endogamous and relationships between members usually are expressed in terms of real or fictive kinship. Tribes may control very large areas and number in the 10s of thousands or more individuals. Leaders can emerge at the head of large factions, and leadership may be, to some degree, passed on within a family. This is not exactly the same as the meaning of "tribe" as often understood in North America, which is based on cultural evolutionary typologies such as those of Sahlins and Service (1960) or the modified form offered by Fried (1967); like the more general "mid-range societies," it incorporates aspects of both chiefdom and tribe as described in those schemes.

Overcoming the high spatial and temporal variability of production in the study area – as in many other parts of Iberia – is a necessary precondition for the survival of an agrarian population. People adopted two contrasting land tenure systems at different times in the past to overcome the problems of spatial and temporal variability in production. These systems were founded on the same or highly similar technologies and resources but entailed different social organization, or relations of production. In one system, very large expanses of land (*latifundia*) were controlled by elite landowning families. Some portion of a large estate was likely to produce a surplus in any given year, and the wealth accumulated by the family during good years maintained them through periods of reduced production. Land use was extensive (as opposed to intensive), and labor was in demand only during brief seasons of planting and harvesting. The majority of surplus was extracted by the elite families from the primary producers – the majority of the population – through slavery or sharecropping or as rent. Due to low demand for labor and a limited rural economy, population densities in rural areas remained low and the majority of the population remained impoverished. The centralized state acted as an enforcer and sometimes provided local famine relief for primary producers in times of extreme need.

In the contrasting system, broad expanses of land were more or less communally controlled by large groups lacking strong institutionalized leadership; historically these have been segmentary societies or "tribes" in the sense that the word is used in Europe. In order to mitigate shortfalls, families negotiated access to land in multiple ecological niches and shared surplus through political alliances, genealogical relationships, and ties between families based on marriages. The centralized state, if present at all, exerted little direct control over the rural economy. The majority of surplus was retained locally and there was a better developed economy, resulting in higher population densities, more intensive land use, and greater accumulation of wealth in producer households.

With the exception of the Islamic period, land tenure systems in the *Baixo Alentejo* have been dominated by *latifundia* since the early Roman period (Boone 2002, 2009; see also Delano Smith 1979). The ubiquity of this form of organization suggests that it is a successful response to high spatial and temporal variability of agricultural production. During the Islamic period, however, rural settlements were small, dispersed

farmsteads and villages without any clear indications that a small group of wealthy families controlled access to land (Boone 2002; Boone and Worman 2007). Archaeological and historical evidence indicate that the alternative tribal land tenure system was dominant during that period. Because the Iberian climate has been relatively static during the Christian era (Bryson 2005, Butzer 2005; Castro *et al.* 2000; Chester and James 1991, 1999; Delano Smith 1979; Gilman and Thornes 1985; Grove and Rackham 2001: 145 – 150; Stevenson and Harrison 1992; van der Schreik *et al.* 2007; Vis *et al.* 2008), the success of the Islamic system for half a millennium suggests that it also was a successful means of minimizing the risk associated with variable yields.

Ethnographically recorded analogs for social organization and the rural agrarian economy in the study area during the Islamic period may be found among the Berbers of North Africa. For example, Peters (1990) has argued that, in Cyrenaica, a pattern of local tribal autonomy incorporating spatially extensive social and political networks developed as a stable response to resource variability. Families negotiated access to land in multiple microenvironments, taking advantage of membership in groups that collectively controlled the land, and they shared surplus – and risk – through genealogical, social and political networks (see also Munson 1989 and Rosen 1979 on collective land tenure systems in North Africa and Boone 2009: chapter 4 on applying this model to Islamic Iberia). Whether these land use systems were introduced to Iberia by immigrant Berbers or they appeared locally as a parallel development during the Late Roman period (or, perhaps, some combination of both) is an open question and one that is exceedingly difficult to answer with any degree of certainty (see discussion in Boone 2009, Chapter 5). Fortunately, resolving the issue of origins is not necessary in order to understand the ecological and socio-political consequences of adopting such land tenure and production systems.

Although it admittedly sidesteps many historically intriguing questions, such as the total number of immigrants entering Iberia, the timing of their arrival, the ethnic makeup of rural communities, and the processes and timing of conversion to Islam among the local populations, this shift of focus to examining economic behavior emphasizes other interesting aspects of the Islamic period. Specifically, it allows investigation of the economic processes of transition, admits the possibility of cultural

syncretization, and permits a consideration of the agency of individuals in cultural, economic, and ecological processes. In addition, this formulation of the problem is more amenable to archaeological investigation than Guichard's because behavioral and economic patterns leave material traces, while the correlates of deep mental structures are likely to be obscure. Finally – and crucially for this research – it also facilitates a comparison of the ecological consequences of different forms of social organization and land use.

Al-Andalus eventually succumbed to the Christian *reconquista*, but the Islamic system had flourished for over five centuries in the study area and it continued for another three in Granada. In fact, given its long-term success and the apparent increase in population density during the Islamic period, the *reconquista* becomes something of a historical conundrum; how could the Christians succeed against a more numerous (and better armed – see Chapter 3) population? Logically, the success and eventual failure of *al-Andalus* are related to its unique characteristics relative to the feudal Christian states that ultimately gained control of Iberia.

There are two plausible alternatives concerning the characteristics of *al-Andalus* that ultimately led to its demise. One possibility is that the Islamic polity failed due to inherent instability. The instability was caused by the incorporation of many autonomous, tribally organized groups into the state and by perennial competition between factions within the Arab, Berber, *muwallad*, and Arabized Christian (*mozarab*) populations. Contemporary documents produced by literate elites embroiled in those conflicts support this view and it is commonly accepted in the historical literature.

Curiously, some variant of this "internal divisions" argument has been proposed as an explanation for the defeat of numerous empires and states at various times and places in world history: the Western Roman Empire in the early 5th century, parts of the Eastern Roman Empire in the late 6th and mid-7th centuries, the Sassanid (Persian) empire in the mid-7th century, the Visigothic kingdom in Iberia in the early 8th century, and the Aztec and Inka Empires in the early 16th century are just a few examples. On the other side of the same coin, incorporation of multiple groups into a single polity is touted as a strength of the Roman and Sassanid empires earlier in their histories, as well as a strength of the Islamic empire during the period of rapid expansion in the 7th century. It seems

likely that factional competition is present, to some degree or other, in every state level polity (and probably also in smaller-scale polities); perhaps the question should be reframed in terms of the conditions that allow such competition to cripple one state or empire while favoring another. In the case of the eventual Christian *reconquista*, the pertinent documents do not suggest that the kingdoms of northern Iberia were free of political intrigue, well-integrated and united, or necessarily more politically stable than *al-Andalus* at some fundamental level; based on the documentary evidence, Lewis characterizes politics there as a self-perpetuating "cycle of fratricide, parochial agendas, and endogamous assassinations" (2008: 351).

A second possibility focuses on the implication that higher rural population densities during the Islamic period necessitated more intensive land use than in other periods. This may have set the stage for anthropogenic degradation of the landscape and a significant reduction in agrarian productive potential. While the Islamic state did not rely directly on extraction of agricultural surplus, particularly from the less productive areas, collapse of the rural economy would engender unrest and rebellion and increase the cost of basic commodities while simultaneously reducing the wealth available to the state through taxation or tribute. Also, depopulation of the countryside would deprive the state of military personnel, clearing the path for the *reconquista*. The relative success of rural populations during the Islamic period may thus have planted the seeds of the eventual demise of the system.

While these possibilities are not mutually exclusive, the long-term sustainability of agrarian land use during the Islamic period is a potentially important variable that has not been evaluated in previous research. Sustainable land use is defined here as a system of production that can continue indefinitely within a given area (i.e. the study area) without causing measurably diminished returns due to anthropogenic alteration of the landscape. At the scale of human generations, both the Islamic and Romano-Christian systems clearly were successful and sustainable adaptations to patchy productivity. At longer time scales, however, anthropogenic landscape change related to the particulars of either structure may have reduced agrarian yields. The changes in the costs and benefits associated with different land use and surplus extraction systems would constrain the economic and political choices made by both elites and primary producers.

If intensive land use caused significant degradation during the post-Roman era, geoarchaeological studies should be able to detect soil erosion and constrain the timing of landscape change. Evidence for widespread erosion during the Islamic period would support the hypothesis that environmental degradation was a factor in the demise of *al-Andalus*. This does not require that the Islamic system be viewed as particularly well integrated or politically stable; it simply clarifies the role of a previously uninvestigated variable. If, on the other hand, there is no evidence that Islamic-period land use was unsustainable at the scale of centuries, the alternative hypothesis is supported.

Importantly, it is not sufficient to determine only whether or not ecological degradation occurred during the Islamic period. While this would provide insight into historical questions concerning the *reconquista*, it is fundamentally uninteresting at a general level to show that increased population density can cause erosion and environmental degradation in a fragile, semi-arid environment. The processes of degradation, its links to social organization, and the contributions of exogenous variables (i.e. climate change) must be considered in order to illuminate "the complex chains of mutual causation in human-environment relations" (Crumley 1994: 2). The research recounted here therefore focuses on exploring the complexities of socio-ecological processes in greater detail in ways that will be clarified in subsequent chapters.

Chapter 2:
Theoretical Considerations

Archaeological theory can be defined broadly as the set of ideas archaeologists use to generate statements about the human past based on the archaeological record and other sources of information. Method, by contrast, is the set of techniques used to investigate, describe, and quantify aspects of the archaeological record. As an heuristic device, theory often is divided into low, middle and high levels (e.g., Thomas and Kelly 2006: 51; Trigger 1989: 19 – 25). Low-level theory concerns identifying relevant sources of information and making observations; it guides the application of method. Mid-level theory consists of arguments linking those observations to past human behavior. At the high level, theory attempts to answer more difficult "why" questions about behavior, culture, social systems, and other general anthropological subjects.[4]

For practical reasons low and some aspects of mid-level theory usually are not discussed explicitly in the context of any given investigation, being treated essentially as a widely accepted set of assumptions and conventions. There is little reason to do otherwise here. In order to situate this research in relation to the relevant scholarship, however, it is important to consider several aspects of mid- and high-level theory, specifically the concepts used in demonstrating causal links between human behavior and ecological change and the broader question of why people caused ecological degradation in the study area in the past. These questions incorporate several overlapping bodies of literature, including varied attempts to understand human-environment interactions, the relationships between elites and producers in complex societies, and modes of explanation applicable to studies of complex socio-natural systems.

Modes of explanation

In a recent article, Karl Butzer (2005) summarized the results of several major programs of research focused on long-term human-environment interactions in Greece

[4] This structure is useful for organizing discussion, but the three levels are inextricably linked in practice. For example, high-level questions have implications for selecting appropriate research methods and the nature of the archaeological record – the nature of the data that can be obtained – inevitably affects the mid- and high-level questions that can be answered in a given situation.

and eastern Spain. Butzer's lengthy article discusses both broad theoretical issues and problems more specific to the environmental history of the Mediterranean world. He considers world systems theory, the problem of conceptualizing degradation in the Mediterranean region, and the roles of human perceptions and attitudes in determining ecological behavior. In addition, Butzer examines narrower technical problems such as measuring ecological degradation and isolating anthropogenic impacts from the effects of external climate change. His considerations of techniques, perceptions, and conceptualizing degradation are discussed further in Chapter 5, below, while the more abstract theoretical concerns related to explanation are weighed here.

Framing his article as a critique of the field of environmental history, Butzer emphasizes the problem of demonstrating cause and effect relationships in socio-ecological systems. In addressing the issue, he discusses at length the sometimes-problematic relationship between the humanistic and natural sciences in environmental history research. This is particularly relevant here because archaeology in general and geoarchaeology in particular frequently operate across the borders between the humanistic and natural sciences. Butzer argues persuasively that the natural sciences lay a necessary foundation for historical reconstruction by addressing questions of how and when the environment changed. They often fail, however, to account for all of the relevant variables in a socio-natural system when attempting to answer why those changes occurred. He proposes that humanistic research is necessary to illuminate the values, perceptions, cultural traditions, and historical contexts that influenced how people interacted with the environment. He contends that only by combining the natural and humanistic sciences is it possible to explain fully a given history of human-environment interactions.

In addition to clarifying the complimentary roles of the natural and social sciences in building explanations, Butzer examines the ways in which each has been applied to environmental history. He notes that the interactions of physical systems (i.e., climate, landscape) and human societies are strongly affected by historical contingencies. Erosion, landscape change, and climate change are complex processes in the narrow sense: the state of the system at any given time is determined not only by mechanistic processes but also by the state of the system at previous times and by changing linkages

between interacting components. Because of this complexity, Butzer argues that a “deductive, theory-driven approach” (2005: 1774) to research is inadequate for determining the historical trajectory of events or the reasons for that trajectory.

Although it is not particularly explicit, Butzer’s argument amounts to a rejection of predictive modeling in the natural sciences and, more specifically, its application to predicting (or “retrodicting”) soil erosion in the past. Because they necessarily involve simplification and focus on mechanical process, predictive models generally perform poorly in attempts to determine the timing or severity of erosion at any particular place or time in the past, especially at scales of interest in archaeology – at human generational time scales and at spatial scales larger than individual slopes and smaller than broad regional generalizations (see Chapter 5 for an extended critique of specific modeling approaches to past soil erosion). Instead, Butzer favors detailed, empirical geomorphic and paleoenvironmental research in an inductive mode to build local chronologies of environmental change.

Examining the role of the social sciences in environmental history, Butzer criticizes world systems theory. While useful as an heuristic, he maintains that it is not properly explanatory for any particular case, largely because statements about ecological change in the past remain undemonstrated or poorly justified in the work of world systems theorists. He adopts from world systems theory the central concept of cycles of intensification and deintensification (or ruralization) which are linked to the waxing and waning of large-scale social systems. He argues, however, that these must be understood from a local perspective in order to gain insight into the ecological history of any particular area. The clear implication is that satisfactory regional environmental histories should be built by aggregating many small-scale, local environmental histories that are based on thorough, well documented natural science investigations.

Demonstrating that the environment changed in particular ways in the past remains, however, only part of an investigation of a socio-natural system; it leaves aside the question of the possible human causes of and reactions to environmental change. Humanistic research is necessary to illuminate the historical and cultural contexts that influenced people to act in the ways that they did. Butzer therefore suggests that it is only by combining the natural and social sciences in programs of long-term

interdisciplinary research focused on small geographic areas that environmental history can achieve its full potential: "a 'deep' understanding, leavened by humanistic insights, and fully cognizant of the multiple contingencies that bedevil most efforts to determine cause-and-effect relationships" (2005: 1774).

Butzer's discussion obliquely raises two fundamental problems with causal explanation, particularly as regards complex socio-natural systems. The first is determining what constitutes a satisfying explanation in terms of the continuum between proximate and ultimate causes. Second is the relationship between generalities (concerning large-scale social systems or the mechanics of erosion, for example) and the specific historical trajectories of complex systems. Ultimately, resolution of both problems involves a researcher making more-or-less aesthetic judgments, and those judgments most appropriately are informed by overall disciplinary goals and the specific research questions at hand.

One basic difficulty with building satisfactory explanations is that "why?" questions can be answered in numerous ways and at many different levels, highlighting the problem of infinite regress[5]. To illustrate, the question of why soil erosion occurred can be answered in terms of a proximate cause that can be deduced from general principles – soil eroded because the forces favoring erosion exceeded the forces holding the soil in place. Of course this begs the question of why those forces changed, which again can be answered mechanically if it is possible to determine that any of the relevant variables changed (i.e. plant cover, slope angle, quantity and timing of precipitation, etc.). But again, the question of why that variable changed legitimately can be posed and, in socio-natural systems, the answer may have to do with human actions – people plowed steep hillslopes or allowed overgrazing, which removed vegetation and therefore reduced resistance to erosion. In the next iteration, the question then becomes, why did people plow the hillslopes or allow overgrazing? The key point that can be picked out of Butzer's argument is that satisfying explanations of the dynamics of socio-ecological systems are to be found at this "proximatish" (Fogelin 2007: 615) level, without

[5] Anyone who has ever attempted to explain something to a precocious child who has recently discovered the question "why?" will be intimately familiar with this problem; explanation of virtually any phenomenon will eventually lead back along a chain of causality to unknowns – ultimately, one will be faced with something like "…but *why* did the 'Big Bang' happen?"

following the chain of causality further into vague, general, and difficult to prove statements concerning human nature. Natural science techniques and general geological principles can answer the proximate, mechanical questions about landscape change, but they do not address questions of human behavior or motivation.

Lars Fogelin's (2007) recent discussion of explanation in archaeology may be useful here. He elucidates the structure of successful arguments as inference to the best explanation and provides a justification for using contrastive, as opposed to causal, forms of explanation. Fundamentally, inference to the best explanation is a variant of the method of multiple working hypotheses (Chamberlin 1965 [1890]). It consists of choosing among multiple possible explanations for empirical phenomena, largely by favoring those that successfully explain more of the data at hand. Contrastive modes help to focus explanation at satisfactory levels by asking, for example, not "why did an event occur?" but "why did this event occur, and not that one?" (or, "why did people plow hillslopes at that time, and not at others?"), thereby limiting the problem of infinite regress. Fogelin also provides a more specific list of overlapping and sometimes contradictory criteria by which explanations can be evaluated: empirical breadth, generality, modesty, refutability, conservatism, simplicity, and multiplicity of foils. His guidelines for evaluating arguments can be used to further focus research and to build strong arguments.

Despite providing useful guidelines for *how* to focus explanations at the appropriate point along the continuum between proximate and ultimate causes, Fogelin's article fails to address clearly *why* researchers should seek to identify any particular point on that continuum as more appropriate than others. For example, any of the three explanations proposed above for soil erosion (i.e., stating that the forces favoring erosion exceeded those holding soil in place, or identifying changes in any particular variable affecting those forces, or inferring that human actions caused changes in one or more of those variables) could be considered a successful argument according to various combinations of his stated criteria. Ultimately, both Fogelin and Butzer state (without elaboration) that successful research focuses on "interesting" questions and explanations, leading both authors to suggest that satisfying explanations involve considerations of human motivations and decision-making within particular historical contexts. Obviously,

this criterion speaks directly to disciplinary goals and the individual researcher's propensities. In this case, reconstructing the trajectory of landscape change in the study area – interesting in and of itself and fully commensurate with disciplinary goals of geology and geomorphology – is insufficient as an explanation of the past because it illuminates only one aspect of the history of the complex socio-natural system. From an archaeological perspective, more satisfying explanations are to be sought in terms of long-term human impacts on and reactions to changes in the environment.

Addressing complex questions about human-environment interactions also entails confronting the second fundamental concern raised above: the appropriate roles of local/ specific data and regional/ general patterns in building explanation. This has been a core problem in archaeological theory since the inception of the discipline, often cast as a dichotomy between the goals of history and science (or between romanticism and positivism; Trigger 1995). At the broadest scale, the tension between specific and general has played out for more than a century in cyclical changes in preferred modes of explanation in Anglophone archaeology: the sweeping generalities of cultural evolutionary schemes prevalent in the later 19th century, the Boaz-inspired particularism of the culture historians of the early 20th century, the return to broad explanatory schemes with cultural ecology and processual archaeology in the mid-20th century, and the postprocessual emphasis on emic, contextual interpretation beginning in the 1980's.

In his article, Butzer (2005) hints at one way to approach the problem: proper explanation is to be found neither in broad, general patterns nor in specific historical trajectories, but in the interactions between the two; the appropriate question is how general patterns (ruralization, for example) played out in particular situations. In several ways this parallels Hodder's (1991) description of hermeneutic interpretation, with its emphasis on a dialectic tension between general and particular. Other scholars have argued more explicitly that the tension between general process and particular historical circumstance should be the focus of explanation in the historical sciences in general. Frodeman (1995), for example, provides a broadly similar discussion for geology, and Bintliff (1999) discusses the interplay of structure and contingency in archaeology. It is no accident that Bintliff borrowed terminology for his discussion from biology; the

clearest statements of the argument are to be found in the literature of evolutionary biology.

Writing about theory and explanation in evolutionary biology, Michael Ghiselin states that, “A diachronic, synthetic science provides an historical narrative that relates sequences of events to laws of nature. Because it deals with both proximate and ultimate factors, it is capable of what we may call ‘ultimate synthesis’.” (1997: 308) To restate his formulation, a historical science seeks both to reconstruct past events and to explain them by reference to natural laws or general principles. His use of the term “laws” in this context is somewhat unfortunate given the long and sometimes acrimonious debate concerning the use – or existence – of laws for explanation in archaeology (e.g., Cartmill 1980; Dunnell 1982, 1989; Flannery 1973; Fritz and Plog 1970; Kelley and Hanen 1987; Levin 1973; Plog 1973; Salmon 1976; Schiffer 1975; Tuggle *et al.* 1972; VanPool and VanPool 1999; Watson *et al.* 1971, 1974, 1984; Wylie 2002).

To clarify, Ghiselin understands relevant laws in the historical sciences to be laws relating to process or, put another way, laws concerning change through time. Importantly, these laws do not state that “action x produces result y”, like the laws of mechanics in physics, but operate at a higher level of abstraction. For example, Darwin’s theory of evolution by natural selection[6] does not specifically predict the presence of elephants or mice in the world. It does, however, successfully explain how both came to exist based on the application of general principles (natural selection) to specific historical trajectories (the evolution of both genera in particular settings). For the purposes of explanation in archaeology, several types of generalization may take the place of such laws in the structure of an argument.

Ghiselin’s model appears superficially similar to Hempel’s (1965 [1942]) deductive-nomological (D-N) model of explanation in science. In the D-N model, an occurrence is explained by a natural law and an argument of relevance showing that the law applied to the particular circumstances of a situation; historical context is reduced to being part of the argument of relevance. This characterization is largely incompatible with the historical sciences, which must approach explanation in a different way. Stephen Jay Gould neatly encapsulates the differences (1984: 255):

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[6] Ghiselin, of course, considers this a “law”.

> The [Nobel] prizes pass over an entire style of scientific work, thus reinforcing a narrow and conventional stereotype about our shared enterprise. The Nobel prizes focus on quantitative, nonhistorical, deductively oriented fields with their methodology of perturbation by experiment and establishment of repeatable chains of relatively simple cause and effect. An entire set of disciplines, different though equal in scope and status, but often subjected to ridicule because they do not follow this pathway of "hard" science, is thereby ignored: the historical sciences, treating immensely complex and nonrepeatable events (and therefore eschewing prediction while seeking explanation for what has happened) and using the methods of observation and comparison.

Building on Gould's understanding of science, Ghiselin's formulation emphasizes the historical context itself – how the particular set of circumstances came to be – as a crucial part of the explanation, not merely a more-or-less instantaneous set of circumstances that simply happened to occur in a particular time and place. Reconstructing particular historical trajectories becomes as much a legitimate component of science as discovering, testing or applying general principles, and the dichotomy between history and science is shown to be empty, even wholly misleading.

This understanding of the proper role of history in a historical, or time-like science such as archaeology, geology, or evolutionary biology (see Dunnell 1982 for an extended discussion of what he terms time-like and space-like sciences) suggests that research focused on any aspect of the particular trajectory of change in a given culture or society appropriately can be viewed as an essential part of a scientific approach to the past. Perhaps to their chagrin, the postprocessual archaeologists who railed against scientism in the discipline (e.g., Shanks and Tilley 1987) have contributed to a scientific understanding of the past wherever they have engaged with empirical data, used those data to constrain their interpretations, and thereby attempted to illuminate aspects of ancient societies (e.g., Tilley 1996). This is especially true in light of the fact that several scholars (e.g., Kantner 2003, VanPool and VanPool 1999) have argued convincingly that postprocessual archaeologists use a coherent body of social theory when constructing their interpretations of the past. This body of thought, drawn largely from the works of Bourdieu, Giddens and others, takes a place analogous to Ghiselin's natural laws in the structure of their arguments even though it often is treated as a set of basic assumptions and is not discussed explicitly.

Second, and conversely, this understanding of explanation suggests that explicitly scientific approaches to archaeology need not be – indeed should not be – anti-humanistic or ahistorical. Although he does not deal with problems of the human past, laws as understood by Ghiselin do not deny the importance of agency, free will, culture or perception. Clearly these are, at the very least, a significant part of the historical context that forms the basis of an explanation in human systems.

Taken together, these ideas suggest that an appropriate mode of explanation for research focused on a socio-natural system involves empirical investigations based in natural science to reconstruct the trajectory of change in the physical system of interest, in this case the landscape of the study area. It also incorporates a more humanistic investigation focused on whether and how people caused those changes. It culminates with an examination of why people caused those changes when and where they did. That examination should relate a detailed understanding of the circumstances and trajectory of change to larger historical processes and general propositions about human behavior. Within this overall mode of explanation different theories concerning human-environment interactions and the relationships between elites and producers remain to be considered, as they help to frame specific problems and provide a few generalities that can illuminate historical and ecological change in the post-Roman era in the study area.

Human-environment interactions

Long-term human interactions with the environment increasingly are becoming an important focus of research in several disciplines, in no small part because of a growing awareness of the global-scale ecological challenges facing humanity today. Specialists in different fields take slightly different approaches to a range of similar questions, conducting research under the rubrics of environmental history, environmental anthropology, historical ecology, political ecology, socioecology, new ecology, geography, investigations of socio-natural systems, resilience theory, and reliance theory, to name a few. Among these specialists, some seem to remain unaware of work in related disciplines that parallels their own (e.g., Pyne 1998 on anthropogenic fire). Archaeologists, by contrast, have a long history of promoting interdisciplinary paleoecological investigations and are favorably situated to take advantage of the conceptual tools offered by many different disciplines.

While the general topic has concerned archaeologists for more than a century, approaches to understanding people and the environment have changed through time within the discipline, following broader trends in the development of archaeological theory. To simplify (perhaps to the point of caricature), proponents of the cultural evolutionary schemes of the later 19th century including Adolf Bastian, Lewis Henry Morgan, and Edward Tylor viewed the environment as determinative; it was a key element dictating the level of culture a people might achieve. The culture historians of the early 20th century treated the environment primarily as the stage on which the play of history was acted out. Important techniques for reconstructing ancient environments were pioneered during that period, however, and seminal investigations began to incorporate ecological reconstruction into holistic investigations of archaeological sites (e.g., Clark 1954) or regions (e.g., Bryan 1942). Particularly in the Old World, attempts to explain historical "events" such as the fall of Rome or the beginnings of farming in southwest Asia prompted early interdisciplinary research into human impacts on or manipulation of ancient environments (e.g., Braidwood and Braidwood 1953; Judson 1963). These projects helped to promote a self-consciously scientific approach to archaeology.

The "new" archaeology of the 1960's built on these developments and strongly emphasized environmental reconstruction. It was a, maybe even *the*, key to understanding the human past because of the new archaeologists' view of culture: "man employs the extrasomatic tradition that we call culture in order to sustain and perpetuate his existence" (White 1959: 8; often restated as "Culture is... the extra-somatic means of adaptation [to the environment] for the human organism" [Binford 1962: 218]); therefore cultures changed in reaction to changes in the environment. The postprocessual reaction in the 1980's reemphasized human perceptions of the environment as an important component of a broader focus on the purposive actions of people in the past, intended to alter the world around them (e.g., Evans 2003; see also Hodder 1990 on domestication and agriculture). In short, archaeologists have vacillated between investigating human reactions to the environment and focusing on human perceptions of or impacts on the environment.

More recent scholarship attempts to incorporate both aspects of the problem by reframing the issue as human interactions with the environment. Historical ecology, resilience theory, and studies of socio-natural systems all emphasize recursive interactions through time as humans modified the world around them and adjusted to changes resulting from the intended and unintended consequences of their actions (e.g., Balée 2006; Crumley 1994; Cumming *et al.* 2006; Fisher and Feinman 2005; Hayashida 2005; Hill 2004; Johnson et al. 2005; Redman 1999). Both within and beyond archaeology, there is a growing emphasis on clearly defining fundamental concepts such as sustainability (e.g., Goodland 1995; Hardin 1998; Rees 1996), and on explicitly considering the associated problems of spatial and temporal scales as they relate to both processes and analyses (e.g., Crumley 2007; Cumming *et al.* 2006; Lucas 2008; Moran 2004; Redman 2005; Redman et al. 2004). Historical ecology in particular focuses research on the landscape as a palimpsest record of the past interactions of humans and the environment, on which identifiable traces of people's modifications of local ecologies often persist for centuries or longer. The spatial scale of analysis is determined by the natural and cultural processes pertinent to the particular research questions.

Another contribution of historical ecology, echoed in the new ecology (e.g., Briggs *et al.* 2006; McAuliffe *et al.* 2001), is the realization that ecosystems across the globe have been deeply impacted by human activities for millennia; the distinction between cultural and natural landscapes is meaningless and often misleading. This has important implications for conceptualizing anthropogenic environmental change. These schools of thought discard the simplistic question of whether an ecosystem has been impacted by humans and challenge the associated romantic assumption that all modifications are inherently negative. In fact, some modifications, particularly those related to terracing, some systems of animal husbandry, and managed fire regimes, frequently increase total bioproductivity, biodiversity, and resistance to soil erosion; significant ecological degradation can occur when human population levels decrease and maintenance ceases (e.g., Hayashida 2005; van Andel *et al.* 1990). In other cases, traditional agriculturalists use an intimate knowledge of the landscape to situate fields in particular landscape contexts where minimal modifications augment natural processes and function to maintain soil fertility indefinitely (see e.g., Homburg *et al.* 2005 and

Sandor *et al.* 2007 for exceptionally detailed studies of Zuni fields that have been in use for as long as a millennium).

In place of assumptions about human impacts on the environment, adherents to these schools of thought espouse measuring ecological changes empirically by examining, for example, species diversity, soil loss, total bioproductivity, or other indicators of ecological change, particularly focusing on the processes, nature, extent, and persistence of modifications. These distinctions are especially important in the Mediterranean world, where many areas continue to be productive and aesthetically attractive despite the fact that humans have extensively and intensively modified the landscape for many millennia. Grove and Rackham (2001) go so far as to argue that there has never been a "natural" Mediterranean ecology; humans were present and actively modifying the landscape by the time a recognizably Mediterranean climate came into existence. Within the broader framework provided by recent scholarship concerning human-environment interactions, additional theoretical insights are drawn from investigations of the ways in which social organization can impact anthropogenic ecological change.

Elites, producers, and the environment

A growing body of literature suggests that there are systematic relationships between the scale of political institutions, the lives of agrarian producers, and anthropogenic modifications of the environment (Butzer 1982, Diamond 2005, Ponting 2007, Redman 1999, and Tainter 1988 offer general treatments from varying perspectives). In general, however, scholars have not explicitly considered the articulation of all three entities; the majority of the literature focuses on relationships between complex polities and the environment, on the interactions of elites and producers, or, less frequently, on the interplay between primary producers and the environment. Examining the relationships between all three is critical because farmers and pastoralists exploit the resources of the landscape to support themselves and to meet the demands imposed on them by elites. In agrarian societies, then, primary producers are the key point of articulation with the environment because it is their activities that are directly responsible for the most extensive and persistent ecological modifications.

Researchers examining the relationship between complex polities and the environment often adopt a world-systems framework (Wallerstein 1979, 1980). World systems theory emphasizes spatially extensive patterns of environmental modification, in particular focusing on the damaging overexploitation of resources in peripheral areas for the benefit of the center(s) of political power (e.g., Bergesen and Bartley 2000; Straussfogel 2000). Several scholars (e.g., Chew 2001, 2007; Ponting 2007; Redman 1999) have argued along similar lines that an inherent property of state-level systems is that they exploit the environment intensively to meet the needs of urban elites. They suggest that this exploitation is almost always unsustainable at long time scales, and that the resulting environmental degradation contributes to the observed temporal pattern of waxing and waning of pre-industrial states and empires (see also Feinman and Marcus 1998). Similarly, Joe Tainter suggests (1988: 123) that the combination of increased food production, growth in system size and complexity, and inevitable environmental vagaries leads directly to the eventual collapse of all complex social systems[7]. Chew (2001, 2007) in particular emphasizes that the period following the dissolution of large systems such as the Roman Empire is one of ecological rebound, lasting in that case until the early days of the industrial revolution.

Logically, it seems that there must be some kernel of truth in the assertion that increasing political complexity generally entails growing environmental costs. As soon as non-farming elites emerge, their continued existence requires that non-elites produce more food than they would need to feed their own households. Moreover, elites generally consume more than non-elites, in part as a way of demonstrating and justifying their favored position. As social systems become more complex elites frequently engage in different forms of competitive consumption, feeding a cycle that necessitates ever-increasing production (e.g., Kristiansen 1998c). As the elite class grows, so does its demand for food and other resources; the creation of a bureaucratic class, support of craft specialists, and the eventual appearance of urban centers all further increase the amount of food each farmer must produce in order to feed the growing proportion of the populace not engaged in food production.

[7] Interestingly, Tainter (2006) vehemently denounced a simplified statement of this position after Diamond (2005) had restated the original formulation in a more popular and commercially-successful form. Tainter shifted his focus instead to examples of extreme environmental events and elite mismanagement.

Although not universally the case, increasing food production frequently entails higher environmental costs. Those costs may be hidden from the elites driving the increase; Diamond (2005: 424 – 426) proposes that insulating elites from the ecological damage associated with their increased levels of consumption is one of the most significant causes of degradation worldwide (see also Tainter 2006). In an analogous way, world systems theory views the political center as the province of elites who insulate themselves from ecological degradation by moving production toward the peripheries of the state or empire (e.g., Chew 2001).

Historians have elaborated on another aspect of this dynamic, emphasizing the social rather than ecological costs of increasing cultural complexity. In a seminal article concerning the transition to feudalism in Europe, Chris Wickham (1984) proposed that an inverse correlation exists between the elaboration of pre-industrial civilizations and the wealth of primary producers because surplus must be expropriated from producers through tribute, taxation or rent to support hierarchical organization. Specifically, he posited that the dissolution of the Western Roman Empire was fundamentally related to a shift from a system based on centralized taxation to a rent-based economy (see also Hopkins 1980). The imperial system failed because the new system of surplus extraction was no longer centralized or efficient enough to generate the resources needed to fund the state apparatus. As taxation declined, the "Dark Ages" were a period of relatively enhanced autonomy and material wealth for rural peasant communities before feudal successor states began proficiently collecting rent and exercising power (see also Bintliff 1999; Hodges 1989; Wickham 1989).

More generally, the dynamics of interaction between the elites of complex polities and the individuals and groups that nominally are their subjects have been an issue of fundamental theoretical concern in the social sciences at least since the era of Karl Marx. Tainter (1988) proposes that theories concerning the origins and functions of complex social systems can be divided into those that focus on integration, or the benefits provided by leaders, and those that focus on conflict, or the costs imposed by leaders. Integration theories posit that elites emerge and continue to exist because they provide necessary services to the polity, for example by organizing long-distance trade or redistributing subsistence resources (e.g., Childe 1950; Flannery 1972; Fried 1967;

Sanders and Webster 1978; Service 1962). This perspective generally has been favored by processual archaeologists.

Wickham's hypothesis (1984, 1989), that primary producers generally will be poorer as civilizations become more elaborate, flies in the face of the progressivist and adaptationist assumptions implicit in these integration-focused theories. Like other conflict theories (e.g., Arnold 1992, 1995; Carniero 1970; Gilman 1981) his analysis downplays the fact that complex systems provide benefits to participants, including primary producers. Drawing inspiration from Marxist thought (either explicitly or implicitly; see Gilman 1989), conflict theories attempt to explain how leaders use coercion, manipulation of ideology, and other tools to maintain a system that imposes costs on followers. In addition to dominating Marxist archaeology, conflict theories have figured prominently in postprocessual archaeology, where they form the basis of examinations of ideology and power in the past, the development of modern ideologies, and deconstructions of the political and ideological entanglements of archaeology itself (e.g., Bawden 1995; De Marrais *et al.* 1996; Hodder 1992b; Leone *et al.* 1987; Leone and Potter 1996).

Several recent considerations of complex polities adopt a political economy analytic framework and focus on the importance of competition and factionalism as leaders build power (e.g., Berdan *et al.* 1996; Brumfiel 1983; Brumfiel and Fox 1994). Essentially a more nuanced form of the conflict theories, these approaches are insightful in their descriptions of the internal dynamics of complex systems and especially the strategies employed by actual and potential leaders. Like other conflict theories, however, they fail to consider what Godelier (1986: 13) called the basic paradox of political life, namely that non-elites cooperate in their own subordination and exploitation. Ultimately, all three perspectives (integration, conflict, and political economy) tend to focus attention on elites and their activities.

Research into the development and dynamics of state-level polities profitably could be extended to focus to a greater extent on primary producers, the majority of the populace. Such a redirection of interest will facilitate the development of a more complete anthropological understanding of complex cultural systems by including actors at all levels within a political hierarchy. A focus on primary producers, taken together

with an appreciation of both conflict and integration perspectives, implies that negotiations between elites and followers are a fundamental dynamic of complex social systems (see Hodder 1985: 5 for a brief assertion along similar lines). People throughout the political spectrum manipulate the resources available to them to negotiate more favorable conditions: leaders use combinations of coercion and bribery to attract and influence followers; followers use the threat or reality of withholding support, backing other leaders, or outright rebellion in their attempts to keep elite demands to a minimum and to maximize the benefits provided to them.

For smaller-scale societies, models of analogous negotiation processes have been used to explain the dynamics of group formation "in terms of the aggregate consequences of individual behavioral strategies" (Boone 1992b: 301). Following from Bourdieu's (1977) perspective that social class strongly influences individual values, Marxist principles can be used to approximate the goals of individuals in different groups in stratified societies. This fosters a new perspective on and extension of Marxist analyses that have been successfully applied to archaeological questions in many settings (e.g., Friedman 1975; Kristiansen 1998a, b, c, d; McGuire 1993, 2008; Parker Pearson 1984). It provides a starting point for building an agent-centered understanding of the dynamics of complex social systems as they emerge and change through time.

In light of the model of explanation outlined above, it is clear that the social, economic, technological, and environmental contexts of negotiations between elites and primary producers determine the costs and benefits of different forms of competition or cooperation. Changes in any one aspect of the context are likely to have recursive effects on any or all of the other important variables. Understanding the broad context at different points in time therefore is necessary for interpreting the dynamics of interaction and for explaining the resulting historical trajectories.

One important variable affecting the interactions of leaders and subjects is the political economy of the state. D'Altroy and Earle (1985) propose that a significant dimension of variability in state level polities is the means of financing the political apparatus. In systems dominated by staple finance, the wealth of the state depends on direct appropriation of agricultural surplus. Wealth-financed states, on the other hand, rely primarily on control of long-distance trade and sumptuary goods. Clearly the

different systems of finance have important ramifications for understanding the conditions that affect interactions between leaders and subjects; specifically, they have different implications for surplus extraction and the agrarian economy. This suggests that Wickham's hypothesis must be modified: in addition to its scale, the form of the state may be an important variable impacting how people within the polity interact with each other and the environment.

Other conditions affecting the negotiations between rulers and the ruled include variables related more directly to the lives of primary producers, specifically rural social, technological, and economic organization. Scholars have explored links between rural social organization, land use patterns, technologies of production, and regional economies from several perspectives (e.g., Boserup 1965; Butzer 2005; Morrison 1994, 1996; Netting 1986, 1993; Stone 1996; Stone and Downum 1999). In general, farmers make production decisions based on their own subsistence needs, available technologies and crops, the demands placed on them by leaders, their access to a market economy, and the nature of that economy. As noted above, leaders typically seek to encourage or force rural populations to increase production in order to meet the needs of urban populations and the state; access to a market economy frequently places similar pressures on producers.

Primary producers have two options to increase production. Intensification involves producing more food per unit of land area; it typically requires investing more energy in production and is associated with more complete alteration of the local ecosystem (Boserup 1965). Alternatively, the producer can cultivate crops or herd animals on a larger land area, a process sometimes referred to as extensification (e.g., Erenstein 2006; see Stone and Downum 1999 for a discussion of this process in an archaeological context). While this process generally does not increase the labor invested or the degree of environmental alteration per unit of land area, it does increase the total labor required for production as well as the total area altered for the purposes of agriculture. Extensification can be particularly important from an environmental standpoint when production expands into new geomorphic and ecological settings. Either choice (i.e., intensification or extensification) entails increased social costs and increased modifications of local ecosystems for the purposes of production. The choice of whether

to intensify production or cultivate larger areas is strongly impacted by ecological variables and extant production and transportation technologies, as these dictate which strategy will be most productive.

Although the terms apparently were first combined in the early 1970's by Eric Wolf (Robbins 1994), political ecology remains a "relatively new field" (Paulson *et al.* 2003: 205). Drawing on diverse backgrounds in anthropology, political science, international development, rural sociology, and geography, political ecology explicitly examines interactions between local communities and larger political or economic institutions, the ramifications of those interactions for local social organization and agrarian production, and the environmental impacts of the resulting changes. To date, the majority of theoretical development and most case studies have focused on globalization, economic development schemes in the third world, and the expansion of market economies into remote areas (e.g., Blaikie 1985; Escobar *et al.* 1999; Paulson *et al.* 2003; Robbins 2004; Scott 1998; Walker 2005; Zimmerer 1993a, 1993b; but see Zimmerer 2000 for a rare application to a pre-modern context).

One key insight of political ecology is that individual producers tend to be conscious of the ecological degradation that can be caused by farming and herding, and they usually take steps to avoid it when possible. Furthermore, their understanding of degradation is attuned to local ecological conditions and production systems. They seek to maintain long-term productivity so long as they can do so while meeting short-term needs. In essence, political ecology studies show that traditional production systems that have developed over centuries or millennia of trial and error tend to be well suited to long-term resilience (i.e., sustainability) in their local ecological settings (see also Lansing and Kremer 1993; beginning from a very different perspective, they arrive at similar conclusions). Local perceptions of negative ecological change, then, often closely approximate the admittedly anthropocentric definition of degradation used here: change that significantly and persistently decreases the productive potential of the landscape, necessitating change in the agrarian system.

A lack of appreciation for this form of local knowledge is a fundamental reason for the widespread failure of agricultural development schemes throughout the third world (e.g., Scott 1998, chapters 8 and 9). For example, development workers trained in

Western forms of agriculture have consistently failed to recognize that shifting swidden ("slash-and-burn") agriculture and polyculture are effective ways to maintain soil fertility and relatively high yields indefinitely in the nutrient-poor soils common in the tropics and neotropics, provided that there is a sufficiently long fallow period between cultivations. In the same ecological contexts, chemical- and labor- (or machinery-) intensive agriculture frequently provides exceptionally high yields for a few years but then causes rapid and (at the time scale of human lives) permanent degradation through processes such as dramatically increased soil salinity or laterization.

There is good reason to believe that this characterization of traditional production systems as likely to be well suited to local environments can be applied to the past, and the historical evidence that this is so is particularly strong for the Mediterranean world. Documentary sources show that people have been aware of and concerned about environmental degradation related to farming since the earliest Classical-era literature about farming itself (Redman 1999: 20). Butzer (1994) traces an intellectual lineage of agronomic writings from the Greek author Hesiod (ca. 700 B.C.E.) through the Classical literature to the medieval Islamic treatises on agriculture. Moreover, he argues that this body of literature as a whole portrays a constant concern with maintaining long-term productivity, expressed as an ethic of responsible farming. Separately, he asserts that traditional agricultural systems in the past tended in general to be well adapted to local environmental conditions (Butzer 1996), paralleling the observations of political ecologists.

That many traditional production systems tend to be ecologically resilient does not mean that any individual system necessarily is. Butzer (*ibid.*) suggests that traditional agriculture often causes ecological degradation when the producers enter a new environment with which they are unfamiliar (see also "false analogy", McGovern 1994: 149). Similarly, rapid and persistent degradation can result from expansion of production systems into new geomorphic and ecological settings (e.g., McAuliffe *et al.* 2001). In this context, the contribution of political ecology is a realization that traditional production systems are not inherently "backwards" or damaging; no type of agriculture or herding is *always* destructive or *always* sustainable. The historical ecologists' emphasis on measuring empirical indices of degradation facilitates using the past as a natural

laboratory for investigating which systems are most productive and resilient in particular contexts.

These different perspectives on interactions between elites, producers and the environment provide insights that are useful in building explanations of the long-term dynamics of socio-ecological systems. They help to identify important variables and some generalities in which they may be interconnected. These variables – including elite needs, the political economy of the state, the presence and nature of a market economy, rural socio-economic organization, and production technologies – largely dictate the costs and benefits of different types of interactions between rural and urban populations. Finally, the literature of political ecology in particular suggests that primary producers generally are aware of the ecological costs of increasing production; those short- and long-term costs are part of the context of their decision-making process.

Application

Examining long-term human-environment interactions involves addressing a nested series of increasingly complex questions within a framework that facilitates bringing together multiple types of data. The beginning point is determining whether there was significant ecological degradation in the study area during the time period of interest. Butzer's (2005) proposition that field-oriented, empirical investigations based on natural science techniques are necessary for illuminating the historical trajectory of landscape change is adopted here. Although specific soil-geomorphic studies are not reported in his article as fully as they might have been, the strategy he proposes is probably the best way to answer questions concerning what happened in the past: instead of using models of soil erosion or slope evolution to determine what *should have* happened in the past given certain conditions, his research and the investigations reported here used field and laboratory techniques to generate empirical data relevant to determining what *actually did* happen, i.e., when and how the landscape changed in the study area. The research focuses on changes in the socio-natural system at the temporal scale of centuries and the spatial scale of the landscape, understood here to be defined by the two 64 km^2 surveyed areas. Whether the results can be generalized to larger areas of Iberia is a separate question and it ultimately should be evaluated through similar research conducted in other areas.

At the next level of complexity is the attempt to determine whether ecological degradation in the study area in the past can be attributed to human activities. Here, archaeological and documentary evidence provide the basis for reconstructing past human actions. Geological techniques are used to determine the extent and timing of soil loss. Temporal correlations between human activities and landscape change are one line of evidence bearing on the question of whether humans caused the observed changes. In addition, two surveyed areas with different histories of land use and soil erosion are compared in an attempt to isolate anthropogenic impacts. To the extent that the data allow, the past climate is investigated in order to determine whether the landscape changed in response to human activities or a climatic shift.

The final and most difficult problem is explaining why people caused ecological change in the study area in the past. Addressing that question requires relating this research to the literature on a broad range of topics including ways to conceptualize human-environment interactions, the various ways in which those interactions may be mediated by social structure, and an appropriate structure for explaining change in complex socio-natural systems. Butzer's and Fogelin's contributions, discussed above, provide further focus for the general question of why people caused degradation. Among a series of possible explanations, the successful one should consider why people caused erosion when and where they did, and why they reacted to ecological change in the ways that they did. As suggested by Butzer in his critique of world systems theory, answering the why questions about people's actions will involve a consideration of local conditions as well as changes in larger-scale social systems.

Recent literature concerning human-environment interactions provides several additional insights that help to guide the current research. Arguments concerning the causes of social and ecological change draw on archaeological, documentary, geological, and paleobotanical data sets without beginning from an assumption that people must either *act on* or *react to* the environment. This approach allows for an examination of both intended and unintended consequences of human modifications of the environment and may to some extent help to differentiate the two. In addition, this investigation incorporates the understanding that not all anthropogenic impacts on the environment necessarily are negative. Therefore, it seeks to measure both the timing and extent of

ecological change in the past in order to evaluate empirically whether and when anthropogenic environmental change became ecological degradation severe enough to impact agrarian production.

Several key issues can be abstracted from the diverse literature concerning the ways in which social organization can mediate anthropogenic ecological change. First, the growth of complex socio-political systems necessarily involves increased social and ecological costs as production increases to support a population that includes elites and others who do not farm. The ways those costs are allocated, in terms of who pays them and how production will be increased, are determined by ongoing negotiations between elites and primary producers. The negotiations, in turn, are strongly affected by the social and ecological context. One key variable is the political economy of the state; whether the political apparatus is wealth or staple financed strongly influences the goals of elites and their options for action. From the perspective of the primary producers, local ecological conditions, extant technologies, and the organization of production similarly constrain goals and options. Producers have two basic options to increase production: intensification and extensification. Both entail increased labor inputs and, although they imply different types of ecological modification at different spatial scales, both involve an overall increase in anthropogenic environmental change.

Another key insight is that traditional agrarian production systems have co-evolved with local ecologies in many parts of the globe such that those systems tend to be resilient and maintain long-term productivity in those particular environments. Primary producers generally perceive the ecological costs of changes in the agrarian systems, often long before those costs become apparent to elites, and knowledge of long-term degradation becomes part of their calculus in negotiations with elites. Empirically measuring the ecological effects of changes in agrarian production systems can both help to determine whether or not they caused degradation and it can generate a better understanding of the context of past production decisions.

Taken together, these ideas suggest that an appropriate mode of explanation for research focused on a complex socio-natural system begins with empirical investigations based in natural science to reconstruct the trajectory of change in the physical system of interest, in this case the landscape of the study area. It also incorporates a more

humanistic investigation focused on whether and how people caused those changes. The humanistic research illuminates the cultural contexts that impacted human perceptions, motivations, and options for action. The research culminates with an examination of why people caused those changes when and where they did. That examination should relate a detailed understanding of the circumstances and trajectory of change to larger historical processes and general propositions about human behavior. The history of the socio-natural system then can be explained by diachronic analysis of choices individuals made within the changing constraints imposed by the social and ecological contexts. The degree to which such an explanation is seen as satisfactory depends on disciplinary goals that, in this case, direct interest toward human impacts on and reactions to changes in the environment. The overall goal is to build and utilize a framework that generates satisfactory answers to interesting questions while being both agent-centered and process oriented, mirroring the goals of recent attempts to synthesize processual and post-processual archaeology variously termed historical processualism (Pauketat 2003) or processual plus (Hegmon 2003).

In addition to explaining the particular historical trajectory of socio-natural change in the study area, this framework allows for exploring general conditions and processes that affect social organization and human-landscape interactions through time. By addressing the interactions of primary producers with both elites and the environment, the hope is to provide a new perspective on several questions posed by archaeologists investigating state-level polities. For example, the results may offer new insights into the apparent pattern of cyclical growth and decline, the internal dynamics of power, and the variety of forms of organization of premodern states and empires (e.g., Feinman and Marcus 1998). Finally, this research hopefully will provide useful insights into some of the ecological problems facing people in the study area today.

Chapter 3:
Previous Research

The history of archaeological research in Portugal arguably is as long and rich as anywhere in the world and a complete review is beyond the scope of this study. Despite a well-established archaeological tradition, relatively few studies focused on the Islamic period were undertaken prior to the last decades of the 20th century. This chapter presents a brief overview of relevant previous research in Iberia, along with a more detailed consideration of recent investigations of the Islamic past in the *Baixo Alentejo*.

Early Years

The early development of antiquarianism and archaeology in Iberia followed a similar trajectory to that seen in other parts of Western Europe. Extant castles and fortifications in Portugal, some of them initially constructed during the Iron Age and with standing architecture dating to the Roman period, were first systematically recorded in the early 16th century as part of an inventory initiated by royal decree and carried out by Duarte D'Armas (Gómez and Lopes 2007). By the 19th century there was growing interest in the more distant past. The deep antiquity of a human presence in Europe had become widely accepted and the antiquarians' focus on collecting "curiosities" gave way to more organized attempts to learn about ancient people through archaeological excavations. Archaeology became a popular pastime of the aristocracy, the wealthy and the intelligentsia (e.g., Trigger 1989: 87 – 102).

In southeast Spain, for example, Louis and Henri Siret excavated dozens of sites in the late 19th and early 20th centuries. Gentlemen mining engineers originally from Belgium, the brothers outlined the culture history of the area from the Neolithic through the Iron Ages (Castro *et al.* 2000; Gilman and Thornes 1985: 15 – 16). In northern Spain, the Abbé Henri Breuil and Hugo Obermaier undertook studies of cave art during the first years of the 20th century. With the patronage of Prince Albert, founder of the *Institut de Paleontologie Humaine* in Paris, they completed significant excavations of Paleolithic cave sites during the years before World War I (Straus 1992, 1994).

In Portugal, Sebastião Phillipes Martins Estácio da Veiga, a member of the petty nobility and a government official, was able to devote his professional life to archaeology for most of the second half of the 19th century; he is considered the father of Portuguese archaeology. With royal patronage, Estácio da Vega completed programs of reconnaissance of archaeological sites and monuments in addition to excavations in the Algarve and Alentejo regions in the 1870s and 1880s. In 1880, he convened the *Congresso Internacional de Antropologia e de Arqueologia Pré-Histórica* (International Congress of Anthropology and Pre-Historic Archaeology) in Lisbon and, prior to his death in 1891, he developed the *Programa para a Instituição dos Estudos Arqueológicos em Portugal* (Program for the Institutionalization of Archaeological Studies in Portugal). He also introduced several advanced fieldwork techniques, including the use of a theodolite and pantrometro compass (also called Galileo's compass) in mapping.

Some of Estácio da Veiga's earliest significant archaeological work took place in and around Mértola, particularly after the destructive floods of 1876 exhumed archaeological materials along the river (Gómez and Lopes 2007). While there, he completed a systematic reconnaissance and produced several maps. He recovered Roman statuary, recorded a Roman or Late Roman mosaic, and noted the presence of important but as-yet unexcavated architectural features such as the Late Roman *cryptoportico*. He recorded artifacts dating to the Islamic period, undertook a study of Arabic epigraphy, and attributed architectural features including parts of the river fortifications (the *Torre do Rio*, or River Tower) and the cistern in the castle to the Islamic period. da Veiga devoted an entire chapter of his *Memórias das Antiguidades de Mértola* (1983 [1880]) to the Islamic period, and he included a sharp criticism of attempts, primarily led by the Catholic church, to destroy or hide evidence of the Islamic past. Interestingly, his investigations in the Roman and Late Roman cemetery adjacent to the *Rossio do Carmo* basilica were continued by his wife Maria Luísa Estácio da Veiga Silva Pereira and their colleague Bandeira Ferreira; they excavated portions of the basilica and opened fifty-two graves.

As in the remainder of Europe, this early phase of archaeology tended to be nationalistic, focused on discovering and documenting the proud past of the people of a given nation (e.g., Trigger 1995). In the last few decades of the 19th century and the first

few of the 20th, however, several scholars in southern Portugal mirrored da Veiga's concerns and wrote books celebrating the Islamic past as the wellspring of the unique character of the region – even though they frequently focused their attentions on Arabized Christians, the *mozarabs* (Vakil 2003). By the 1930s, nationalism had largely triumphed over regionalism; many regional museums were closed and their collections removed to the national museum in Lisbon. At the national level, archaeologists had established that Portugal was a major center of megalithic culture and they had devoted a great deal of energy to demonstrating cultural continuity from the Copper Age through to the beginnings of the modern nation-state. Unfortunately, the fascist regimes that dominated both Spain and Portugal through the middle of the 20th century chose to emphasize Christian medieval history and the Age of Exploration in their narratives of national identity, and archaeology in Iberia generally began to lag behind the rest of Europe (Trigger 2006: 253).

The Fascist Era

The regime of António de Oliveira Salazar controlled Portugal from 1932 until the revolution of 1974, with Salazar himself leading the government from 1932 to 1968. The military coup that ended the fascist regime is often called the Carnation Revolution in remembrance of the flowers military insurgents in Lisbon placed in the barrels of their guns to show their support for political change. Alternatively, it is known as the *25 de abril* for the date on which it began. The revolution remains a crucially significant event in the national psyche.

Salazar and his allies energetically promoted a national narrative in which Portuguese identity was born of the Christian *reconquista*. Across the country, Christian medieval castles were reconstructed as powerful symbols of the heritage of conquest[8], but the restorations seldom included formal archaeological investigations. They had the effect on the castles and monuments – many of them on the sites of Islamic period and older fortifications – of "previligiando o seu valor histórico em detrimento da sua historicidade" (privileging their historical value to the detriment of their historicity; Jorge Rodrigues, quoted in Vakil 2003: 5). History textbooks used in the national education

[8] A popular brand of beer still carries the slogan "O sabor da conquista" (The flavor of the conquest).

system characterized the castle of Guimarães, from which the campaign to retake Lisbon was launched with the help of crusading knights, as a "sítio sagrado, onde há mais de oito séculos os primeiros portugueses decidiram fazer Portugal" (sacred site where, more than eight centuries ago, the first Portuguese decided to create Portugal; Vakil 2003:6). The Portuguese were emphatically Latin Christians, created and defined in opposition to the Muslim other[9].

Although museums and universities conducted pioneering investigations, archaeology remained largely a pastime of dilettante elites through the middle part of the 20th century. Wealthy landowners hired laborers to excavate in promising locations, usually focusing on Roman-era sites or Visigothic cemeteries. They were inspired by the perception that the forefathers of the first (Christian) Portuguese were the nobility of the Visigothic kingdom of late antiquity, and through that heritage they traced national history back to Roman *Lusitania*. Similarly, in Spain there was virtually no interest in the archaeology of the Islamic period, and the only sustained attention to the issue was by a French-funded research institution, the Casa de Velázquez in Madrid. The Islamic period generally was viewed as a foreign occupation with little relevance for understanding the history or modern character of the Iberian nations; it was a historical parenthesis (Guichard 1976: 24). Alternative notions of the history of Spain and Portugal were published only by scholars living in exile in other countries (Boone 2009: 11 – 16).

This bias against investigating – or even acknowledging – the Islamic period remains visible in many museums constructed during the fascist period. For example, the Museo Arqueológico de Almuñecar (in southern Spain) exhibits thousands of artifacts from the Phoenician, Greek, Roman, Late Roman and Christian Medieval periods in well-lit display cases, most with written interpretations. When the author visited in the summer of 2003, the only items explicitly attributed to the Islamic period were the skeletal remains of two individuals reputed to have been Muslim soldiers killed during the Christian reconquest of the city, visible in the bottom of a poorly-lit cistern. Part of the museum is housed in the Cueva de Siete Palacios, the subterranean remains of a large Roman era structure. Ironically enough, the rest is located in the Castillo de San Miguel,

[9] This is not without precedent. The word "European" comes from the word "Europenses", coined by Isidore Pacensis to identify the Christian victors in the Battle of Poitiers where Charles Martel's (later Charlemagne) troops turned back the Islamic *jihad* in 732 C.E. (Lewis 2008: 172).

an impressive fortress that was constructed primarily during the Islamic period. In the Castillo, there was a large display case containing dozens of artifacts dating to the Islamic period; the interpretive sign simply identified them as 'other items encountered during excavations'.

The pervasive bias is mirrored in the paucity of archaeological investigations of Islamic sites conducted during the fascist era. A bibliography of Portuguese archaeological publications covering the years 1935 – 1969 (Pires 1984) contains only one entry for "Arabs" in the subject index, a second for "Arabic Civilization" and no entries whatsoever for any plausible synonyms or related topics such as Moor, Islam, Muslim, or Berber. The article listed under the general heading for Arabs is a brief (4 page) compilation of older references to the populations of Beja in antiquity, taken from a manuscript written in 1802. The listing for Arabic Civilization refers to a short newspaper article, "*Aspectos de civilização arábico-lusitana*" (Aspects of Arabic-Lusitanian Civilization) penned in 1952 by José Garcia Dominguez.

Of the 3,334 books and articles listed in the bibliography, only 23 – or about 2/3 of 1% – are concerned with any aspect of the more than 500 years during which at least the southern half of the country was part of the Muslim world. Of those 23, 11 are about Arabic-inscribed coins, 6 focus on Arabic epigraphy, and two describe *lagares* (traditional vessels used to crush and ferment grapes for wine) inferred to have been used during the Islamic period. Of the remainder, one article describes Islamic period ovens and a second, washbasins. By comparison, the same bibliography lists no less than 20 works about *terra sigillata*, one type of ceramic produced during the Roman era. Excluding more specific aspects of each, there are 75 general entries for megalithism and 97 for the Paleolithic.

An analogous bibliography for the years 1970 – 1979 (Pires 1985) reveals that similar patterns continued in the first years after the Carnation Revolution. Of the 1,534 books and articles listed, 8 – about ½ of 1% – concern the Islamic period. The first of the two articles listed under the general heading "Arabs" summarizes the work of the 19th century historian, author, and politician Alexandre Herculano in relation to archaeology. Herculano's influential histories traced the birth of the Portuguese nation to Medieval Christian struggles against the Muslims and are firmly in line with the notion of a

fundamentally Romano-Christian nation briefly occupied by Islamic interlopers. The second article under that heading is a 6-page description of Lisbon during the Islamic period. Of the remaining articles, three describe “Hispano-Arab” coins, and single articles discuss Arab epigraphy, ceramics, and washbasins. By contrast, there are 29 articles about *terra sigillata* listed. Clearly, despite more than a century of formal archaeological research, it is fair to say that the Islamic period was a neglected topic in Iberia.

Recent Work

Archaeologists in Portugal and Spain have shown considerably more interest in the Islamic period in the decades since the overthrow of the fascist regimes in 1974 and 1975, respectively. A brief perusal of the bibliographic database maintained by the *Instituto Português de Arqueologia* (2009) shows that they currently list more than 700 archaeological publications keyed to the terms “Arab” or “Islamic”. This represents at least a twenty-four fold increase over the total number of publications prior to 1980 that were even tangentially related to the topic.

The virtual explosion in research into the Islamic period can be attributed to at least three trends. First, cultural resources are legally protected in Iberia. As in most of the rest of the developed world (with the notable exception of the United States), all archaeological sites are afforded some protection regardless of whether they are located on public or private property. Sites threatened with destruction are excavated and published in ways analogous to the cultural resource management (CRM) investigations conducted on public lands in the United States (e.g., Valdés and Díaz 2002). Iberian archaeologists cannot help but confront the Islamic past.

Second, Pierre Guichard’s (1976) challenge to the traditionalist historiography of the Islamic period in Spain, mentioned in the introductory chapter, has stimulated archaeological investigations since the early 1980s. Several archaeologists, perhaps most notably André Bazzana and Patrice Cressier, have undertaken large-scale research projects in southeastern Spain designed to document the *hisn/ qarya* (castle/ village) complex that Guichard saw as an architectural reflection of the segmentary tribal organization of the Arabs and Berbers in Iberia (Bazzana *et al.* 1988; Bazzana et al. 1982; Cressier 1991, 1992; see also Almansa 1998; Guttierez-Lloret 1989; Reynolds 1993; and

summaries in Boone 2009: 18 – 19, 92 – 104, 110 – 115). The *hisn/ qarya* complex they examined is a fortification of the countryside during the early medieval period that is broadly analogous to the *castellamento* described by Pierre Toubert in Italy. Unlike the Italian *castellamento*, however, Bazzana, Cressier, and Guichard argue that the Spanish fortifications were not built by or for local nobility as part of a process that gave rise to feudalism; they interpret the fortifications in rural Islamic Iberia as structures built by tribal groups for their collective protection and defense.

The final trend, perhaps inspired to some degree by the second, reflects an ideological shift that has taken root since the fall of the fascist regimes. Partly in reaction to the omissions of the previous half-century, historians, archaeologists, politicians, artists, novelists, and others among the intelligentsia increasingly have focused attention on Portugal's Islamic past (Vakil 2003). The eminent Portuguese medieval historian José Mattoso, for example, argues that a reconsideration of the Islamic period is the most pressing issue in the field today; not only will the reevaluation elevate the Islamic period to its rightful place in the narrative of the national past, it promises to elucidate numerous aspects of the subsequent Christian medieval period (Mattoso 2001). Taking a more radical position, Claudio Torres, director of the Campo Arqueológico de Mértola and a leading scholar of the Islamic period, has stated, "a filiação genética do povo português é predominantemente berbére (do Norte de África) e tem pouco a ver com a genética europeia… do outro lado do mar Mediterrâneo está o nosso passado, a nossa História" (the genetic affiliation of the Portuguese people is predominantly Berber (from North Africa) and has little to do with the European genetic [heritage]... our past, our history is on the other side of the Mediterranean; quoted in Vakil 2003: 13).

The rapid growth in archaeological and historical investigations into Iberia's Islamic past has contributed immeasurably to a more complete understanding of that time period among specialists. Moreover, there have been exemplary moves to communicate a revisionist view of Iberian history to the public. For example, there have been a number of high-profile museum exhibits such as the Museu Nacional de Arqueologia's *Portugal Islâmico* (scientific coordination by Santiago Macias and Cláudio Torres, Susana Gómez Martínez completed the catalogue of ceramics), and the touring exhibit *Memórias Árabes-Islâmicas em Portugal*. In Mértola, the *Colecção de arte Islâmica* is

probably the most significant collection of Islamic period art and artifacts in Portugal. It is one of the collections housed in several separate facilities that, together, make up *Mértola Vila Museu* (Mértola, Museum Village), and is included in the recent Museums Without Borders[10] initiative alongside museums in Spain, North Africa, and elsewhere in Portugal. Official recognition of the Museums Without Borders initiative prompted a televised ceremonial visit to Mértola by the President of Portugal in the summer of 2007. *O Legado Islâmico em Portugal* by Cláudio Torres and Santiago Macias is widely available in several editions, and José Mattoso's *Historia de Portugal* was a bestseller in Portugal; it includes a full chapter devoted to the Islamic period written by Torres and Macias.

Embracing the Islamic past has become an important element in Portugal's attempt to build a new identity as a modern, multicultural, post-colonial nation. At the same time, it serves as a way to highlight Iberia's cultural distinctiveness as the political and economic integration of the European Union threaten to homogenize the continent. That the acceptance – even celebration – of the Islamic past is not limited to a small circle of intellectuals is demonstrated by the fact that tens of thousands of people travel to Mértola from all parts of Portugal to take part in the biannual *Festival Islâmico,* sponsored by the municipal government and the Campo Arqueológico. In addition to drawing attention to the archaeology of the Islamic period, the festival brings guests from North Africa to demonstrate traditional Berber arts, crafts, music, and gastronomy, showing in concrete ways that the Islamic heritage contributed directly to traditional rural lifeways in southern Portugal.

In addition to this wider cultural milieu, the nature of recent scholarship concerning the Islamic period reflects the context of research, the relative neglect of the subject through much of the 20th century, and the disciplinary and ideological commitments of the Portuguese and Spanish scholars who have, appropriately, been at the forefront of investigations. As in the United States, a high proportion of the archaeological investigations undertaken today in Iberia occur as CRM work. Because of that context (and, again, as in the United States), the majority of the resulting publications are primarily descriptive (e.g., Gómez and Lopes 2003; Valdés and Díaz 2002); even

[10] Unfortunately, this is sometimes translated into English as "Museums With No Frontiers".

large CRM projects often do not include adequate funding for generating broad syntheses. In contrast to North America, however, major foci of CRM work in Iberia are preservation and presentation of sites and artifacts specifically for the purposes of tourism and education (e.g., Gómez 2003a; Lança 2002). Because the Islamic past is coming to be seen as an integral part of the Iberian heritage, archaeology does not experience conflicts over legitimacy, ownership, control, and presentation of the past to the same degree as research where an indigenous peoples' past is investigated by non-indigenous archaeologists (e.g., Watkins 2005). This situation facilitates a more successful application of CRM studies to fostering public outreach and, in particular, to expanding tourism.

The prevalence of a descriptive approach also is a direct consequence of the overall lack of investigations undertaken during the fascist era; to a large extent, archaeological research into the Islamic period began in earnest only after the mid-1970s. A great deal of work in the past three decades therefore has focused on the foundational types of studies that are necessary beginning points in the archaeological endeavor, such as building typologies and chronologies to organize studies of the material culture of *al-Andalus*. For example, the first major typologies of ceramics of the Islamic period were not published until the late 1980s (Guttierez-Lloret 1988; Torres 1987; but see also Rosselló's earlier [1978] typology for Mallorca; Gómez 1998 provides a concise historical review). Analogous work continues to refine typologies for various parts of Iberia and to delimit the temporal and spatial distributions of different artifact types (e.g., Gómez 1998, 2003b, 2005; Retuerce 1998; Torres *et al.* 2003). Many Americanist archaeologists no longer engage in this essential kind of work and some seem to view it as vaguely inferior or uninteresting, but this is a luxury afforded them by working in areas where the culture-historical frameworks largely have been in place for well over half a century.

The disciplinary context in which the recent scholarship of the Islamic period is produced is at least equally influential. Archaeology in Europe is not always considered a subfield of anthropology. Pre-historic archaeology may be closely related to anthropology or it may be affiliated with a department of Quaternary Studies, as is commonly the case in France. Archaeology of the historic period (extending well over

two millennia into the past) often is closely linked to departments of history, and many professional archaeologists hold advanced degrees not in archaeology or anthropology but in history, art history or historic preservation. Historic period archaeology therefore tends towards a slightly different set of disciplinary and ideological commitments than are common in anthropological archaeology programs in North America.

Several scholars (e.g., Gosden 2001; Trigger 1996) have detailed the colonialist legacy of Americanist anthropology and archaeology and relate it to a tendency to study the "other" in terms of comparisons and generalities. Historical studies of the "self" (broadly conceived), on the other hand, are more likely to focus on particular trajectories, including narratives emphasizing active individuals and their roles in important events. These disciplinary entanglements may help to explain why, in North America, archaeology is usually located in the sciences, while the classics departments (including classical archaeology) are part of the humanities; archaeology is the scientific study of "them", classics is the humanistic study of "us". The disciplinary histories probably also contributed to the rise of post-processual archaeology in Europe, largely in reaction to the self-consciously scientific processual archaeology generally focused on the Native American past and centered primarily in North America[11].

As a result of these subtle and often non-discursive disciplinary differences, archaeological studies of the Islamic period frequently are framed in different terms than are common in North America. For example, many investigations of the material culture of the Islamic period are art-historical in nature or blend art-historical and archaeological approaches (e.g., R. Benito *et al.* 2003; Vílchez 2003; see Lopes 2003 for a mixed-approach study of the Late Roman period in the *Baixo Alentejo*). In other cases, scholars work to link sites to locations or events mentioned in historical documents (e.g., Catarino 2003; Rei 2003; Romero 2003; Uribelarrea and Benito 2008; Vílchez 2003). In general, archaeological investigations of the Islamic period are reminiscent of historical archaeology in North America (something of a minority specialization), and the similarities extend beyond the simple availability of pertinent documentary evidence.

[11] This is not to suggest that archaeology in Europe is scientifically or technically inferior to Americanist archaeology. In fact, a recent study found that more funding has been devoted to developing new scientific techniques for archaeology in Europe than in the United States over the last decade, with the predictable result that North American institutions are beginning to lag behind their European counterparts (Killick and Goldberg 2009). I refer here to different philosophical orientations, not techniques or their application.

Historical questions are more likely to drive research than broader comparative studies or anthropological considerations of social structure; archaeological studies of the historic period are highly unlikely to be framed, for example, in terms of adaptations to the local environment.

Perhaps this influence is most clearly visible in the Iberian emphasis on archaeology as social history, a means of exploring the daily lives of the 'common people'. This focus parallels trends in European and North American historiography over roughly the past half-century (e.g., Braudel 1976 [1949]; Goody 1984; Zinn 1980; see also Glick 1995 on Iberia in particular) and also mirrors concerns expressed in the writings of some influential anthropologists (e.g., Wolf 1982). Introductions to archaeological studies often include statements such as, "En los últimos años ha ido creciendo el interés del público en general por conocer las formas de vida de las gentes del pasado… La arqueología ha sido una fuente de información importante para estas síntesis del la vida privada" (In recent years, general public interest in learning about the lifeways of past peoples has grown… Archaeology has been an important source of information for these syntheses of private life; Gómez 2002: 241.) Or, to paraphrase (probably poorly, but hopefully without significant distortion) part of a speech by Cláudio Torres, introducing Virgílio Lopes' (2003) inventory and synthesis of the archaeology of the Late Roman period in and around Mértola, 'we know a great deal about the past from the written record. But only the wealthy and educated were literate, and it is possible to lie with words. It is not possible to lie with artifacts, the physical remains of the past. So archaeology provides an entirely different way of learning about the past, one that includes a window on the daily lives of all people, not just the literate elites.' Perhaps the closest and most well-known analogue in Americanist archaeology for this philosophical approach is in the work of the group of Marxist historical archaeologists associated with the Annapolis Project (e.g., Leone *et al.* 1987; Leone and Potter 1996).

The Campo Arqueológico de Mértola

The largest coherent body of scholarship concerning the Islamic period in the *Baixo Alentejo* has been produced by people working for or with the Campo Arqueológico de Mértola, and their work both reflects and has been influential in shaping

the trends in recent scholarship discussed above. A complete history of this remarkable institution would require a separate volume, but the brief sketch given here helps to contextualize both this study and James Boone's Alcaria Longa project, summarized in the next chapter. This overview is drawn primarily from a history written by Susana Gómez Martínez (2003) and a very brief outline included in an article by Abdoolkarim Vakil (2003), augmented by personal observations and conversations with colleagues at the Campo.

The beginnings of the Campo Arqueológico de Mértola date to 1978, when Serrão Martins, then mayor of Mértola, invited his former professor Cláudio Torres to conduct excavations in the town. The regional economy had collapsed after the closure of the local copper mines in the 1960s. The vast majority of land in the region was owned by absentee landlords, unemployment and underemployment were rampant, and the population had fallen by as much as two thirds due to out-migration to Lisbon and other cities. The *concelho* (a political entity roughly equivalent to a county in the United States) was predominantly rural and severely underdeveloped; a majority of the population lacked access to electricity or running water. It is little wonder that, in the post-revolutionary context, the area became a stronghold of the communist party of Portugal (*Partido Comunista Português;* PCP), which promised development and land reform. Dr. Torres, a leftist activist and scholar, agreed to return from political exile to begin excavations.[12]

More than just a series of archaeological investigations, the project was conceived from the beginning as an integrated program of research and sustainable economic development, very much an innovative idea in the late 1970s. In 1980, the core group of investigators, university students, and local youth formed the *Asociación para la Defensa del Patrimonio de Mértola* (ADPM) to study, preserve and create respect for the cultural and natural patrimony (or heritage) of Mértola. With some grant funding from the European Economic Community, the group was able to expand their activities and, in addition to the ongoing archaeological investigations, they organized archival, ethnographic, architectural, and biological studies and began various preservation

[12] It is worth noting here that Cláudio's father was a prominent leftist historian who had also been forced into exile where he lived out the latter part of his life, dying shortly after the revolution.

projects. By the late 1980s, they had opened small museums in Mértola, providing benefits to the community in the form of permanent jobs and laying the groundwork for a tourist infrastructure. In 1988, the historical and archaeological section of ADPM became the Campo Arqueológico de Mértola, and other branches also formed independent entities focused on traditional weaving (the *Cooperativa-Oficina de Tecelagem*) and the creation of reproductions and art inspired by archaeological finds (the *Oficina de Ourivesaria*).

The project expanded simultaneously in two directions during the 1990s. One initiative focused on creating additional museums and continuing archaeological investigations. This eventually resulted in today's *Mértola Vila Museu*, which integrates several small museums throughout the town with walking tours of historical architecture and otherwise promotes tourism. The second initiative prioritized providing educational opportunities, and led to the creation of the *Instituto de Emprego e Formação Profissional* (IEFP; the Institute of Employment and Professional Training). As the name implies, it creates opportunities for practical education for the local workforce, mostly emphasizing various aspects of tourism and historic preservation. The institute works in cooperation with the local secondary school and a professional school, offering something similar to technical college training and, in concert with the Campo Arqueológico, recently began offering baccalaureate and masters' level courses in Mértola in cooperation with the Universidade do Algarve.

By the early 2000s, *Mértola Vila Museu* was attracting more than 15,000 visitors each year, roughly 70% of them Portuguese, and visitation continues to increase. Its developments emphasize the old town, particularly the medieval quarter, the castle, and the *Igreja Matriz.* The last is one of only two mosques built during the Islamic period that remain standing in Portugal. Built on the site of a Late Roman Christian church, it was reconverted to a church after the *reconquista;* recent renovations highlight the architectural elements dating to the Islamic period, including horseshoe-arched doorways and the *mihrab*. There are additional loci of interest in other parts of town, particularly related to old cemeteries. *Mértola Vila Museu* incorporates six exhibition spaces housing artifacts from the Roman, Late Roman, Islamic, Christian Medieval, and early modern periods, as well as numerous buildings and architectural features with interpretive signs

and a new Center for Islamic and Mediterranean Studies, with offices, meeting spaces, a small store, and lodging for visiting scholars. Other associated facilities include laboratories for study and preservation of artifacts, an osteological laboratory, curation space, an office of tourism, and shops specializing in historically- or ethnographically-themed items.

It would be difficult to overstate the importance of the economic benefits that the program brings to Mértola; it is a town of just over 3,000 people, and there are fewer than 10,000 in the entire *concelho*. The benefits include the direct infusion of tourist money through museum entrance fees and purchases at restaurants, shops, and hotels. In addition, the museums and ongoing educational and research activities provide opportunities for local employment, salaries for scholars living in the community, and they fund construction and restoration projects. Cláudio Torres' vision has profoundly shaped Mértola as it is today, and his efforts have been recognized in appointments to various committees, such as the Conselho Consultivo do Instituto Português de Arqueologia (the Consulting Committee of the Portuguese Institute of Archaeology) and the International Committee of UNESCO. The Campo currently lists within its scientific unit nine PhD's, three investigators with Masters' degrees and numerous employees with Bachelor's degrees or Licenses (the last roughly equivalent to an Associate's degree), as well as many permanent collaborators with advanced degrees.

The Campo, in its various incarnations, has carried out archaeological excavations every year since 1978. These include research conducted for the purposes of scientific investigation, often funded by independently-obtained grant money, work done to prepare various areas for presentation to the public, and salvage excavations associated with virtually every major construction project undertaken in the municipality. Their excavation teams also have taken on projects outside of Mértola, both within the *Baixo Alentejo* and farther away, and their preservation experts similarly work on local, national, and international projects. The work has produced an impressive series of publications, including more than twenty monographs on archaeology, history, urban organization, physical anthropological studies of cemetery populations, and historical architecture in Mértola, as well as ethnographic studies and recent inventories of known archaeological sites in the *concelho*. The Campo also has published numerous illustrated

and annotated museum catalogues and the proceedings of at least five international conferences focused on various aspects of the medieval era. Finally, they have published 9 editions of the periodical *Arqueologia Medieval*, the only scientific periodical dedicated exclusively to the medieval period (understood to include both the Islamic and Christian medieval periods) that is published in Portugal. Each edition is several hundred pages long and presents over a dozen (usually approximately twenty) articles, written in Portuguese, Spanish, English, French, or Italian.

While each publication obviously cannot be reviewed here, it is reasonable to say that, just as the work of the Campo Arqueológico has transformed Mértola, it also has transformed knowledge of the Late Roman and Islamic periods in southern Portugal. In addition to reports detailing specific investigations, scholars at the Campo have made enormous contributions to building the basic typologies and chronologies needed to organize archaeological investigations, particularly of the Islamic period (e.g., Gómez 2002, 2003b, 2005; Torres 1987; Torres *et al.* 2003). They also have written overviews of the history of archaeological research in the region (Gómez and Lopes 2007) and produced several useful syntheses of the results of recent archaeological and archival research (e.g., Macias 1993, 2007; Torres and Macias n.d.; see Lopes 2003 on the Late Roman period).

The vast majority of the Campo's work has been focused within the town of Mértola itself. Now at the beginning of their fourth decade, the excavations have revealed a complicated palimpsest of architecture and artifacts deposited during at least three millennia of dense settlement. The findings pertinent to this research can be summarized as follows: Because of its strategic location at the highest point on the Rio Guadiana navigable by oceangoing vessels, Mértola has been the site of a fortified town at least since the Iron Age when a large stone wall encircling the settlement was first constructed. The old city began to approximate its current form during the Roman era, with a walled settlement, forum, and a complex of civic structures (Roman *Myrtilis*) located immediately above the confluence of the Guadiana and a large tributary, the Ribeira de Oeiras. In addition, Roman roads went north from Mértola to the *plano dourado*, Beja (Roman *Pax Julia*), and Évora. Across the Guadiana, beginning from a ferry landing used until the later 20th century, another road led east towards the location

of the historical copper mines at Mina de São Domingos. The mines are located at the west end of the Iberian pyrite belt, a significant source of metal ores at least since the Iron Age. Other Roman roads carried overland traffic west and southwest and the river conveyed travelers and goods south. Modern roads and most major extant towns in the region generally are located on or near Roman era roads and settlements (c.f. findings of the ARCHAEOMEDES project for southern France, reported in van der Leeuw 2000).

While long-distance trade and urban centers generally declined in Iberia during the Late Roman period, Mértola persisted as a major inland port city and trade center. Roads to the west and southwest may have fallen into disuse, but the roads north and east remained important for significant regional commerce (compare figures 12 and 39, Lopes 2003). Part of the Roman forum was converted to a baptismal complex, basilica, and residence for clerical elites (possibly an episcopate palace), and a second basilica, the *Rossio do Carmo* was constructed near the road towards Beja. Technological and stylistic similarities between the mosaics discovered in the baptismal complex indicate that they were created by the same skilled craftsperson or small group of people. The subjects and styles show strong connections to North Africa, indicating cultural contacts and possibly construction by foreign artisans.

Cemeteries sited along the roads out of town, the typical Roman configuration, continued in use. Funerary inscriptions dating to the Late Roman period indicate the presence of Greek-speaking Byzantine and North African traders and strong influences (probably also resident traders) from the Eastern Mediterranean, Italy, and southern Gaul, as well as a small Jewish population. Mértola appears to have retained the cosmopolitan character of a Roman port city, with the addition of a strong Christian clerical presence. Although crews from the Campo Arqueológico recently unearthed the graves of several Visigoth warriors in Mértola, it remains unclear whether it ever was directly controlled by the Visigothic kingdom or remained to a large degree politically independent after the collapse of Byzantine control of much of southern and southeastern Iberia in the late 6th century.

The political uncertainties and conflicts of the Late Roman era are reflected in various defensive structures built during that time period. Mértola's inhabitants constructed port fortifications, portions of which remain standing; they include a large

tower and structures on each side of the Guadiana built such that a heavy chain could be drawn between them to close the inner harbor[13]. These fortifications no doubt reflect the ongoing importance of maritime trade as well as a fear of naval attack. In addition, the large bunker-like *cryptoportico* was built beneath the baptismal complex, creating part of an imposing wall that protected the complex itself, the city walls were maintained and possibly augmented, and deep wells were excavated that could provide water for the walled city in case of a prolonged siege. Despite the evident concern with conflict, some portion of the population lived in neighborhoods outside the city walls, particularly along the river.

The Muslim conquerors who arrived at Mértola shortly after the invasion of 711 C.E. no doubt offered the local populace the standard choices: convert to Islam and become part of the *ummah* (the community of believers); accept Islamic rule, retain your faith, and pay a tax levied on non-believers; or resist by force of arms and let Allah decide your fate. Mértola, like many cities in Iberia, seems to have taken the second path and accepted Muslim rule without an extended siege. The transition probably was facilitated by long-extant cultural and economic ties to North Africa and a nominal or entirely nonexistent Visigoth presence around which to organize resistance.

Historical Context: al-Andalus

A brief summary of the history of *al-Andalus* as known from documentary sources and ably summarized in several books (e.g., Boone 2009; Collins 1983, 1989; Glick 1995; Lewis 2008) provides useful context for examining developments in Mértola. Very likely, the first few decades of the Islamic period saw little change in Mértola and other areas outside of the Guadalquivir valley; local notables remained in charge of local affairs and long-distance trade. Taxes were collected – probably as inefficiently as before – in the name of the *wali* (governor) in Córdoba who ruled Iberia as a province of *Ifriqya* (North Africa) instead of in the name of a Visigothic king in Toledo.

By the 740s, Syrian *junds* (Arab military units organized by tribe) began arriving in large numbers in Iberia, fleeing conflict with rebellious Berbers in North Africa. Large numbers of Berbers also immigrated to Iberia in the 8th century (Guichard's (1976)

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[13] Lopes (2003) shows that da Veiga's initial interpretation of the *Torre do Rio* as a structure dating to the Islamic period was incorrect.

estimates run to the 10s or 100s of thousands). For the most part, they were illiterate and their perspectives rarely are reflected in the documentary record. Perhaps they were fleeing the same conflicts as the *junds* as well as seeking new opportunities, but both groups imported barely-concealed rivalries that would come to the surface repeatedly in the succeeding centuries. One of the *junds*, the *Banu Fihri*, settled around Beja. For a time they put aside a long-standing enmity and joined an army of Yemeni Arabs sent by the Baghdad Abbasids to challenge ʻAbd al-Rahman I's attempts in the late 750s – 760s to create an Umayyad emirate independent of the Abbasid Caliphate (Lewis 2008: 197 – 202). Mértola seems, again, to have been at the margins of the territory controlled by the central state. ʻAbd al-Rahman I ultimately was successful in consolidating power and reuniting the peninsula and he generally is credited with laying the groundwork for the vaunted *convivencia* of *al-Andalus*.

During the Emiral period (756 – 929 C.E.) the population of Iberia began a trajectory of rapid growth that lasted for several centuries; cities and long-distance trade rebounded from their Late Roman nadir. Córdoba in particular became a cosmopolitan city of Arabs, Berbers, *muwalladun*, Jews, and Christians. As a center of population, trade, manufacturing, and learning it dwarfed everything on the European continent with the exception of Constantinople.

During this period of initial growth, the central state remained relatively weak. Most historians attribute this weakness to perpetual conflicts between various factions of *baladiyyun* (descendants of the first Arab conquerors), Syrian and Yemeni Arabs, Berbers, *muwalladun*, *mozarabs*, and Jews. The *muwalladun*, the frequently-marginalized heirs of important Hispano-Roman families that converted to Islam shortly after the conquest, seem to have been particularly troublesome. The moniker became, for a time, synonymous with "rebel" or "renegade", before they were more completely incorporated into *Andalusi* life in the subsequent Califal period.

Beyond the simple existence of these cultural and ethnic rivalries, however, there was a structural component that allowed them to play out as significant political divisions: the economic and military systems were decentralized and local leaders held the power to raise armies and levy taxes. The system of taxation was unsystematic and virtually incomprehensible, relying on a series of treaties dating to the initial Muslim

conquest as well as separate taxation and legal systems governing Muslims, Jews, and Christians. In addition, the scriptural proscription against taxing fellow Muslims inevitably led to various attempts to contravene that proscription. The situation provided ample opportunities for local leaders to build their own bases of power and challenge the central state. To the evident consternation of the *emirs*, they joined in shifting alliances with each other, the Arab state, or adjacent Christian kingdoms and principalities as suited their needs of the moment.

The Caliphs in Córdoba consolidated power over *al-Andalus* during the subsequent Califal period (929 – 1009 C.E.). Largely, this was because ‘Abd al-Rahman III, the first Iberian Caliph, was able to bring to fruition plans begun by his grandfather (‘Abd al-Rahman I) to build a professional military answerable to the central state. With his army of Berbers, Africans, and Slavs, he was finally able in 928 to crush the most recalcitrant of the rebellious territories where Umar ibn Hafsun and, later, his four sons had defied state rule from their fortress of Bobastro (near Ronda) for almost fifty years[14]. He continued southward across the Mediterranean and established for the first time an Iberian outpost in Ceuta and also brought to heel the local Berber and *muwallad* leaders in the marches, whose allegiances had always been somewhat questionable.

‘Abd al-Rahman III built the spectacular palace city of *Madinat al-Zahra* just outside of Córdoba. It is larger than Louis XIV’s Versailles and was, for the time period, at least as opulent. Córdoba itself continued to flourish as a center of learning and commerce that stood in stark contrast to Europe beyond the Pyrenees. Córdoba had no fewer than 70 libraries, the largest with at least 400,000 volumes, while at the same time the famous Benedictine center of learning, the abbey at St. Gall in Switzerland which was reputed to house the largest library in Christian Western Europe, counted only 600 books in its collections (Lewis 2008: 326). This cultural fluorescence was founded on a vibrant economy, also dramatically different from that in the rest of Western Europe. In the words of Lewis (2008: 327), *al-Andalus* was, “City-ruled, agriculturally productive, its trade globally powered, its commerce transacted in silver and gold coinage… To a large extent, the business of *al-Andalus* was business, in great contrast to Carolingian Europe,

[14] By then the *Andalusis* had long since given up on conquering the Basques, who had already been successfully resisting attempts to integrate them into larger states and empires for over a millennium.

where warfare comprised most of the business and the *raison d'être* of a specific caste [i.e., the elites] was the perpetuation of war." The economy of Carolingian Europe had reverted in all important aspects to something very like the Iron Age economy, and production systems had followed suit. Agricultural innovations that improved yields and preserved long-term soil fertility (e.g. regular crop rotation, manuring, and the three field system) would not be adopted in Christian Europe for several centuries.

Although its wealth far outshone that of any polity in Western Europe, it was not because agrarian production was efficiently taxed by the centralized state in *al-Andalus*. James Scott (1998: Chapter 1) argues convincingly that efficient centralized taxation of rural production is virtually impossible in a premodern context, lacking reliable communication, systematic weights and measures, codified and recorded land tenure systems, and reliable state knowledge of agricultural potential, yields, and variability (the Romans are an exception, notable primarily because they developed many of these tools). The necessary response is some form of state dependence on local leadership. In Carolingian Europe, feudal lords swore fealty to the king and paid their taxes by equipping and training armed knights who they rallied to his banner for annual military campaigns that were expected to fill the king's coffers. In *al-Andalus*, local leaders forwarded taxes to the state in coin but often retained stronger allegiance to the local community.

The combination of economic fragmentation and long-standing ethnic and tribal rivalries eventually played out in the triumph of regional interests over the centralizing tendencies of the state in Córdoba. The Caliphate disintegrated rapidly in the early 11th century in the aftermath of a civil war in 1009-1010 C.E. that pitted one califal claimant against another; Sulayman al-Musta'in, backed by Castilians and a recently-imported Berber army, fought against Muhammad II al-Mahdi, who was backed by the remains of the army established by ʻAbd al-Rahman III and the Catalonians. A bewildering series of inconclusive battles, shifting loyalties, and califal claimants ensued, effectively ending all semblance of centralized power. In place of the caliphate grew a series of smaller *taifal* states that usually consisted of one or a few larger towns or cities and the immediate hinterland (they often are called city-states, but see Marcus and Feinman 1998 on problems with the term). The small states squabbled among themselves and Córdoba's

importance eventually was eclipsed by Seville. Mértola was the center of a *taifa* from 1031 until it was conquered by the kingdom of Seville in 1044.

While the regional economy based on commerce, manufacturing, and productive irrigation agriculture continued to thrive, the military apparatus once again became fragmented and dominated by local leaders. The Christian kingdoms to the north took advantage of the situation and pushed southward, often in concert with disaffected *taifal* leaders in the marches; together they no doubt coveted the wealth of the cities of southern *al-Andalus*. The northern kingdoms were supported by Papal calls to bring Christianity to the Muslims, leading to the siege and capture of Barbastro in 1064 by three thousand French, Norman, and Italian knights in something like a dress rehearsal for the First Crusade that began a generation later in 1095. The knights were an "international force of freebooters, second sons without prospects, and grimly motivated penitents… the unbathed, larcenous forerunners of a hundred thousand holy warriors whose sins would be forgiven in advance and salvation certified by Christ's vicar" (Lewis 2008: 353 – 354). Toledo fell in 1085 and the specter of being conquered by the benighted Christians, who were beginning to show signs of what would later become their famous religious intolerance, prompted the faithful to call for aid from the Berber Almoravids of North Africa.

In 1086, Almoravid armies led by Yusuf ibn Tashfin rallied what remained of *al-Andalus* and inflicted severe defeats on the Christian armies. ibn Tashfin, backed by a *fatwa* (religious decree) that legitimated his opinion of the *taifal* leaders as impious and morally bankrupt, systematically deposed them and imposed a strict, orthodox Malakite Islam. By the end of the decade the Almoravids had seized power in virtually all of Islamic Iberia. Almoravid zealotry was the beginning of the end of more than three centuries of mostly-peaceful cohabitation by Muslims, Christians, and Jews in *al-Andalus*. At the same time, Christian leaders in northern Iberia, stung by defeat and very likely influenced by the proto-Crusaders, became increasingly virulent in their persecution of nonbelievers. They began violating treaties, demolishing mosques in conquered cities, and turning their backs on Muslim former allies. Local leaders in *al-Andalus* chafed under both centralized control and the imposition of religious strictures,

and centripetal tendencies again came to the fore; Almoravid power declined rapidly after the death of Yusuf ibn Tashfin in 1106.

After several decades of stalemate, the Christians resumed their push southward, winning major battles in the 1130s and 1140s. In 1139 Afonso Henriques defeated the army led by Yusuf's son, Ali ibn Yusuf, at the battle of Ourique, thereby being proclaimed King Afonso I of Portugal. Local leaders in *al-Andalus* continued to increase their power at the expense of the state, and several *taifas* were reestablished in the 1140s; the mid-12th century generally is considered a second *taifal* period. At the same time, the Almohads were advancing against the Almoravid Empire in Africa, assuming at least nominal control of some of the Almohad holdings in Iberia in 1145, killing ibn Yusuf's son and successor in Africa in 1146, and conquering the Almoravid capital at Marrakech in 1147. In that same year, Lisbon fell to the Christians.

Local resistance to the Almoravids in the *Baixo Alentejo* crystallized around one Abu'l-Qâsim Ahmad Ibn al-Husayn Ibn Qasi, who established a rebel *taifal* state in Mértola in 1144. Something of a local hero to this day, he symbolizes local independence and resistance to oppression and is the subject of a nearly-life-size bronze statue showing him mounted in full battle regalia near the entrance to the castle in Mértola. Ibn Qasi's remarkable life as known from the historical record is recounted by Artur Goulart (1992) and it illustrates the complicated relationships between local leaders and the state in the last days of Almoravid ascendancy. Ibn Qasi was born on an unknown date to a wealthy family in Silves in the Algarve, roughly 85 km southwest of Mértola. His name indicates that they almost certainly were a *muwallad* family of the influential *Banu Qasi* clan (Macias 1993: 427). After an aimless youth, he reputedly sold all of his belongings, donated the proceeds to the poor, and resolved to follow the life of an ascetic Sufi mystic. He traveled to Almería to become a disciple of Ibn al-Arif, whose influential school eventually attracted the unwanted attentions of the Almoravids; Ibn al-Arif was officially denounced as a heretic and exiled to a prison in North Africa.

After a period of travel in Andalucía, Ibn Qasi returned to Silves where he continued to study Sufi writings and founded his own *rábita* (religious school), wrote a religious treatise, and attracted a large following. Several miracles were attributed to him, and some of his followers declared him *al-Mahdi*, or "the guided one" (sometimes

also translated as “the expected one”), the prophesied redeemer of Islam who would portend the second coming of Jesus and join him to rid the world of sin on the day of resurrection. Ostensibly in order to prepare the world, Ibn Qasi set out to establish an independent state in southwestern Portugal. After several failed attacks on Almoravid outposts and a time in hiding, Ibn Qasi’s lieutenant organized a surprise ambush of the Almoravid garrison on the 14th of August 1144 and took Mértola. Almoravid forces were unable to retake the city, very likely because locals helped to defend it, and on the 1st of September, Ibn Qasi entered the city and was declared *Imam*. His success and his religious teachings inspired others, and leaders in Évora and Silves mounted their own successful revolts and declared their allegiance to Ibn Qasi. His followers went on to take Huelva and Niebla (in present-day Spain), and attacked Seville before being turned back.

For at least a year (as many as three according to some sources), Ibn Qasi ruled unopposed from Mértola, minting his own coins. He occasionally sent troops to fight in various rebellions, mostly in Andalucía, apparently with the goal of expanding his influence into the Guadalquivir valley. Eventually, he was betrayed by Ibn Wazir, the leader of the revolt in Évora who had earlier declared his allegiance and been granted governorship of Beja in return. Ibn Wazir took Mértola and ruled it together with Beja, Badajoz, Évora, and the area to the west. Ibn Qasi fled to North Africa to seek help from the Almohads. Although they looked suspiciously on his Sufi teachings and title of *al-Mahdi*, the Almohads eventually received Ibn Qasi and agreed to send an army to Iberia where they occupied Jerez, Niebla, Mértola and, with Ibn Qasi’s help, Silves. Ibn Wazir surrendered Beja and Badajoz and joined in alliance with the Almohad army to take Seville in 1148.

Conquest was easier than rule for the Almohads and as soon as their armies had disappeared over the horizon local leaders again declared their independence as *taifal* states. Confusion and political fragmentation ruled until the Almohad leader Abd al-Mu’min traveled personally to Andalucía in 1151 to demand that the *taifal* kings fall in line. Fearing the return of the Almohad army, they acquiesced with the single exception of Ibn Qasi who refused to cede control of Silves. In preparation for the inevitable confrontation with the vastly more powerful Abd al-Mu’min, Ibn Qasi sought an alliance

with the Christian King Afonso I, apparently enraging his own followers; the devout among them assassinated Ibn Qasi in August or September 1151.

The Almohads, Berbers from North Africa like the Almoravids before them, consolidated power in *al-Andalus* after 1151. They brought their own reformist brand of Islam to Iberia, preaching a strict fundamentalist uniformitarianism tinged with mysticism and intolerant of any perceived impiety or moral laxity. Initially, they superseded the Almoravids in their persecution of *dhimmis* (non-Muslims), reputedly killing thousands of Jews during their conquest of North Africa. The intolerance they brought to Iberia was another nail in the coffin of the *convivencia*. Faced with the choice of conversion or death, *Mozarabs* and some Jews fled north out of the still-vibrant center of *al-Andalus* at a greater rate than before, taking with them considerable resources. Christian intolerance in the northern kingdoms increased apace, but the Muslims forced to flee south from the conquered peripheral Islamic states often had lost everything in battles in which the Christians had been victorious; it was an uneven exchange. Jews were left without state-sanctioned safe haven, and used their wealth, education, and commercial resources to garner protection from powerful and amenable local leaders wherever they could find them. Many emigrated for other more tolerant parts of the civilized (Muslim) world, taking refuge in the cities of the eastern Mediterranean.

The Almohads took their turn at trying to consolidate a fractious *al-Andalus*. They moved their capital to Seville in 1170 and built the famous *Giralda* there in 1184, at the time the tallest structure in the world. For a time they were successful, bringing many of the reemerged *taifal* states under their sway and holding back the Christian advance until the beginning of the 13th century. They also gradually absorbed the culture of *al-Andalus* and moderated their persecution of the *dhimmis*. But old *Andalusi* rivalries and separatist tendencies did not disappear, while the Christian kingdoms of the north became increasingly united.

In 1212, Pope Innocent III called on the knights of the Holy Roman Empire, France, and the Christian Kings of northern Iberia to undertake a crusade to expel the Muslims from *al-Andalus*. The Pope also sent money, blanket indulgences, and the knights of the orders of the Templars, Calatrava, and Santiago. That summer, at the battle of Las Navas de Tolosa, the Christian alliance met the armies of *al-Andalus*.

Capping one and a quarter centuries of increasing intolerance and persecution on both sides, it "was the first war fought by Christians and Muslims exclusively *as* Muslims and *as* Christians" (Lewis 2008: 378; emphases in original), and not as warriors aligned with individual leaders in whatever alliances they had formed.

The Christians dealt the larger Muslim army a crushing defeat and continued on to besiege and take the towns and cities of southern Iberia one by one. Córdoba fell in 1236, Mértola was conquered by King Sancho II of Portugal and the knights of the order of Santiago in 1238, and Seville was taken in 1248. The Almohads retreated to North Africa where, interestingly, they continued the policy of relative tolerance of *dhimmis* adopted in *al-Andalus*. Thousands of the more wealthy Muslims gathered their resources and fled to the cities of North Africa, while those lacking the means to leave maintained a low profile; the official purges of Muslims from Iberia were still centuries in the future. Islamic political power in Iberia was reduced to the Nasrid kingdom of Granada, which survived as a tributary state to the Christian kingdoms from 1252 until January 1, 1492.

Archaeology of the Islamic period in Mértola

Archaeological evidence related specifically to the earliest years of the Islamic period in Mértola remains scarce. For the most part, this is due to the fact that across Iberia there were few changes in material culture coincident with the Islamic conquest, and immigration from North Africa and the eastern Mediterranean initially was somewhat limited. The invasion itself therefore left virtually no recognizable archaeological signature. The single important exception is a series of rare gold *dinars* (coins), the earliest bearing both Latin and Arabic script, minted sporadically from 712 to 745 (Boone 2009: 66 – 67); none of these have been recovered in Mértola.

Despite the lack of clear archaeological signatures, circumstantial evidence (i.e., the settling of the *Banu Fihri* around Beja in the 740s) suggests that Mértola must have continued as an important inland port and trade center, transferring resources from the *plano dourado* and the pyrite belt southward and importing various manufactured goods from the Mediterranean world. It almost certainly remained outside the sphere politically controlled by the center during the initial struggles to establish the Umayyad emirate. The lack of any written references to rebellions prior to the 12th century suggests, however, that Mértola became integrated into the economic and political life of *al-*

Andalus during the Emiral period; rebellions were the only events that occurred in the hinterland that appear to have been recorded consistently by the literate urban elites.

By the early 10th century, coinciding approximately with the founding of the Iberian Caliphate, an Islamic period material culture begins to be identifiable as such, primarily in the form of particular glazed ceramic types used to serve food (Gómez 1998 provides a concise and useful overview of the glazed wares; see also Gutierrez-Lloret 1988, and discussion in Boone 2009: 138 – 145). The economic collapse of the Late Roman period had caused ceramic production to become decentralized, and the vast majority of pieces were formed by hand or on a slow wheel, predominantly in domestic settings. The profusion of local handbuilt and slow wheel traditions continued with little change through the Emiral period. Beginning in the mid-9th, but especially in the 10th century, however, the flourishing economy of *al-Andalus* supported the appearance of specialized ceramic manufactories producing a range of wheel-made wares, including both utilitarian (unglazed cooking forms) and decorated (glazed serving forms) ceramics. These rapidly replaced locally made handbuilt and slow wheel ceramics with the exception of *jarritas*, a class of unglazed cups or tankards that continued to be made by hand. The particular forms of the glazed wares – large bowls, platters, tureens, and pitchers (*redomas*) – are a marked change from the generally smaller forms of earlier periods, apparently reflecting the adoption of the Islamic practice of communal dining.

Of the different glazed wares, one with a honey-colored, brownish or greenish lead glaze and black manganese paint (*melado e manganês*) became widespread in the 10th century and continued to be ubiquitous throughout the Islamic period. Production of a white tin-glazed type with black paint (*branco e manganês*) appears to be restricted to the 10th and 11th centuries. It is closely related to a polychrome type that also incorporated green copper oxide paint (*verde e manganês*) that initially was produced at ‘Abd al-Rahman III’s *Madinat al Zahra*. The latter appears to have been presented commonly as an ambassadorial gift in outlying provinces, demonstrating a material connection to the Caliph. Beginning in the 11th century and reaching its apogee in the 12th, a highly decorated polychrome glaze ware known as *corda seca* (or *corda seca total*) also was produced in Iberia using a variant of the wax-resist glazing technique. Interestingly, all of these glazed wares and the last in particular were decorated with a

variety of motifs, including anthropomorphic and zoomorphic representations in addition to script, pseudo-script, and various geometric designs, providing yet another Iberian example of Islamic representational art (see Goody 2004 for an extended discussion of the common misconception that Islamic art is universally non-representational).

As in other parts of Iberia, these ceramic wares provide the most commonly-used means of identifying and differentiating Islamic period archaeological deposits in Mértola. Excavations led by Virgílio Lopes in the summer of 2007, in addition to several earlier, smaller investigations by the Campo, uncovered portions of a neighborhood along the river, outside the city walls. Based on the associated ceramics, it dates to the 10th to 12th centuries (preliminary observations are presented in Gómez and Lopes 2007[15]). Excavations revealed parts of several buildings that appear to have been domiciles with several rooms arranged around interior patios; in at least one case, there are two clear occupation levels, but they yielded a similar suite of temporally diagnostic ceramics. In addition to the buildings there were the remains of planned, well constructed streets and a well developed drainage and sewer system. Various artifacts and its location led the excavators to call the area a fishing village, but the presence of large quantities of glass slag in all of the excavated structures also suggested to them that the neighborhood may have been the site of a glass manufactory.

The Campo's long-term excavations in the castle and in the adjacent area where the *Igreja Matriz* and Late Roman baptismal complex are located have produced evidence of a major urban rebuilding and reorganization effort during the Almohad period (mid-12th to mid-13th century). The former mosque probably was constructed at that time. In addition, investigations revealed an Islamic quarter (or neighborhood; the *bairro islâmico*) where the Campo excavated all or parts of fifteen houses constructed during that period. Their layouts are typical of Islamic period urban dwellings excavated elsewhere in Iberia (and in parts of North Africa; see Boone and Benco 1999): each house consisted of a few square or rectangular rooms – including a kitchen and adjacent storage space, latrine, and sleeping rooms – each of which opened onto an enclosed

[15] In literal translation, they refer to the neighborhood as a suburb, although it is within a few minutes' walk of the fortified town center and the houses are closely-set, giving it an urban character.

courtyard that, in turn, opened through a small atrium or entry room onto straight roads of rammed earth.

The latrines and many of the kitchens were connected to an integrated drainage and sewer system. All of the houses were constructed using similar techniques, with plastered adobe or rammed earth walls approximately 50 cm thick on masonry foundations, and roofed with tile. The only characteristic that showed considerable variability was flooring and courtyard paving; the materials used included ceramic tile, schist flagstones, painted masonry, and rammed earth. The overall impression is that the houses were all built at approximately the same time, by the same group of people, as part of a planned program of construction within the most easily-defended sector of the walled town.

Architectural analyses and archaeological investigations in the castle have shown that the much of the impressive extant structure was constructed or remodeled during the Islamic period. (The most significant exception is the central keep, which was finished in the 1290s by the knights of the order of Santiago; Mértola was donated to them after the Christian *reconquista* and they maintained their seat of power there until 1316. The castle was "restored" in the mid-20th century by the Salazar regime.) The construction efforts appear to have focused on increasing the defensibility of the structure, for example by installing a large cistern and a system of canals for capturing rainwater. Excavations also yielded evidence of a silversmith's workshop in the castle, probably dating to the later Islamic period.

In order to investigate aspects of trade and commerce in Mértola during the 12th and 13th centuries, Susana Gómez Martínez organized a series of technical studies of the decorated ceramics recovered from excavations in the Islamic quarter and castle (Gómez 2003b). A combination of neutron activation analysis, petrographic thin section analysis, and stylistic and formal analyses demonstrated multiple origins for the different decorated glazed wares. The majority of the *corda seca* ceramics and a finely made type known as graffiti ceramics probably were produced in Almería and were imported to Mértola for the local and regional markets. Other types, including the green and manganese polychromes had more diverse origins, possibly including a manufactory in or near Mértola. In the context of her discussion of local industries, Gómez also notes that

excavations in the Islamic quarter and castle recovered a large number of implements used in textile production, suggesting that it was another important local industry. The data show that Mértola remained an important trade center throughout the Islamic period and that it also very likely became a center of production of textiles, glass, and ceramics.

In addition to architecture and artifacts, excavators have unearthed an astonishing number of graves in Mértola dating to the Roman, Late Roman, Islamic, and Christian Medieval periods (for example, Campo teams have excavated more than 670 interments from the last period alone; Gómez and Lopes 2007). In order to gain some insight into the origins of the Islamic period population of Mértola, Garnett McMillan (McMillan and Boone 1999; see also McMillan 1997) conducted an analysis of the presence or absence of 65 discrete cranial-morphological traits in 111 individuals. Fifty-seven (57) of the individuals were recovered from cysts excavated into bedrock beneath the floor of the Late Roman era basilica and the adjacent paved plaza. Stratigraphic position and inscribed tombstones covering some of the cysts show that they were interred between the 5th and the end of the 7th centuries. The remaining 44 individuals were excavated from the rubble mound created when the basilica fell into disuse and collapsed during the Islamic period. Stratigraphic position and body orientation – on the side, slightly flexed, with the head to the south and the face to the east, toward Mecca, as opposed to supine with the head towards the west as seen in burials from Christian periods – indicate that the rubble mound burials date to some time during the Islamic period[16]. Statistical analyses of the resulting data suggest that the two burial populations were not closely related genetically; the clear implication is that there was a significant population influx to urban Mértola during the Islamic period. Although the skeletal data do not provide any direct means of evaluating the origins of the new population, it seems likely that they came largely from North Africa and/ or the Eastern Mediterranean. The urban population may have been dominated by Arabs during the Islamic period; at a minimum, the population was strongly arabized.

Unlike the beginning of the Islamic period, there are several clear archaeological indications of its end in Mértola. Probably the most graphic is the skeletal remains of

[16] Because a majority of Muslims interpret a scriptural passage stating that we all are equal before Allah in death as a proscription against burial goods, and many also did not use grave markers during various historical periods, graves from the Islamic period often are difficult to date with any accuracy.

more than two dozen individuals encountered on the floor during the Campo's excavation of the *cryptoportico*. Associated artifacts suggest that these individuals were the last of the Muslim soldiers who died defending Mértola against the Christians. The random orientations and positioning of the bodies imply that they either were dumped in the *cryptoportico* after the city was taken or were left where they fell, defeated at the end of a dramatic last stand against the invaders from the north; the Christians subsequently filled the *cryptoportico*.

In more general terms, the regional economy fell into severe decline following the Christian *reconquista*. Mértola itself suffered from the severing of trade ties to North Africa and the decline in trade with the (still predominantly Muslim) Mediterranean world. Production and trade of fine decorated ceramics ceased, and the most common Christian medieval glazed ceramics are coarse vessels covered with a heavy green lead-based glaze. Coarse red-brown wares, produced during the Late Roman period and in small quantities through the Islamic period, again become ubiquitous. Portugal began the long, slow transition to its eventual place as one of the key players in the emerging Atlantic economy of the early modern world.

Summary

Despite early efforts in the 19th century, few archaeological investigations focused on the Islamic period were undertaken in Iberia before the fall of the fascist regimes in Portugal and Spain in the 1970s. Since the early 1980s, however, there has been a dramatic increase in historical and archaeological research. Because of the scarcity of previous studies, a great deal of the recent archaeological work has been directed at building the basic chronologies and typologies necessary for organizing investigations of the material culture of *al-Andalus*. In terms of the foci of research, European scholars in the field often view their work as a form of social history, illuminating the lives of the non-literate majority of the population and aspects of the past not recorded in historical documents. Their research remains intimately involved in the politics of constructing the historical narratives and national identities of Portugal and Spain as modern countries with a past that stands out as unique among the members of the European Union. It would be difficult to overstate the impacts of the newfound appreciation of the significance of the Islamic period both in the academy and among the public; the

historian Thomas Glick (1995: xii – xvii) probably is correct in his assertion that archaeology has played a larger role in re-imagining the social and cultural history of Iberia than it has in any other part of the world.

Since 1978, scholars associated with the Campo Arqueológico de Mértola have been at the forefront of archaeological and historical investigations of *Al-Andalus*, particularly in the *Baixo Alentejo*. Their excavations and archival research have elucidated numerous facets of life during the Late Roman, Islamic, and Christian medieval periods in and around Mértola. In particular, they have been able to trace a complicated history of urban settlement, renovation, and reorganization going back roughly three millennia. Their research also has illuminated patterns of economic change, as Mértola has played a key role in regional and long-distance trade connected to the waxing and waning of the great empires of classical antiquity and the Islamic world.

The picture that is emerging is one of both historical and more general anthropological interest. Through the Late Roman and Islamic periods, Mértola was an important port city, a node in trading networks that reached North Africa, Southern Europe, and the Eastern Mediterranean. Excavations in Mértola suggest that a large neighborhood outside the city walls was established by the beginning of the Califal period (when a specifically Islamic period material culture became recognizable) and persisted from roughly the 10th through the mid-12th century. In addition to fishing, the inhabitants may have produced glass. During the subsequent Almohad period (mid-12th to mid-13th century), settlements outside the city walls appear to have been abandoned and there is clear evidence for a major program of urban reorganization in the fortified center of Mértola. Although it is impossible to rule out the continued presence of neighborhoods outside the city walls without completing a massive program of systematic test excavations, it is tempting to see the reorganization as evidence of an organized effort to increase the defensibility of the city. Archaeological data also show that Mértola probably became a center of various industrial activities in the later Islamic period, including metalworking, textile production, and ceramic manufacturing.

The study area presents a microcosm of cultural and ecological interactions in the parts of *al-Andalus* lacking large tracts of irrigable land; Mértola was a point of articulation between the urban-based Arab state and tribally organized rural populations.

The research reported in subsequent chapters shows that there was a significant increase in population densities in rural areas during the Islamic period and examines the ecological impacts of the resulting changes in land use. Hopefully, it will illuminate a heretofore unexplored aspect of the history of *al-Andalus* and provide a case study of the ways in which social, political, and economic organization mediate human impacts on the environment at the time scale of centuries.

Chapter 4:
Rural Archaeology and Site Survey

The ADPM and Campo Arqueológico de Mértola have been active in recent efforts to promote rural tourism in the *concelho*, including establishing the *Parque Natural do Vale do Guadiana* (Guadiana Valley Natural Park) along with various signed tourism routes through rural areas. In addition, they have led efforts in recent years to preserve and renovate a Late Roman era monastery in the village of Mosteiro north of Mértola, and Virgilio Lópes directed limited excavations in the churchyard there in 2007. In addition to Lópes' (2003) inventory of Late Roman sites in the *concelho*, the Campo also has undertaken an inventory of known archaeological sites from all time periods. Overall, however, archaeological investigations in rural areas have lagged behind work in Mértola itself, in part because construction and development threaten fewer known sites in the countryside.

James Boone saw an opportunity in the situation, and he began collaborating with the Campo Arqueológico de Mértola shortly after joining the anthropology faculty of the University of New Mexico in 1987. His work has included documenting rural settlement patterns through pedestrian survey (Boone 1994, 2002; Boone and Worman 2007; Dinsmore 1994), showing how human occupation of the landscape changed as the Roman world disintegrated, during a subsequent transitional phase, and through the Islamic period. In addition, his excavations at small rural villages and farmsteads dating to the transitional and Islamic periods have begun to illuminate interactions between the urban and rural spheres and provide information relevant to addressing the extremely difficult questions of the origins and ethnicity of the rural populations (Boone 1992a, 1993, 1994, 1996, 2002). Building on his dissertation research in Morocco, he also has worked with various colleagues to place developments in *al-Andalus* in a broader regional perspective (Boone 2009; Boone and Benco 1999; see also Boone *et al.* 1990). His work is summarized in this chapter, and the results of a more recent survey completed with Worman during the 2004 – 2005 field seasons are presented.

The Alcaria Longa Project

Boone's investigations began with extensive excavations at the village of Alcaria Longa, located near the modern village of the same name approximately 24 km west of Mértola. In several seasons between 1988 and 1994, Boone directed excavation of more than 700 square meters of the site, which covers approximately 1.6 hectares on the slopes and summit of a hill overlooking the Ribeira de Carreiras, a tributary to the Guadiana. His investigations revealed roughly 35 house compounds dating to the later Islamic period, with initial occupation beginning approximately in the mid-10th century and rapid abandonment of the site in the mid-12th century. He also identified a limited Christian medieval reoccupation in the form of a small fortification or watchtower built at the highest point of the site.

Boone's team excavated all or nearly all of three Islamic period house compounds (a mature olive tree was left in place along the wall of one structure and part of another had been badly damaged by plowing). Each of the three compounds included a large rectangular structure internally divided into three smaller areas, with features indicating food preparation and storage; very likely these structures also were sleeping areas. These buildings opened to the south-southeast onto enclosed patios, with a second, smaller rectangular structure forming the northeast boundary of each. In two, smaller walls enclosed the remainder of the patio, while in the third compound a small, unroofed structure interpreted as an animal pen defined the northeastern side of the patio and a small roofed structure analogous to those in the other compounds was located along the southwest side. Except for the animal pen, all of the structures had tile roofs, and all were constructed of masonry and built directly on the bedrock surface, with no indications of prior occupations. Based on architectural remains visible at the surface, the layouts of these household compounds probably are repeated in the majority of structures at Alcaria Longa.

Interestingly, features in the smaller structures along the side of each patio and different artifacts present in each compound suggest specialized household industries. In one compound, two fire pits in the smaller structure were partially filled with coke and slag and an iron hammer was recovered, suggesting a blacksmith's forge. In the compound with the small unroofed structure adjacent to the patio, two bronze spindles

and a bone distaff end-piece were found during excavation, indicating spinning of wool into yarn or thread. A small cast lead ring from that compound may also have been part of a tool used in textile production (perhaps a weaving spacer or other piece of a loom?) and an unusual thermal feature may have been part of a facility used to preserve meat by smoking. While artifacts reflecting a particular recognizable production activity were not present in the third compound, a complex arrangement of five hearths in the smaller structure suggests some kind of light industrial activity, perhaps wool dyeing.

Small whole and fragmentary millstones were present across the site and were recorded in several excavated contexts where they mostly appear to have been reused as architectural elements or to support vessels over hearths during cooking. The millstones suggest household grinding of grain for bread. Because of acidic soils at the site, faunal remains were preserved only in the alkaline ashes of hearths in the long buildings; thermal features in the smaller buildings lacked faunal remains, reinforcing the impression of a spatial separation of cooking and sleeping from activities of an industrial character. Ovicaprids (sheep and goats) dominated the counts of recognizable elements (69.7% of identifiable elements), followed by cattle (13.2%). Deer, rabbits or hares, and dogs rounded out the assemblage in roughly equal proportions, and there were also a few identified elements from small galliform birds, probably quail or partridge (Boone and Worman 2007; Boone 1993 presents slightly different proportions from an earlier analysis, which found galliform birds to be more numerous). No elements attributable to wild or domestic pigs were present. It is worth noting that sheep, goats, cattle, and pigs are raised in the area today, and both tourists and locals hunt rabbits, hares, quail, partridge, deer, and wild boar; the absence of pig remains in the faunal assemblage from Alcaria Longa very likely reflects a cultural aversion.

In addition to the iron, bronze, and lead tools used for textile production and blacksmithing, other artifacts recovered from the three excavated house compounds at Alcaria Longa clearly reflect access to an extra-local market economy. The ceramics were wheel-thrown and apparently mass produced. Petrographic and limited neutron activation analyses suggest that the orange plainwares that make up slightly more than three quarters of the assemblage were made from clays derived from sedimentary deposits that outcrop north of Mértola, near the village of Corte do Gafo approximately

30 – 40 km from Alcaria Longa. Coarse red-brown wares, which account for roughly 17% of the analyzed sample, most likely were produced near Beja about 50 km north of the site. Buff plainwares and melado glazed pieces, accounting for just over 4 and 3% of the sample respectively, were formed using calcareous clays; they probably were manufactured in the vicinity of Seville, some 160 km to the southeast. A large mass of partially melted wasters encountered at the site shows that ceramic rooftiles were produced locally.

Artifacts recovered during the excavation also suggest that the inhabitants controlled and displayed a fair amount of personal wealth. Among these were a decorated bronze and iron dagger hilt, a bronze ring from a harness or belt, a portion of a metal strap handle, fragments of a silver chain, a silver filigree earring, two silver finger rings with glass stones, one stone bead, a fragment of a yellow-green glass bottle, two perforated coins, and two marine shells of unknown utility. Although the Arabic script on the coins was for the most part illegible, the lead-alloy coin probably was struck during the Califal period. The silver coin dates to some time during the Islamic period prior to the Almohad ascendance in the mid-12th century and may, in fact, have been one of the coins struck in Mértola in the name of Ibn Qasi; if so, its loss was closely coincident with abandonment of the site.

Boone suggests that these items of adornment and weaponry indicate a high degree of local control of agricultural surplus and the absence of the highly-exploitive sharecropping, serfdom, and rent-based feudal economies that were developing in Christian Europe at the time. Instead, he proposes a type of semi-autonomous tribal organization similar to that recorded ethnographically among the Berbers of North Africa. In that context, wealth is stored as jewelry (including perforated coins worn as jewelry) that can be converted to food in times of need. Typically the jewelry is worn by women to display familial wealth, playing a role in the negotiation of marriages that, in turn, form the basis of family and clan alliances. The alliances are crucial for negotiating access to important resources including separate parcels of arable land and grazing territory within an area that is controlled by a large kin-based corporate group (i.e. tribe). Moreover, he argues that this combination of land tenure systems and portable wealth is typical of environments in which production is highly variable in space and time and

direct ownership of small to moderate tracts of land as familial wealth therefore provides minimal subsistence security (Boone 1994 provides the clearest statement of this position and several references; see also Peters 1990 concerning North Africa). Similarly, decorated weaponry is extremely rare among the dependent peasantry of Medieval Christian Europe and its presence at Alcaria Longa implies that military activities were not the sole purview of elites in *al-Andalus* in the way that they were in feudal Europe.

Boone's excavations at Alcaria Longa yielded tantalizing clues that the Islamic period inhabitants were at least strongly influenced by Arab and Berber culture and may have belonged to a Berber population that originated in North Africa. In addition to the inferred patterns of personal adornment and the presence of weaponry, the forms of the house compounds appeared similar to contemporary excavated urban households in Iberia that had been occupied by Arab and Arabized populations and they closely resembled the Berber "Rifian courtyard" still common in parts of North Africa. The hearths used for food preparation also were similar in form to Berber griddle-hearths used to prepare bread, and ceramic serving vessels indicated communal food consumption in the Muslim tradition. Finally, a single roof tile inscribed with Arabic script was recovered, suggesting that the inhabitants spoke Arabic even if they may not have been Muslim. Ethnicity is, however, notoriously difficult to determine archaeologically in the absence of highly specific ethnic markers (e.g., Jones 1997) and information about the Late Roman and earlier Islamic periods in rural areas was almost entirely lacking, further complicating attempts to trace the origin and development of the various traits that might indicate Islamization or Berberization.

Settlement Patterns

In 1992, Boone led a systematic pedestrian survey of an 8 by 8 km block in the area around Alcaria Longa and through the early 1990's he undertook excavations at several smaller rural sites. The program of research largely was designed to illuminate the process of Islamization (or Berberization) as reflected in changes in settlement patterns, house forms, and other aspects of material culture from the Roman through the later Islamic periods. The investigation included what was probably the first systematic pedestrian survey completed in the *Baixo Alentejo*; most of the older and more recent site inventories rely on interviews with local farmers and shepherds to identify the locations

of archaeological sites. In addition, he excavated what were probably the first Late Roman to early Islamic, rural, non-elite (i.e. "peasant") residences to be professionally excavated in Iberia (certainly they were the first in southern Portugal), and they remain among a very small handful of such sites reported to date.

During the survey, field crews recorded and mapped the locations of 35 Bronze and Iron Age sites, 22 Roman sites, and 157 sites dating to the Islamic period, with time periods assigned based on the presence of temporally diagnostic surface artifacts. The earliest Roman period sites included a fortified hilltop *villa* (a type sometimes called a *castellum*) built in the first century B.C.E. and occupied for no more than two centuries. Like twenty similar sites known in the *Baixo Alentejo*, it appears to have been founded as part of an organized colonization effort sponsored by Pompey or Julius Caesar with the goal of protecting a trade route between the pyrite belt and the port at Mértola. In addition, there were four roughly contemporaneous hilltop settlements with mixed Roman and local Iron Age artifact types, suggestive of indigenous settlements involved in trade-and-raid relationships with the Romans. Later Roman sites occupied into the 5th century C.E. were modest, unfortified *villae rusticae*, or rural farmsteads. They were located in valleys and on lower hillslopes, suggesting that site locations were not chosen with defense in mind.

As discussed above, there were few significant changes in material culture associated with the earliest portion of the Islamic period. Therefore it initially was not possible to differentiate Late Roman from early Islamic period sites. Sites with *imbrex* roof tiles (a tapered, half-cylindrical form easily distinguished from the thick, flat tiles called *tegulae* used during the Roman era) were assigned to the Islamic period unless there was separate evidence of a Roman period occupation (i.e. temporally diagnostic ceramics or a few *tegulae*), in which case they were assigned to an undetermined Roman category. The Islamic period sites included small farmsteads consisting of a few structures, single-structure field houses, and larger villages like Alcaria Longa, some as large as almost four hectares. The Islamic period sites represent a six- to eightfold increase in total settlement area and number of sites over the preceding Roman period. Moreover, there were more than eight times as many Islamic sites as post-Medieval sites, and they covered a total settlement area more than double the total area occupied at all

times since the Islamic period, including existing villages. The patterns clearly suggest that the Islamic period was characterized by high rural population densities, probably the highest the area ever supported.

Locational analyses completed by Elisabeth Dinsmore (1994) showed that the later Roman *villae rusticae* and undetermined Roman sites preferentially were located in broad, shallow, trough-shaped basins, a landform known locally as a *chada* (plural *chadas*), where relatively thick soils are present and amenable to cultivation with traditional technologies. A statistical comparison of settlement locations and soil maps also shows a significant correlation between these later Roman and undetermined Roman sites and thicker, richer soils mapped as *pardos mediterranicos* (Mediterranean gray or brown; they are often present in *chadas*, suggesting some autocorrelation). Sites assigned to the later Islamic period, on the other hand, were not preferentially located with respect to soils (at least as mapped; SRAO 1959) or particular landforms, aside from a general preference for the upper portions of southeast-facing hillslopes. The change implies a shift in the agrarian economy such that a higher proportion of the landscape was utilized during the Islamic period, very likely resulting from an increased dependence on livestock. Analyses comparing the locations of large and small sites within each time period suggest that small sites were spatially separated from *villae* during the Roman period and from the large *quintas* (ranches roughly equivalent to the Spanish *hacienda*) owned by wealthier landholding families from the late Christian medieval period to the present. The pattern seems to be a spatial reflection of the social separation of the wealthy from primary producers. During the Islamic period large and small sites were intermixed, implying a different social relationship between the inhabitants of each.

In the summers of 1994 and 1995, Boone directed excavations at the site of Pego Real, a small rooftile kiln site adjacent to the Ribeira de Carreiras a few kilometers downstream from Alcaria Longa. Three distinct strata were present below the plow zone, indicating at least three distinct episodes of use. The lowest level included Roman-style rooftiles (*tegulae*) and clearly dates to the Roman period. Mixed rooftile types were present in the middle level and its exact chronological placement is uncertain. Tiles in the uppermost level were the *imbrex* type and some had finger impressed zig-zag designs made by running two fingers along the wet clay, parallel to the long axis of the tile. Such

zig-zag designs were known from Alcaria Longa and the later Islamic levels excavated in Mértola, and similar designs had been recorded, albeit extremely rarely, on Roman *tegulae* at a few sites in the region. The zig-zag pattern seems to first appear in the Roman era, becoming common in the Late Roman period, and it continued to be inscribed on rooftiles until the Christian *reconquista* at the end of the Islamic period.

Significantly, many of the tiles in the upper level at Pego Real also were marked with thumb impressions along the long-axis lateral margins, forming something of a lip in cross-section where the tiles would have overlapped adjacent tiles when placed on a roof. A charcoal sample from the upper level produced an accelerator mass spectrometer (AMS) radiocarbon date of 1190 +/- 60 B.P., corresponding to calibrated 2-sigma date ranges of 688 – 754 and 766 – 983 C.E., and a calibrated median date of 834 C.E. (Geochron sample GX-21338)[17]. These thumb impressions, which are reminiscent of a pie crust, were also present on tiles from the occupation sites adjacent to two hilltop monasteries or hermitages (*ermidas*) in the *concelho* known to date from the Late Roman era, São Bartolomeu de Via Gloria and Nossa Senhora de Amparo[18]. Moreover, the thumb impressions have not been recorded at Roman era sites and, of the thousands of decorated tiles observed at Alcaria Longa, only one small fragment had similar thumb impressions; they appear to be a reliable chronological marker for the Late Roman and Early Islamic periods.

The chronological significance of the thumb-impressed tiles was tested further during the summer of 1995 when Boone led excavations at three small rural habitation sites where such tiles had been recorded in surface assemblages. The sites consisted of the remains of from one to three large, internally-divided masonry buildings each, suggesting small hamlets comprised of perhaps three or four households. Of the three sites, thumb-impressed tiles were most common at Queimada, and both thumb-impressed

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[17] All radiocarbon dates presented in this volume were calibrated using CALIB version 5.0 (Stuiver and Reimer 1993). The radiocarbon calibration curve for the time period includes a relatively high degree of error due to rapid fluctuations in atmospheric ^{14}C during the 8th and 9th centuries, an ongoing problem for dating Late Roman and early Islamic sites.

[18] Interestingly, churches were constructed on these sites when the parochial system was formed in the area in the 16th and 17th centuries, even though they were not – and are not – adjacent to settlements. There is no evidence of occupation or use in the intervening centuries. As noted by Boone (2002: 112), this suggests "either a remarkable locational coincidence or an equally remarkable continuity of cultural memory present in the area during the Medieval Islamic period."

and zig-zag impressed tiles were present at Costa #2 and Raposeira. A series of 26 radiocarbon dates (25 AMS and one standard date, which is from the Christian medieval reoccupation at Alcaria Longa; dates are reported fully in Boone and Worman 2007) confirms that the small sites with thumb-impressed tiles were occupied from approximately 600 – 950 C.E. and that the thumb-impressed tiles were more common in the earlier parts of that time period. Also, the series of dates shows that larger villages like Alcaria Longa were founded during the Califal period (i.e. after 929 C.E., in all likelihood after ~950) and occupied until the mid-12th century. Widely separated dates at some of the smaller sites combined with the absence of thick midden deposits suggest a pattern of episodic abandonment and reuse, while the later villages clearly were inhabited continuously.

The identification of a chronological marker for the Late Roman to early Islamic periods led Boone to propose a refined chronology based on the archaeological evidence as opposed to one based on historically recorded events. Specifically, he proposed that the period from roughly 600 – 950 C.E. should be considered a transitional period between the Roman era and the medieval Islamic period. Sites dating before 600 C.E. usually are readily identifiable as Roman or Late Roman based on the presence of *tegulae* and *terra sigillata* or other late red-slipped, wheel-made wares (it is worth reiterating here that Byzantium directly ruled parts of Iberia and remained an important political, economic, and cultural presence in the study area at least until the beginnings of the 7th century). Transitional period sites are marked by *imbrex* rooftiles, some with the lateral thumb impressions and others with the zig-zag pattern which became more common towards the end of the transitional period. Culinary ceramics at transitional sites are largely handbuilt, locally made wares, but wheel made pieces appear during the later transitional period in small quantities and become increasingly common towards its end. Later medieval Islamic sites, dating from approximately 950 C.E. to the Christian *reconquista* in the mid-13th century, are marked by *imbrex* tiles, some with the zig-zag design, and the ceramics are mostly wheel made and often include fragments of a few melado or other glazed ware vessels.

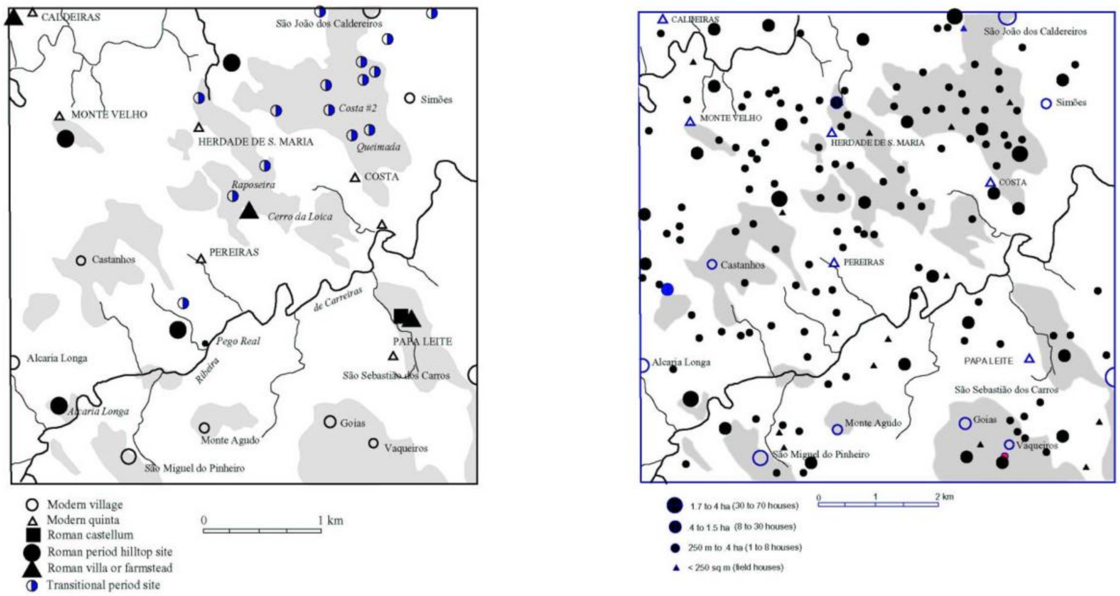

Figure 4.1: Maps showing the locations of Roman and Late Roman (left) and Islamic period (right) sites in the 1992 survey area. Gray areas indicate the location of *pardos mediterránicos.* (Reproduced from Boone and Worman 2007.)

Boone's refined chronology led to a reassessment of the 1992 survey data. The primary change was that the undetermined Roman sites were almost all reassigned to the transitional period, as depicted in figure 4.1. In summary, the reexamined survey data indicate only eight sites dating to the Roman period: the fortified *villa*/ *castellum* and the four sites with indigenous Iron Age populations engaged in trade-and-raid relationships with the Romans, both types probably abandoned by the end of the first century C.E., and three unfortified *villae rusticae*, or farmsteads. The Roman farmsteads were abandoned roughly at the time of the collapse of the Roman military presence in Iberia in the first decades of the fifth century. At present, there are no known sites in the survey area that were occupied between the early fifth and the mid-seventh centuries, although Mértola and several other sites in the region – primarily villages adjacent to sites with religious importance such as monasteries and *ermidas* – continued to be occupied. Seventeen (17) sites are now dated to the transitional period and, mirroring Dinsmore's analysis (in which most of them were classified as unidentified Roman) they show a statistically significant pattern of being preferentially located on or immediately adjacent to the soils mapped as *pardos mediterránicos*. Many of the sites are clustered near the largest of the

Roman farmsteads, Cerro da Loiça. The remaining 157 sites recorded during the survey are assigned to the medieval Islamic period, after ~ 950.

Two important conclusions can be drawn from this reassessment: First, it seems clear that after a period of depopulation small hamlets and villages appeared in rural parts of the study area as much as a century before the Muslim invasion of 711 C.E., and they persisted without major changes in material culture until the Califal period. From their reemergence in the Late Roman period until rural areas were abandoned in the late Islamic period, rural agro-pastoralists retained a high degree of independence and a tribal form of organization that empowered them in their relationship with the state. Tribal organization also helped to reduce the risks associated with unpredictable agrarian production by allowing families to negotiate access to multiple parcels of productive land based on kinship relationships.

Second, the data suggest a population explosion in the Califal period. The second inference, however, is somewhat problematic in that assigning sites to the transitional period relies on the recognition of thumb-impressed *imbrex* tiles in surface assemblages. Although it seems certain that the thumb-impressed tiles were made almost exclusively during the transitional period, many of the tiles produced during that period also were either plain or had the zig-zag design. Therefore, while sites with thumb-impressed tiles can be assigned with certainty to the transitional period, sites with zig-zag tiles may date to either the transitional or later Islamic medieval period, and sites with only plain handmade *imbrex* tiles could date to any time between the early 7th and early 20th centuries[19].

Until a larger sample of small sites assigned to the Islamic period are excavated and dated more closely by independent means, there are two possible interpretations of the survey data: the population may have grown rapidly during the Califal period, suggesting a large and rapid influx of immigrants; alternatively, it may have followed a slower trajectory of increase beginning in the transitional period, implying some population growth due to local reproduction, a more significant Hispano-Roman contribution to the eventually large rural population, and consistent with the significant

[19] Fortunately, it is almost always possible to differentiate transitional and Islamic period sites from later sites based on other finds, particularly diagnostic ceramic types. Also, settlement locations appear to have been remarkably stable since the area was resettled in the 15th – 16th centuries.

historically recorded Berber immigration to the area in the 8th century. Finally, because of the lack of excavations at small sites assigned to the medieval Islamic period, it is not possible to determine at present whether some of those sites may have been episodically abandoned and reoccupied, as the data suggest was probably the case for the excavated transitional period sites. Very likely some of the smallest sites are field houses that were used only episodically, and a pattern of episodic reuse of sites can have a dramatic impact on population estimates derived from site numbers and settlement areas (e.g. Roberts 1992).

Regardless of which of these interpretations is correct, the fact that the larger village sites were continuously occupied from roughly 950 to 1150 C.E. suggests that, even if only some portion of the smaller sites were occupied at the same time, population densities were relatively high during the medieval Islamic period. The larger villages by themselves cover an area comparable to that covered by all known later sites. Rural population densities during the Islamic period were far higher than during the Roman era and at the very least comparable to the 20th century prior to the local economic collapse in the 1960's.

Ethnicity

Material culture, particularly house forms, may provide some insight into the origins of the people who occupied the rural sites. Boone's excavations at the small transitional period sites revealed that domestic architecture at all three consisted of long rectangular blocks of three or more adjacent rooms. Each room could only be entered through doorways through the south or southeast walls; the rooms were not connected to each other by internal doorways. This form is visibly different from the courtyard-focused house compounds excavated at Alcaria Longa, in the Islamic quarter of Mértola, and in other Islamic period urban settings. However, a space syntax analysis of access patterns (Boone 2002) suggests that it may actually be more closely related to the courtyard compound than to the typical Christian medieval form, which consists of a superficially similar long rectangular block of rooms. The important difference is that the Christian medieval houses are entered through a single doorway into the kitchen, and access to all other rooms is through internal doorways. Comparing the transitional forms to the compounds at Alcaria Longa, the significant difference is that the rooms at the

latter are arranged around an enclosed courtyard. Boone argues that the courtyards may reflect a need for privacy in larger villages that was absent at the small isolated hamlets; one or more rooms from the typical transitional period layout were rotated 90 degrees and the houses simply "curled" around a private courtyard without changing in other significant ways.

The architectural forms appear to reflect different relationships between cooking and other activities in different time periods and settings, providing an interesting but as-yet not fully explored window on gender relationships. In particular, cooking in the transitional period houses and the compounds at Alcaria Longa was done in separate rooms within the main building. In Islamic period urban house compounds excavated in Mértola and elsewhere in Iberia, cooking took place in separate buildings within the compound. In Christian medieval houses, by contrast, the hearth was in the central room of the home, a room used for virtually all activities that took place in the household. These spatial arrangements reflect different general patterns prevalent in the Mediterranean vs. northern European worlds. In the Roman and Muslim worlds, cooking and women typically were separated from the public space in a home where food was served and other activities performed. In Germanic northern Europe, the hearth typically was the center of the home and women frequently played a larger role in public life. Rural transitional and Islamic period domestic architecture seem to reflect a hybridization of the spatial arrangements typical of the Mediterranean and northern European spheres, calling into question the inference that the inhabitants of Alcaria Longa were entirely descended from North African Berbers.

Ceramics provide another line of evidence suggesting some degree of continuity from the late Roman through the Islamic period. Berbers in North Africa have maintained a persistent tradition of household production of handbuilt ceramics from before the Roman conquest through to the present. At the investigated rural sites in the study area, however, handbuilt ceramics are common during the Late Roman period and virtually disappear by the Califal period – *after* the historically recorded movement of large numbers of Berbers into *al-Andalus*. The pattern is inconsistent with what would be expected had Alcaria Longa been settled exclusively by Berbers but, interestingly, it is repeated in other parts of Iberia where settlement by large groups of Berbers is

historically documented. It remains an open question why Berbers in Iberia would have abandoned handbuilt ceramics while maintaining the tradition in North Africa. Finally, archaeological evidence indicates that the griddle-hearth typically used for food preparation at Alcaria Longa has several European predecessors, including similar forms found in Chalcolithic (Copper age) contexts on the Northern Meseta of Iberia and in Iron Age France (Boone 2002: 119).

In sum, the rural sites of the Islamic medieval period exhibit a hybrid material culture that probably has roots in Berber North Africa, Hispano-Roman Iberia, and pre-Roman or non-Roman Europe, in addition to Arab influences. The relative importance of each of these strands to the identity or ethnicity of rural populations remains open to debate, and is further complicated by the historically recorded movement of North African Berbers into Iberia in the 2nd century C.E.; Berber influences may already have been present during the Roman era. Ultimately, it might be most productive to reframe the questions of Islamization and Berberization of rural populations in terms of ethnogenesis during the transitional and Islamic periods. At the very least, it is exceptionally unlikely that the rural people (or, for that matter, anyone during the Islamic period) thought of ethnicity in terms even remotely similar to the modern concept.

Macrobotanical Data

Related research of particular importance for understanding human-environment interactions during the transitional and Islamic periods includes a study in which Yolanda Carrión Marco analyzed carbonized macrobotanical remains recovered during Boone’s excavations at Queimada, Raposeira, and Alcaria Longa (Carrión 2006). Her study showed evidence for an increase through time in the ratio of smaller shrub species to larger tree species in wood used for cooking, heating, and other domestic activities. Two hundred seventy-three (273) macrobotanical specimens were identified at the genus level from the transitional period sites of Queimada and Raposeira (600 – 950 C.E.), along with 878 from the later Islamic period village of Alcaria Longa (950 – 1150 C.E.). A comparison showed that tree species accounted for nearly 90% of the plants burned at the earlier sites, compared to just over 40% at the later site, with the difference being made up by an increased reliance on shrubby species, as shown in figure 4.2.

In addition, charcoal at the earlier sites represented fewer taxa; they included only oak, olive, and the shrub *esteva* (*Cistus sp.*). The samples from Alcaria Longa included at least three additional tree taxa (*Arbustus unedo*, strawberry tree; *Fraxinus sp.*, ash; *Pistacia lentiscus* and *Pistacia sp.*, mastic tree or evergreen pistache, a shrubby tree) and five additional shrub taxa (*Ephedra*, *Erica*, *Labiatae*, *Maloideae*, and *Myrica gale*; ephedra, heather, mint family, apple subfamily within the rose family, and bog myrtle or sweet gale). Given the size of the samples, it is unlikely that the increase in diversity or the apparently increased reliance on shrubby species is due solely to sampling error. The patterns suggest that the inhabitants could choose the most desirable species during the earlier period, and that fuelwood gathering became more opportunistic later in time, possibly reflecting progressive deforestation during the Islamic period.

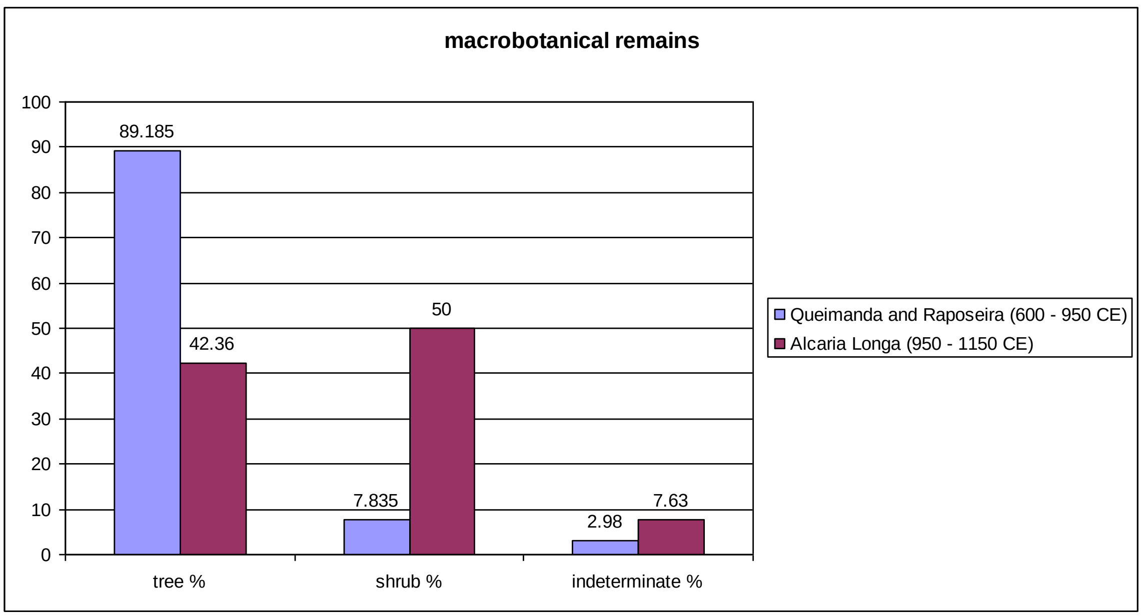

Figure 4.2: Percentages of tree vs. shrub species in macrobotanical remains recovered from hearths at Queimada, Raposeira, and Alcaria Longa.

Alternatively, because the samples reflect human action and not a random sample of the wood available in the environment, the data may indicate the beginnings of a tradition of managing woodlands by selective pruning and clearing of the shrubby understory, a pattern that became widespread in conjunction with extensive reliance on animal husbandry across much of Iberia (Stevenson and Harrison 1992), and which is documented as an established practice in Spanish texts dating to 1270 (Grove and

Rackham 2001:202). The Iberian managed savannah woodlands are ecologically stable at long time scales and increase total productivity and species diversity by providing a patchwork of sun and shade (*ibid*: 190 – 207), so the observed changes may not reflect degradation *per se*. In either case, they suggest a reduction in the number of large trees on the landscape. In addition, the macrobotanical remains from Alcaria Longa included ephedra and heather, which may reflect some degradation of rangelands due to overgrazing. Because of the nature of the data it is not clear that there was widespread degradation of plant communities in the study area. It is, however, clear that there were changes in the ways people impacted those plant communities during the Islamic period.

For the purposes of environmental reconstruction it certainly would be preferable to have palynological data reflecting general changes in the makeup of plant communities as opposed to charcoal reflecting the plants humans selected from the local environment for domestic use. However, a pilot study completed in the summer of 2003 failed to recover preserved pollen from any of the tested loci in the study area. Very likely, this is because of strong seasonal fluctuations in rainfall, soil moisture, and the depth of the water table; repeated cycles of wetting and drying are the single condition most likely to degrade pollen in archaeological contexts (Bryant and Hall 1993). In any case, the extant data suggest significant changes in plant communities and perhaps some amount of deforestation and rangeland degradation by the 12th century.

Regional Context

Beyond his work in the *concelho* of Mértola, Boone has worked with colleagues who conduct archaeological and historical research in North Africa to place developments in *al-Andalus* in a macro-regional perspective. Several aspects of that work are salient here. In a 1990 article, Boone and colleagues reviewed the archaeological and historical evidence pertinent to the medieval Maghreb (northwest Africa) and built an argument that there was a significant shift in the political economy of the states and empires that emerged there in the eighth and persisted through the late 15th centuries. Moreover, they proposed that this shift was reflected in changing patterns of urbanism.

Specifically, Boone *et al.* (1990) posited that the Idrisid Empire (8th through 10th centuries C.E.) was built primarily on revenues extracted as taxes and tribute from the

Berber agriculturalists living in the fertile valleys of Morocco north of the Atlas Mountains. The resulting regional settlement pattern was one in which there were multiple relatively large cities, each of them located in a fertile region, and a multi-tiered settlement hierarchy. When the empire was divided among seven of the sons of Idris II, son of the founder Idris b. Abdallah (or Moulay Idris), each of them ruled a semi-independent princedom focused on one of those cities and the fertile agricultural land surrounding it. There were the seven seats of the princedoms, each roughly equal in size and controlling a territory determined largely by geographic barriers, as well as Fez, the initial capital founded by Idris b. Abdallah. Significantly, taxation and tribute were collected by local tribal leaders and passed on to the Idrisid sultans and not taken directly from individuals by the state or its appointed officials.

The political economy of the state shifted to a different form under the subsequent three dynasties, the Almoravids, Almohads, and Marinids. By the later 9th century, the primary trade routes connecting sub-Saharan West Africa to the eastern Mediterranean via the northern Sahel and southern Sahara had shifted to a western route that ran directly northward through the Maghreb. Spices, ivory, slaves, and especially gold were transported northward, while textiles, salt, metal tools, and military equipment were traded south. The Almoravids and their successors built their fortunes – and their empires – around direct participation in and control of that trade and they augmented their wealth with the treasure captured in successive waves of conquest of adjacent areas. The Almoravids destroyed or reduced each of the cities at the center of the Idrisid principalities, and the regional settlement pattern became one of two major centers, at Fez in the north and Marrakech in the south, typifying a primate settlement hierarchy. Far smaller cities were located in agriculturally productive areas and around the peripheries of the empire.

Based on the observed patterns, the authors propose that the political economy of pre-industrial states can be conceptualized as a continuum. Polities at one extreme are funded by extraction of agricultural surplus (the Idrisids) and those at the other are

funded by control of long-distance trade (the Almoravids, Almohads, and Marinids)[20]. They note that there is a significant literature about states of the first type, while the second has received less academic attention despite the fact that primate settlement patterns apparently typical of the trade-financed states are well documented archaeologically in many parts of the world.

In detailing their model, the authors discuss the relationship between the political economy of the state and different types of urbanism or, more precisely, the different economic functions of cities. Here, they create a tripartite division: the dynastic capitals of the later medieval Maghrebian empires existed and prospered because they were situated between the geographically separated resources and markets of the Mediterranean and West Africa; they controlled trade routes. Smaller cities around the peripheries of the empires, such as the trade entrepôts on the Mediterranean coast or at the edges of the Sahara, bulked and stored trade goods and repacked them for different types of transport (i.e. caravan vs. maritime shipping). They were of necessity more cosmopolitan in order to serve as intermediaries between the empires and foreign trade partners, and were most successful when loosely aligned with or even entirely independent of the central state. The third type of urban economy is built on transferring goods between the urban sphere and the rural hinterland; these included the cities of the Idrisid period as well as many later small cities that were sited in areas favorable for agrarian production. The last type, then, can overlap with either of the first two. In addition it is, in general, the most resilient in that the local economy is for the most part disconnected from the vacillating fortunes of the central state – although that independence can become a liability when perceived by the state as a threat, as played out in the Almoravid destruction of many regional centers.

At different times during the Late Roman and Islamic periods, Mértola appears to have taken on each of the three roles that Boone *et al.* (1990) propose as the economic foundations on which the medieval cities of North Africa were built. When it was an independent entity, as during parts of the *taifal* periods and at least some of the Late Roman period, Mértola took advantage of its location between the resources of the *plano*

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[20] Their structure is analogous to the distinction between staple financed and wealth financed states proposed by D'Altroy and Earle (1985), although the authors do not apply those specific terms to the medieval Maghreb or Iberia until later publications (e.g., Boone and Benco 1999).

dourado and pyrite belt and the markets of the Mediterranean world; it benefited from control of an important trade route. When a stronger central state was present, Mértola continued to function as a port of trade, bulking, storing, and repacking goods at the boundary between maritime and overland trade. Frequently, it appears to have remained at the margins of direct state control, perhaps facilitating commerce in ways analogous to the trade *entrepôts* of medieval coastal North Africa. Finally, excavations at Alcaria Longa clearly show that rural populations there had access to the urban-based market economy with an extensive network of trade connections; Mértola was a locus of trade with the immediate hinterland.

In later publications (e.g. Boone and Benco 1999; Boone 2009), Boone applied several of these ideas to Islamic Iberia. Specifically, he suggests that *al-Andalus* was a tributary state based on tribally organized production, particularly in the Emiral period. Taxes were collected by local tribal leaders (*qaids*) and not levied directly on individuals by the state or its appointed representatives. This pattern of taxation was established in some places by treaties Visigoth leaders entered into with the conquering Muslims. In other locations, it may be a replication of taxation practices in North Africa (specifically the Idrisid Maghreb), where taxes were levied on Berber tribes and collected by tribal leaders.

This structure created a rupture at the local level in the chains of taxation and personal dependence that characterized the feudal system emerging beyond the Pyrenees. The less direct connection between the rural economy and the state center facilitated the persistence of tribal organization and translated into a higher measure of rural autonomy and wealth, as reflected in the artifacts recovered from Alcaria Longa. Put simply, "There is strength in numbers, which would imply a significantly increased bargaining power on the part of the tribe in contrast to the individual serf" (Boone 2009: 115). The origins of that rural tribal organization – whether a direct import from Berber North Africa or a local response to the power vacuum created by the dissolution of the Western Roman Empire – remain open to debate, as should be clear from the preceding discussion of the problem of ethnicity. However, they are not necessarily relevant for understanding how the social structure impacted rural-urban interaction.

Although Boone has only begun to build the argument in his published work (e.g. 2009: 160), it is likely that *al-Andalus* followed a trajectory parallel to the Maghreb's transition from an agrarian and staple-financed, to a primarily wealth- and trade-financed political economy. Instead of gold from West Africa, *al-Andalus* was situated to export – both to the Muslim Mediterranean world and to Christian Europe – its own mineral wealth, along with steel tools, leather, textiles, and foodstuffs (e.g. olive oil, wine) produced or processed largely in and around the cities of the Guadalquivir valley. In addition, they exported slaves and "dancing girls" captured from the Christians to the Mediterranean world, while they transshipped high-value manufactured and exotic goods in the other direction. As the economy expanded during the Emiral period, so too did opportunities for the emirs (and later the caliphs) to participate in and to tax this trade and industry. In addition, the emirs and caliphs clearly filled their own treasuries with booty taken in military campaigns against the Christians just as the later medieval Maghrebian emperors did in military campaigns against adjacent polities.

By the time Al-Hakam II succeeded his father 'Abd al-Rahman III and became the second Iberian caliph, taxation of trade and the spoils of war clearly were significant sources of state income. The North African chronicler Ahmed Mohammed al-Makkari (also al-Maqqari)[21] gives the following estimates of annual state revenues at the time: 5,480,000 gold dinars from the *kharaj* (a land tax ostensibly levied on non-Muslims, but often also demanded of the *muwalladun* and more recent converts in *al-Andalus*); 765,000 dinars from duties and indirect taxes (probably a gross underestimate because it was a tax by Muslims on Muslims, an activity that is strictly regulated in *shari'a* law [Boone 2009: 79 – 83]); and the fortunes going directly to the royal treasury, "being the fifth of the spoils taken from the infidels, they were beyond calculation and cannot be estimated, as no precise account of them was kept in the treasury books" (quoted in Lewis 2008: 332).

For rural communities outside of the highly productive irrigated river valleys taxation rates probably remained relatively low through the Califal period and may even

[21] al-Makkari wrote his histories during the early 17th century. His assertions are probably based on older manuscripts that have since been lost or destroyed. Citation practices (or more precisely the lack thereof) in traditional Arabic historiography make it exceedingly difficult to trace the exact origins of different historical "facts" in order to evaluate their reliability.

have diminished as conversions to Islam increased and the elites turned increasingly to trade and commerce. In general, the Islamic state probably invested little in extracting surplus from rural areas where agrarian production was marginal and unpredictable, as in the region around Mértola (Dinsmore 1995); urban elites focused their attentions on more reliable sources of revenue. Episodically, however, there were attempts to raise funds for the state by increasing direct taxation. Because of the continuation of tribal organization in rural areas, these appear to have been met with resistance, including, at times, armed rebellion. A major impetus for rebellions such as the one led by Ibn Qasi probably was Almoravid attempts to impose taxes.

The 2004 – 2005 Survey

Building on the research discussed above, Boone and Worman completed a second large-scale pedestrian survey in 2004 and 2005. The locations of the surveyed areas are shown in Figure 1.1, above (chapter 1). In order to produce comparable data, most of the methods used in the 1992 survey were replicated. In addition, the 2004 – 05 survey covered an area of slightly more than 6 by 10 km, approximately the same spatial extent as the earlier survey of an 8 by 8 km block. This section presents a brief description of the methods and results of the survey[22]. The significance of the results for Worman's geoarchaeological research presented in subsequent chapters is that they demonstrate different histories of settlement and land use for the 1992 and 2004 – 05 survey areas.

Survey Methods

Archaeological survey has become a cornerstone of the discipline since the first large-scale systematic surveys were undertaken in the mid-20th century by pioneering researchers like Gordon Willey (1953) and Robert McCormick Adams (1965; see also Sanders *et al.* 1979 for an example of the increasing sophistication of regional-scale investigations in subsequent decades). Those early surveys were designed primarily to discover large archaeological sites and to begin to characterize settlement patterns in complex societies; a frequently-repeated and possibly apocryphal story claims that

[22] Many of the results of the survey have been presented in an article co-authored with Dr. Boone and submitted in September 2009 to the Journal of Field Archaeology with a working title of "Settlement survey and landscape geoarchaeology in the Lower Alentejo of Portugal, 2004-05."

Gordon Willey didn't consider a site worth recording unless he was forced to put his truck into 4-wheel drive to get over it.

Survey methods have changed dramatically since those earliest investigations. From the beginning, salvage archaeology projects attempted to identify and record sites of all sizes and dating to all time periods in areas that would be affected by various large-scale undertakings such as dam or pipeline construction (e.g. Fennegan and Wendorf 1956) or the detonations of nuclear bombs at the Nevada Test Sites (Worman 1969). One of the greatest contributions of the "New Archaeology" of the 1960's was the realization that the largest sites could only be properly understood in the context of the full settlement pattern (Binford 1964), prompting academic archaeologists also to investigate sites of various sizes. A fundamental re-evaluation of the goals and methods of archaeological survey was instigated by Dunnell and Dancey's (1983) proposition that investigations need not – in fact in some cases should not – focus specifically on discovering and recording sites (see also Ebert 1992; Thomas 1975). During the past three decades there have been numerous advances in "siteless survey" methods, many of them pioneered in the Mediterranean world where thousands of years of occupation have created a landscape carpeted in places by a dense palimpsest of archaeological materials (e.g. Alcock and Cherry 2004; Athanassopoulos and Wandsneider 2004).

Archaeologists continue to examine and refine survey methods in attempts to identify appropriate units of analysis and to quantify the effectiveness of survey for discovering archaeological materials on a landscape (e.g. Banning *et al.* 2006; Burger *et al.* 2004; Sullivan *et al.* 2007; Wandsneider 1998). Recent advances in Geographic Information Systems (GIS) technologies and the use of spatial statistics have opened the doors to new ways of analyzing survey data in order to address increasingly complicated questions, for example concerning human-environment interactions (e.g. Hill 2004) or the connections between ancient communities (e.g. Kantner 2004). In addition, several researchers have begun to consider in detail the complicated relationships between the archaeological materials visible at the surface and local histories of landscape change; they have expanded survey methods to include a consideration of both sampling strategies and the geomorphic, cultural, and biological processes that affect such basic variables as site visibility (e.g. Barton *et al.* 1999, 2002, 2004; Burger *et al.* 2006, 2008).

While methods continue to be debated, systematic surveys now are considered a fundamental element of almost all archaeological research, and a regional perspective has become ubiquitous (Kantner 2008).

A critical reading of the recent literature on survey methods suggests three things relevant to the current research. First, a truly "full coverage" or "100% sample" survey is practically impossible and would be prohibitively time-consuming and unpleasant (see Burger *et al.* 2004 on the results of various types of resampling, including a shoulder-to-shoulder crawl survey). Second, research design must take into account local conditions, including the nature of the archaeological record and various landscape parameters such as vegetation cover and recent sedimentation or erosion. Finally, because it is impractical to identify and record all archaeological materials in any given area, it logically follows that surveys should be designed to answer particular questions by identifying an appropriate subset of the archaeological materials present.

Surface visibility typically is very high in the study area considered here. By the early summer months, when our investigations were conducted, the majority of the cultivated fields have been harvested leaving only low stubble that often is further reduced by grazing. Vegetation in fallow fields is relatively sparse, grasses are dormant, and much of the area has been heavily grazed; only in very rare circumstances is it difficult to see the ground surface. In addition, significant recent (i.e. past few centuries) alluviation is almost entirely absent aside from small areas at the base of steep slopes and narrow floodplains along drainages. Archaeological remains from at least the past two millennia are easily visible while walking and very few sites are buried at any significant depth or obscured by vegetation.

Beyond these landscape conditions, the nature of the archaeological record and the research questions further informed the survey methodology. In particular, the questions driving the investigation concerned settlement patterns and agrarian land use from the Roman period to the present; therefore it was appropriate to focus on architectural sites including villages, hamlets, isolated farmsteads and special-use structures such as field houses. Previous research has shown that, beginning in the Roman era, structures typically were constructed of quarried stone or pisé (rammed earth) and roofed with ceramic tile. Temporally diagnostic ceramics indicate that, aside from

animal pens, the only structural sites in the study area lacking ceramic roof tiles can be attributed to the pre-Roman past (i.e. Neolithic – Iron Age; see Boone and Worman 2007). The sites of interest, then, were readily discernable as large scatters of building stone and fragmentary roof tiles and ceramics, often associated with one or more low ovate mounds indicating collapsed structures.

Given the conditions of excellent surface visibility and a focus on architectural sites, crews walked widely-spaced survey transects 50 m apart. Bearings were selected and monitored using handheld GPS units (Garmin, GPSmap 76s)[23], and those units also were used to measure and record the locations of archaeological sites and soil-stratigraphic study units. In addition, sites were manually plotted on a topographic base map photocopied from the mid-20th century series of *Cartas Militares* (Military Maps), drawn from low-altitude aerial photography at a scale of 1: 25,000. The maps showed the locations of the older settlements and farmsteads in the area and also indicated the locations of some large archaeological sites as well as other important features such as wells. As noted by Boone (2009: 91), these older maps "record a wealth of local toponymic lore reflecting a cultural landscape that has now all but disappeared."

Survey crews recorded sites using a standardized form adapted from those used in 1992. On one side, the crews recorded information such as site number and name and locational information including GPS unit and waypoint number, date recorded, UTM coordinates, elevation, and notes on the number of averaged GPS readings and estimated accuracy. In addition, the form included space for descriptions of the sites, including the type of site (i.e. sherd scatter, tile scatter, building stone scatter), estimated number of tiles and sherds visible on the surface, types of standing walls, if any, additional features, vegetation cover, chronological interpretation and criteria for chronological placement, spatial extent, and any additional notes. On the reverse, each form was printed with graph paper to facilitate sketch-mapping of the sites.

Given the conditions and survey methods, it is reasonable to suggest that the survey crews identified and recorded the vast majority, if not all, of the architectural sites constructed since the early Roman period in the survey area. It is equally reasonable to

[23] The use of GPS units is the only difference in methods between the 1992 and 2004 – 05 surveys; the 1992 survey was completed using traditional map and compass techniques.

assume that the crews did not detect every small scatter of pottery or stone tools representing earlier occupations or ephemeral use of a given area; the survey was not designed to identify all such sites. The earlier sites and isolated artifacts from all pre-modern time periods were, of course, recorded when encountered, but the survey must be considered a sample of such less-visible archaeological remains; a resurvey with transects at substantially closer intervals no doubt would document additional earlier sites and isolated occurrences. Because the transect spacing and survey techniques were the same in the 1992 and 2004 – 05 surveys, they are comparable samples and the relative frequency of occurrences of architectural as well as less-visible (i.e. earlier) archaeological sites can be compared directly between the two areas.

Results

Overall, the 2004-05 survey area has far fewer archaeological sites than the quadrat surveyed in 1992. Nine Roman or Late Roman sites and 16 Islamic period sites were recorded, as shown in figure 4.3, along with two earlier sites and several isolated occurrences of chipped stone tools that can be assigned to the Neolithic or earlier periods. These totals can be compared to the eight Roman, 17 Late Roman and transitional and 157 Islamic period sites documented in the 1992 survey area (see figure 4.1 above). In that survey area, the single chipped stone artifact encountered by the crews was a gunflint. The reasons for the disparities in settlement density and the ages of sites were not immediately evident, as modern settlement densities and current land use practices are similar in both areas.

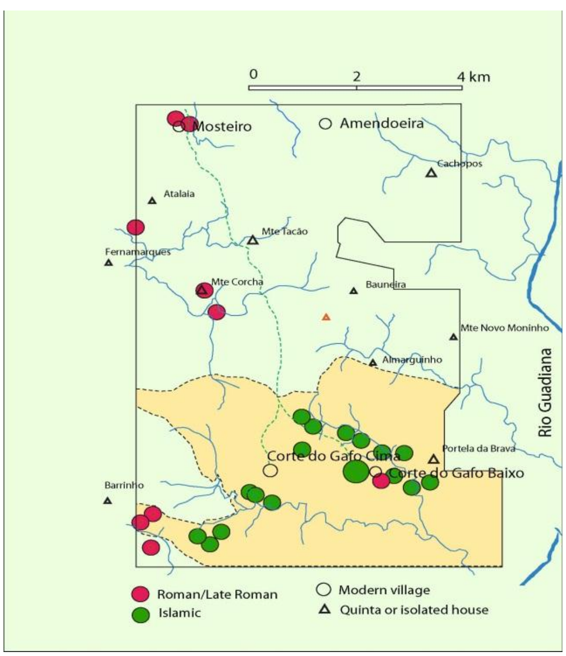

Figure 4.3: Map showing the locations of Roman/ Late Roman and Islamic period sites in the 2004 - 05 survey area. Tan area corresponds to soils mapped as *pardos mediterranicos*.

Roman and Late Roman Sites

Three groups of Roman-Late Roman habitation sites were recorded along the western margin of the survey area. One was found in the vicinity of Monte Corcha,

an occupied historical *quinta* (a ranch compound equivalent to a Spanish *cortijo; fazenda* [Portuguese] or *hacienda* [Spanish] if in the New World). In that area, three scatters of fragmentary *tegulae* were recorded, two immediately adjacent to the historical buildings and one some distance to the northeast adjacent to a small seasonal stream. Together, they indicate the past presence of a small farm compound. Similarly, the three sites identified in the southeast corner of the survey area consisted of scatters of fragmentary *tegulae* and building stone. Very likely, they also are associated with a Roman era farm site, the center of which is located outside the survey area at the *monte* (small rural farmstead) of Barrinho; that site had been previously recorded (Lopes 2003).

No temporally diagnostic culinary ceramics were recovered at either cluster of sites that would allow for the identification of a narrower time range of occupation within the Roman-Late Roman period. Small numbers of fragmentary, zig-zag impressed *imbrex* tiles at Monte Corcha do, however, suggest the possibility of continued occupation into, or limited re-occupation during the Islamic period. Previous research also suggests that small, unfortified *villae rusticae* such as these probably date to the later portion of the Roman era, after the 1st century C.E. The vast majority of the *villae rusticae* appear to have been abandoned when the Roman military presence in Iberia dissolved in the early 5th century, and they were not reoccupied during the subsequent Late Roman period (Boone 2002; Boone and Worman 2007; Dinsmore 1994).

The two Roman/ Late Roman sites in the northwestern corner of the survey area are at the Ermida (Hermitage) de São Salvador, a Late Roman period parochial church and monastic community. The sites include the partially-standing church and an adjacent artifact scatter and, several tens of meters away around the summit of a prominent hill, fragmentary *tegulae* and architectural features that appear to be the remains of foundations of small buildings. Both are located within the modern village of Mosteiro; the name of the village means monastery.

The church building first was identified as an ancient basilica in the 1980s by Cláudio Torres and Justino Maciel on the basis of a surviving wall. Subsequent study showed that the wall formed the apse of the original structure, which dated to the 5th and 6th centuries. Although heavily eroded, the wall was intact to a height of about two and a half meters. The inhabitants of the village are well aware that the building was once a

church and a white cross, fashioned out of quartz cobbles, can be seen built into the dry-stone masonry wall of the adjoining house. At the time of our recording, the remains of the old church building had been incorporated into a modern house compound and were being used as a barn. Fragments of marble columns and Roman *tegulae* were visible where they have been incorporated into the dry stone masonry walls of the more recent construction. A broken carved stone basin, which was almost certainly the baptistery or holy water font in the original church, was being used to feed and water turkeys in the yard outside the building.

Archival research revealed that the standing building probably has not been used as a church since the 7th or 8th century. It was never mentioned in the inventories of churches made by the Portuguese in 1482 and 1565, although it should be noted that these were completed more than two centuries after the Christian reconquest of the area in the mid-13th century. The only mention of the church that has been found in written documents was in an inventory collated by a Benedictine order in 1644 (*Obra Beneditina Lusitana*), which indicates that it had been a church called São Salvador before the "coming of the Moors," and had been associated with a Benedictine monastery. This information was almost certainly taken from earlier documents that no longer exist.

Justino Maciel has suggested that the community may have served as a *xenodochium*, or wayhouse for travelers and pilgrims. It is located along the Roman road that connected Mértola to Beja (Roman *Pax Julia*), and the road continued to be used through the Late Roman period (Lopes 2003: 33, figure 12). During the survey, buried segments of flagstone paving that probably are remnants of that road were recorded where they are eroding into a small incised stream channel immediately south of Mosteiro. It is very likely that there was a modest *villa* here earlier in the Roman period, as Late Roman monasteries and basilicas commonly grew out of former *villae*; perhaps the *villa* was in the location of the artifacts and architectural remains around the hilltop.

In 2005, investigators from the Campo Arqueológico de Mértola started a project to restore and excavate the church site. The walls were stabilized and a new tile roof was installed. In 2007, they began excavations around the exterior of the building. A series of burials with stone slab coverings has been uncovered in front of the building, and the graves clearly are associated with its use as a church. Their future publications hopefully

will illuminate heretofore poorly-known aspects of life in this type of religious community during the Late Roman period.

The final Roman era site encountered during the survey is Eira do Ti Zé Tomé (Uncle Joe Tom's threshing floor), a cemetery used during the middle to later Roman period. The time range of use is inferred from the presence of *terra sigilata clara,* or African Red-slipped Ware, a ceramic type produced from the 3rd to the early 5th century. The site is located on the southeastern edge of the modern village of Corte do Gafo de Baixo, in the southeastern quadrant of the survey area. Boone first observed this site in 1989, at which time it was being heavily looted. Five looted graves were recorded in 1989, each of which consisted of an opened grave cyst that had been carved into the bedrock, and broken pots and glassware found scattered nearby. The graves lay just below the surface, under a thin veneer of soil. Since then, the entire area has been bulldozed and it is difficult today to find any trace of the site on the surface. The cemetery was almost certainly associated with a Roman community, the remains of which lie buried under the adjacent village.

Islamic Period Sites

All but one of the 16 Islamic period sites recorded in the survey area were small scatters of building stone associated with fragments of pottery and curved *imbrex* roof tiles. Each of these sites appears to represent a small hamlet of one to four house compounds. The very few fragments of temporally diagnostic ceramics that were present indicate that the sites date to the Caliphal and Taifal periods (roughly 950 through 1150). Interestingly, most of the surface assemblages also included lumps of iron slag, which was rarely observed at the small hamlet sites recorded in the 1992 survey area. Considerable amounts of slag were, however, found at the Islamic period village of Alcaria Longa in the 1992 survey area, and a building in one of the excavated house compounds there appears to have been the site of a blacksmith's workshop (Boone 1993).

The remaining Islamic period site was a village covering an area of roughly 4 ha, located adjacent to the modern village of Corte do Gafo de Cima. Referred to locally as Corte do Gafo a Velha (Old Corte do Gafo), the site has gained notoriety from the fact that in the mid-1980s a hoard of gold Califal period *dinars* was found there by two farmers plowing a field. The village site is on a hill overlooking what was almost

certainly the junction where an ancient road to an access point on the Guadiana River to the southeast met the main Roman road between Mértola and Beja.

Unlike the Roman and Late Roman sites, Islamic period settlements are found only in the southern half of the survey area, and their distribution coincides with a particular soil type identified in the Carta dos Solos (soil map; SRAO 1959) as *pardos mediterranicos* (Mediterranean grays or browns; area in tan on figure 4.1). These are the same soils that are present across the entire 1992 survey quadrat. They derive from the underlying Mértola Formation and, in the 2004-05 area, the Gafo Formation (Oliveira 1989). Both formations consist of very weakly metamorphosed carbonaceous greywackes, turbidites, and siltites that make up the *flysch* formations that are the bedrock in nearly the entire Lower Alentejo.

In the northern half of the 2004-05 survey area, the Gafo Formation abruptly gives way to a more recent (Devonian) and more strongly metamorphosed set of marine sedimentary formations composed of phyllites, quartzites, slates, and red schists. These contain more clay forming minerals than the bedrock to the south and the soils derived from this parent material are red and clayey. The difference in the soil types is clearly visible on the ground. By the end of the survey it was possible to predict accurately where Islamic sites would and would not be located based on soil color; it appears that something about the red soils discouraged Islamic settlement.

There are other landscape differences between the gray and red soil areas. Today, large areas of the red soils are planted with managed evergreen oak savannas called *montados* (or *dehesas* in Spain), as depicted in figure 4.4. The trees are pruned episodically such that agricultural equipment can be used to cultivate the area beneath them, and they provide a source of firewood for the local communities. These managed oak groves are not entirely absent on the gray soils, but they are not nearly as common. Aside from the presence or absence of trees, however, current agrarian production practices are essentially the same on the two soil types. Cereal crops (primarily wheat, but also oats) are planted on a rotating basis, with individual plots cultivated roughly every 7 years. Fallowed fields are used to pasture flocks of sheep and goats or, less frequently, herds of cattle or pigs.

Figure 4.4: Oskar Burger surveying a field near Amendoeira. The image shows the *montado* vegetation (managed oak savanna) typical of the northern portion of the 2004 – 05 survey area.

Other Sites and Isolated Occurrences

In addition to the sites described above, two pre-Roman sites were recorded during the survey. The first is located on a hilltop along a back road leading towards the *quinta* of Bauneira (see figure 4.3). It consists of a small circle of standing stones enclosing a space approximately 2 m in diameter, with the largest of the stones measuring roughly 1 m tall, as shown in figure 4.5. The site has been impacted by recent human activities, including the use of the larger standing stones to stabilize a modern fence. In addition, the small pile of rubble adjacent to the larger stones suggests that the site very likely has been looted, and no artifacts were visible at the surface.

In overall form, the site appears to be the remnants of a Neolithic passage grave of a type known locally as *antas.* It is similar to larger and better-preserved examples that are parts of a large megalithic site complex located immediately to the northeast of the survey area along the road to a geological landmark on the Portuguese-Spanish border called *Pula do Lobo* (Wolf's Leap). By analogy to similar sites in the region, it very likely functioned as a territorial marker and a repository for the secondary burial of human remains.

Figure 4.5: Remains of a probable Neolithic site in the 2004 - 05 survey area.

The second clearly pre-Roman site consists of a small, diffuse scatter of chipped stone flakes and debitage located to the north of the small Islamic period hamlet sites north of Corte do Gafo Baixo. All of the artifacts were made from a fine-grained purplish rhyolite with light-colored phenocrysts that outcrops in the high hills along the southern boundary of the survey area. One was a blade that is morphologically similar to those made during the Upper Paleolithic (Lawrence Straus, personal communication to Boone). Otherwise, no formal tools or temporally diagnostic artifacts were present at the surface. The site may date to the Upper Paleolithic or, based on the presence of known Neolithic sites and the rarity of earlier open-air sites in the region, it could be Neolithic. All that can be said with certainty is that it dates to the time before the use of metal for tools became common in the area during the first millennium B.C.E.

Four isolated occurrences of similar chipped stone tools were recorded during the survey. Three isolated flakes were encountered in the southernmost portion of the survey area, near the apparent source of the raw material. One flake of the same material was encountered in a recently plowed field adjacent to the paved road east of Monte Corcha.

It had steep retouch along one edge, suggesting that it was fashioned and used as a scraper. The final isolated occurrence consisted of three sherds of a ceramic vessel dating to the Christian Medieval period, encountered near a historical pig barn northwest of Corte do Gafo Cima. The sherds may reflect continued travel along the road connecting Beja and Mértola after the Christian Reconquista.

Discussion

The 2004 – 05 investigations showed that the surveyed area was far less densely occupied during the Roman, Late Roman, and Islamic periods than the 1992 survey area had been. Roman and Late Roman sites were roughly half as common in the 2004 – 05 survey area. The differences in the relative densities of Islamic period sites are even more striking. In the 1992 survey area, there are roughly 2.3/ km^2, as opposed to only .27 for the 2004-05 survey area. Even when only the southern portion of the 2004-05 survey area is considered, the density of Islamic period sites is .53/ km^2, less than ¼ of what it was in the 1992 survey area.

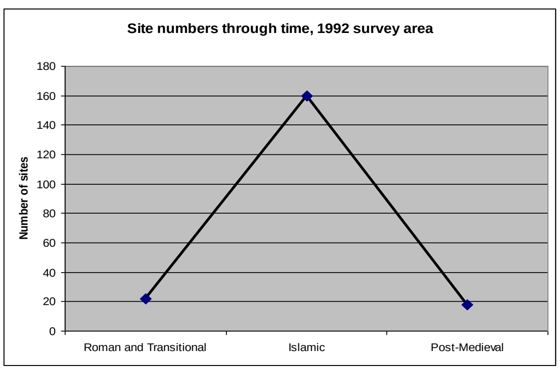

Figure 4.6: Graph showing the number of sites assigned to each time period in the 1992 survey area.

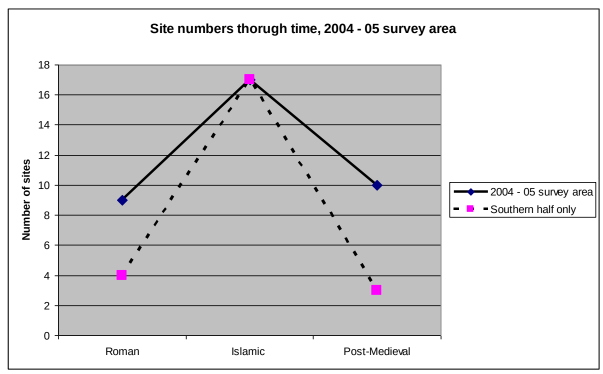

Figure 4.7: Graph showing the number of sites assigned to each time period in the 2004 – 05 survey area; solid line represents the entire area, dashed line represents the southern half.

Despite the absolute differences in settlement density, the relative increase and decrease in settlement through time is similar in both of the surveyed areas, as shown in figures 4.6 and 4.7 (note differing scales on the y-axes). The pattern is even more striking when the analysis is limited to areas with similar soils, i.e. the 1992 survey area and the southern half of the 2004-05 survey area where all of the Islamic period sites are clustered. The overall pattern suggests that rural populations in the region flourished and

declined in response to the same set of broader socio-political circumstances, although the 2004 – 05 survey area consistently was occupied by fewer people.

The 2004 – 05 survey also demonstrated that large portions of the region (i.e. the area of red soils) remained sparsely settled during the Islamic period. Although they seem to reflect a preference for the gray soils during the Islamic period, the reasons for the difference in settlement patterns between the southern and northern halves of the survey area are not fully known. Some contemporary agricultural treatises suggest that farmers would have avoided clayey red soils such as are found in the northern portion of survey area. For example, Sa'ad ibn Luyūn, writing in Granada in the mid-14th century, stated in his classification of soils, "De todas las tierras, las peores son: la salina, la pizarrosa, y la hedionda" (Of all soils, the worst are: saline, red clay soils derived from slate, and stinky [i.e., saturated bog soils], Luyūn 1988 [1348]: 200). That the red soils are productively farmed today may due to the availability of mechanized equipment to turn the heavy soil and to additions of chemical fertilizers.

Avoidance of the red soils during the Islamic period provides some circumstantial evidence that cereal cultivation was a mainstay of the rural economy. Roman and Late Roman sites and the currently inhabited villages in the northern half of the 2004 – 05 survey area all are located in or adjacent to broad valley bottoms where large fenced gardens with wells are used for the production of vegetables and tree crops such as olives, pomegranates, and loquats. Many of these fenced gardens are built on the locations of similar gardens surrounded by masonry walls that date to the late 19th and early 20th centuries, when the local economy focused on sheep herding with supplemental horticulture. One hypothesis meriting further investigation, then, would be that household production of grains to meet basic subsistence needs was more significant in rural parts of the study area during the Islamic period than it was in other time periods when the centralized state was more directly involved in the rural economy.

Another pattern worthy of consideration is the difference between the two surveyed areas in terms of the presence or visibility of pre-Roman sites. While several pre-Roman ceramic sites were identified during the 1992 survey, there were no sites or isolated occurrences consisting of chipped stone artifacts. Aside from a single gunflint recorded during the survey, the only known chipped stone artifact from the 1992 survey

area was a small piece of debitage recovered from a soil test pit at the base of the hill below Alcaria Longa; it was recovered from a stratum representing the ground surface prior to significant deposition caused by erosion on the adjacent hillslope during the later Islamic period (see chapter 9, below).

The ceramic sites, with associated charcoal-stained soils, appear to represent Neolithic – Iron Age residential sites in the 1992 survey area. Lithic scatters and isolated occurrences of chipped stone artifacts in the 2004 – 05 survey area, on the other hand, appear to reflect ephemeral camps related to hunting and perhaps procurement of stone for tool production. Although the evidence is again largely circumstantial, it is plausible that the vast majority of chipped stone artifacts representing ephemeral occupations in the 1992 survey area were removed or buried by widespread erosion during the Islamic period; only the remnants of more substantial occupational sites are still visible, and they are all located on or near the summits of hills in areas not subject to burial by natural processes. By contrast, recent erosion in the 2004 – 05 survey area has exposed the remains of ephemeral occupations in other landscape contexts and may have begun to transport the artifacts towards the trunk streams.

Summary

Boone's investigations in the *concelho* have focused to a large degree on the origins and ethnicity of post-Roman rural populations. Documentary sources record the movement of large numbers of Berbers into Iberia in the 8th century C.E., similar movements as early as the 2nd century, and others later during the Islamic period; on the other hand, historical writings also suggest that there were several million Hispano-Romans in Iberia at the time of the Muslim conquest in 711. The results to date suggest that the situation is far more complicated than simply differentiating between population continuity and replacement. Excavations at Alcaria Longa and at smaller rural farmsteads have revealed evidence of innovation and change during the Islamic period as well as continuity through the transition from the Late Roman to the Islamic world. The results imply a situation of ethnogenesis, with rural populations building an identity around contributions from the Berber, Arab, Late Roman, and non-Roman European worlds.

While the question of ethnicity has proven difficult to resolve, investigations at transitional period sites clearly document the emergence of independent rural communities during the Late Roman period, a pattern repeated in post-Roman contexts across much of Europe. As the Islamic state coalesced in *al-Andalus,* rural communities appear to have retained a great deal of independence, in contrast to the loss of rural autonomy that occurred as feudal successor states emerged in the power vacuum that persisted across the remainder of Europe after the dissolution of the western Roman empire. The occupants of Alcaria Longa retained more of their agricultural surplus than their contemporaries in feudal Europe, participated in a monetized market economy, stored wealth in the form of silver coins and jewelry, and owned weaponry.

There also was a dramatic increase in population density in both survey areas during the Islamic period, although it is at present unclear whether that increase began during the transitional period or occurred as late as the Califal era; in either case, many rural areas were densely settled at a minimum from the 10^{th} until the mid-12^{th} century when the villages were rapidly abandoned. Analyses of carbonized plant remains are somewhat equivocal but suggest deforestation and some degree of overgrazing during that period of high population density, and possibly the emergence of a tradition of actively managing savannah woodlands.

The independence and relative wealth of Islamic period rural populations in the study area appears to be linked to two particular features of governance in *al-Andalus*. First, the state did not tax rural individuals directly; taxes were collected by local leaders and forwarded to the central state from the group as a whole. The collectivization of monetary obligations to the state gave local leaders a degree of independence and power their contemporaries did not enjoy in feudal systems. They were able to maintain relatively low levels of taxation and often fomented revolt when state demands increased beyond acceptable levels.

The second feature is directly related to the political economy of the state. By the Califal period, the state drew significant revenue from taxation and more-or-less direct control of long distance trade, large-scale manufacturing, and intensive irrigation agriculture in the large river valleys of southern Iberia. Probably in part because of scriptural proscriptions against taxing fellow Muslims, these sources of revenue became

increasingly important through time. The wealth-financed Islamic state invested little in extracting surplus from the distant rural hinterlands, particularly in areas where agrarian production was marginal and unpredictable due to environmental constraints. In return for accepting relatively low levels of tax revenue, the state demanded military aid in times of crisis (such as when the Christians advanced southward) and required that rural populations not interfere with long-distance trade.

Of particular importance to the remainder of this study is the fact that the more recent survey documented significant differences in settlement density between the 1992 and 2004-05 survey areas. This provides one means of testing whether past landscape degradation was caused by human activities. It is reasonable to assume that past anthropogenic impacts on the environment were less severe in the 2004-05 survey area due to lower population densities. Direct comparisons between the 1992 survey area and the southern half of the 2004-05 survey area are warranted because climate, biotic communities, topography, bedrock geology, and the timing of initial deposition of soil parent material are similar (see Jenny 1941). If differences in fluvial stratigraphy and in the soils and sediments on hillslopes can be demonstrated, those differences likely are due to past human activities. The author's geoarchaeological studies focused on identifying the timing, extent and causes of past landscape change are the subject of subsequent chapters.

Chapter 5:

Introduction to Geoarchaeological Research

Since the inception of a broadly scientific approach in the discipline, archaeologists have had to confront geological questions in order to understand the material record of past human activities. For example, collaborations between archaeologists (or antiquarians) and geologists during the 18^{th} and 19^{th} Centuries were crucial in untangling the complicated archaeological records encountered in Paleolithic cave sites and in establishing the deep antiquity of human presence in Europe (e.g., Daniel 1967: 46 – 78; Trigger 1989: 87 – 102). More recently, archaeologists have addressed explicitly the interpretive problems posed by the movement of artifacts in various ways from the locations of use to where they were initially deposited, and then to the location of eventual recovery (e.g., Schiffer 1972). Geoarchaeology has emerged as the sub-discipline in archaeology most concerned with taphonomy and other related issues (e.g., Dincauze 2000; Rapp and Hill 1998; Stein and Farrand 2001; Waters 1992); geoarchaeological studies often focus on site formation processes, the depositional context of cultural materials, post-depositional disturbance, and other questions investigated at the scale of individual sites. Such studies produce information concerning the nature of the archaeological record that is a fundamental first step towards reconstructing past human behaviors.

Beginning in the 1950's with large, systematic archaeological surveys that investigated settlement patterns (e.g., Willey 1953) and continuing through the 1970's with catchment analyses that reconstructed the resources available near particular sites (e.g., Higgs and Vita-Finzi 1970; see Clark 1954 for a pioneering early example), the focus of archaeological research has shifted increasingly towards larger spatial scales. Within the past decade, diachronic studies of "socio-natural systems" focused on long-term recursive interactions between humans and the environment have emerged as a significant domain of study within archaeology (e.g., Butzer 2005; Fisher and Feinman 2005; Hill 2004; Johnson *et al.* 2005; Redman 1999; Van der Leeuw and Redman 2002; Van der Leeuw 2000; Butzer 1982 and Vayda 1969 are two earlier works that presage many of these more recent studies) and the closely related field of historical ecology

(e.g., Balée 2006; Briggs *et al.* 2006; Crumley 1994, 1998, 2007). In these studies, the spatial scale of observation and analysis is the landscape (Crumley and Marquardt 1987). The broadening geographic scope of archaeological investigations has stimulated the parallel growth of geoarchaeological research at the landscape and regional scales (e.g., Ballais 2000; Bintliff 1977, 1992, 2002; Bintliff and Zeist 1982; Deckers 2005; Gilman and Thornes 1985; Pope and van Andel 1984; Thornes and Gilman 1983; van Andel *et al.* 1990; see Bryan 1940, 1942, and Hack 1942 for important early work.) The research presented here is intended as a contribution to this growing corpus of work, which could be called landscape geoarchaeology.

Geomorphology is the discipline that specifically focuses on landscapes and how they change through time. At the simplest level, "Geomorphology is best… defined as the study of landforms" (Ritter *et al.* 1995: 3). In the United States it typically is considered a part of geology, while in Europe geomorphologists often hold appointments in geography departments. The contributions of geomorphologists have been significant as archaeologists have worked to develop landscape- and regional-scale approaches to investigating past human behaviors and interactions with the physical environment.

As in archaeology, the discipline of geomorphology has undergone a transformation in recent decades from one focused on historical reconstruction towards an emphasis on exploring processes related to change, in this case processes related to landscape evolution (*ibid.*, see also Baker 1988). Hopefully the two disciplines now are forging syntheses in which both history and process contribute to explanation, as is appropriate for historical sciences (see Ghiselin 1997 for a broad discussion of historical science, Bintliff 1999 on archaeology, Frodeman 1995 on geology). One goal of the present research is a historical reconstruction of landscape change in the study area based on an understanding of the relevant geological and cultural processes.

A second parallel between archaeology and geomorphology is that the general subject material of either discipline can be approached from many angles. There has been a proliferation of specialized subfields in geomorphology such as fluvial geomorphology, hillslope process geomorphology, soils geomorphology, glacial geomorphology, tectonic geomorphology, etc. This is analogous to the appearance in archaeology of specializations like geoarchaeology, environmental archaeology,

bioarchaeology, zooarchaeology, and others. For the current research, fluvial geomorphology, hillslope process studies, and pedological (soil) research are the most pertinent aspects of geomorphology.

Mediterranean Area Landscape Geoarchaeology

Contemporary observers and scholars studying the past have written about soil erosion and anthropogenic landscape change in the Mediterranean region at least since classical times (Grove and Rackham 2001: 241, 288; Montgomery 2007: 49 – 51, 58 – 62; Ponting 2007: 75 – 77; Redman 1999: 17 – 23). Historical writings have contributed to a vision of the region as a "ruined landscape," perhaps the quintessential cautionary tale of population growth, overshoot, and ecological disaster despite the fact that empirical evidence of persistent environmental degradation is surprisingly uncommon (Grove and Rackham 2001: Chapter 1). By the 1960's, geologists, geographers, and archaeologists were collaborating to investigate empirically the timing, extent, and causes of past erosion in the vicinity of classical period urban centers like Rome (e.g., Judson 1963). In his seminal book *The Mediterranean Valleys: Geological Changes in Historical Times*, published in 1969, Claudio Vita-Finzi summarized alluvial sequences from river valleys in Libya, Tunisia, Algeria, Morocco, Jordan, Spain, Italy, and Greece. He proposed that there were two contemporaneous episodes of alluviation throughout the circum-Mediterranean region. His "older fill" was deposited during the Pleistocene, after which the river systems incised their floodplains prior to emplacement of the "younger fill" beginning in late Roman and Medieval times. Based on the apparent contemporaneity of alluviation throughout the region, Vita-Finzi argued that the landscape changes were caused by climatic shifts.

Since its publication, *The Mediterranean Valleys* has informed an enormous amount of research into the chronology and causes of landscape change in the Mediterranean region. Many studies adopted Vita-Finzi's framework and augmented his research by investigating different areas in the region or elaborating on the details of geomorphic change (e.g., Bintliff 1977; Bintliff and Zeist 1982; Davidson 1980; Potter 1976; Vita-Finzi 1976). Other research, perhaps most prominently that of the geologist Tjeerd van Andel, began to challenge the conclusion that alluvial sequences were contemporaneous throughout the Mediterranean basin; the varied timing of landscape

change in different areas suggested to these researchers anthropogenic causes for hillslope erosion and valley filling during the Holocene (e.g., Pope and van Andel 1984; van Andel 1986; van Andel et al. 1990). Numerous reviews of this debate over anthropogenic versus climatic causes of landscape change have been published as articles (e.g., Bintliff 1992, 2002) or as sections in more general books (e.g., Dincauze 2000: 320 – 325; Greene 1986: 85 – 86; Grove and Rackham 2001: 288 – 311; Montgomery 2007: 55 – 56; Redman 1999: 111 – 117). More recently, many researchers have moved away from regional generalization and begun to focus on specific aspects of settlement patterns and land use as they relate to landscape change in circumscribed areas (e.g., Barker 1989; Stevenson and Harrison 1992). Most have adopted increasingly nuanced explanatory frameworks that reject a simple dichotomy between climatic and anthropogenic causes of geomorphic change (e.g., Ballais 2000; Butzer 2005; Chester and James 1991, 1999; Deckers 2005; Hill 2004; van der Leeuw 2000).

Regardless of whether they ultimately favor climatic or anthropogenic causes of landscape change, the studies cited above almost always incorporate aspects of geomorphology, fluvial stratigraphy, and pedology alongside more traditional archaeological investigation. For the most part, they focus on possible correlations of landscape change with widespread changes in land use. These changes include, among others, the initial adoption and subsequent intensification of farming, the impacts of Roman settlement, its later decline, and renewed intensive land use during the medieval period or later. The techniques developed in this body of research address aspects of human-environment interaction, often at the scale of landscapes or regions; studies such as these have laid the foundations for examinations of many aspects of the socio-natural system.

To date, and in no small part because of the influence of Vita-Finzi's work, most of the regional-scale studies of landscape change in the Mediterranean area have focused on stratigraphic investigations, relying particularly on analyses of strata deposited by large fluvial systems (but see Thornes and Gilman 1983 and Wainwright 1994 for examples of research focused on upland contexts). While examinations of fluvial strata are useful for inferring that there was erosion of soils from upland locations in the past, research that relies exclusively on such data is likely to be incomplete. Subsistence

activities such as dry farming and pastoralism occur in upland environments and it is difficult, at best, to determine the degree and areal extent of degradation of those upland environments solely by studying fluvial deposits (e.g., Grove and Rackham 2001: 246). In addition, the relationships between hillslope erosion, sediment transport, and deposition by fluvial systems are neither simple nor strictly mechanical.

Numerous studies have shown that ephemeral stream systems in particular can remove or deposit sediments without any apparent direct connection to external conditions (e.g., Patton and Schumm 1981, Schumm 1977; Schumm and Parker 1973). In addition, the movement of sediments within and through a drainage basin is complex: "There is no simple relationship between the flux of sediment measured at a particular location and the area that contributes to that flux." (Parsons *et al.* 2004: 1295; see also Gellis *et al.* 2004, and Wilcox *et al.* 2003). The disparity, called the sediment delivery ratio, is due to sediment storage at various points along hillslopes and within catchments, and it dramatically affects how erosion impacts landscapes. Therefore, it is essential to generate information about landscape change within entire drainage basins in order to interpret floodplain stratigraphy correctly (e.g., McFadden and McAuliffe 1997; Tillery *et al.* 2003) and to begin to isolate the effects of human activity on the landscape.

A second shortcoming of many studies of human – environment interactions in the Mediterranean region is that they often have not demonstrated clear causal connections between landscape change and human activity. Many rely on demonstrating temporal correlation, and infer causality from this correlation. Therefore, debate continues among archaeologists working in the Mediterranean region concerning the relative importance of human impacts and external environmental changes (i.e. changes in temperature, effective precipitation, and plant cover) in effecting erosion and alluviation (see Bintliff 1992, 2002, and Butzer 2005 for discussions).

Following the logic of Vita-Finzi, one approach used by many researchers to address the problem of isolating anthropogenic impacts from changes in external conditions has been to determine the timing of episodes of erosion and deposition over large areas and in multiple drainage basins (e.g., Ballais 2000, Van Andel *et al.* 1990 1994). The basic assumption behind these studies is that climatic variation affects entire regions simultaneously while anthropogenic impacts are more localized and are likely to

differ spatially and temporally within a region. If human activities were demonstrably different in two adjacent areas, and if the areas have different histories of landscape change, it stands to reason that the different trajectories of landscape evolution may be due to human activity.

Although the logic of comparing different areas or drainage basins within a region is sound, the numerous variables that influence landscape change must be considered. Hans Jenny's (1941) soil "equation"[24] provides a useful framework for identifying the factors that influence soil development and landscape evolution. The key factors he identifies in the "ClORPT equation" are Climate, Organic inputs, Relief, Parent material and Time. To this may be added that the alteration of surface deposits as soils develop becomes significant in itself in affecting long-term trajectories of landscape change (e.g., Eppes *et al.* 2002, 2003). In addition, beyond providing organic inputs to the solum, some researchers have emphasized the importance of biota in affecting soil development through various types of bioturbation (e.g., Johnson 2002). In order to isolate anthropogenic impacts, it is necessary to show first that these many other factors are comparable between the two areas chosen for comparison.

Within a region, it generally is reasonable to argue that climate has been the same in two study areas that today have the same climate. Relief also can be evaluated in the two areas and in most cases is unlikely to have been radically different in the past, at least on historical time scales and in the absence of major movement along faults. Geologic maps provide baseline information concerning soil parent materials. In the absence of evidence to the contrary, the initial deposition of soil parent material and important subsequent inputs such as dust are likely to be comparable across a region in which climate, relief, and bedrock geology are constant. Similarly, assuming that the other factors are equivalent in the two areas, organic inputs and bioturbation also should be comparable in the absence of human impacts, as plant and animal communities within a region are largely determined by climate, topography, and substrate.

Humans primarily influence soil development and landscape change through the factors of organic inputs (Thornes 1987, 1990) and time; people dramatically alter biotic

[24] It really isn't an equation in the strict mathematical sense. The variables are not independent, nor are they related by exact mathematical functions like multiplication. It is, properly speaking, a list of potentially important, interrelated factors.

communities through fire, animal herding, and agriculture. Forest clearance, herding, and plow agriculture in particular can increase rates of soil erosion by orders of magnitude (Grove and Rackham 2001: 268; Selby 1993: 229). Significant erosion can remove some or all of the soil in an area, altering runoff and infiltration characteristics and exposing at the surface bedrock or sediments that previously were unaltered by pedogenic processes, thereby essentially resetting the clock on soil formation. Therefore, different degrees of soil development in different areas within a region where climate, relief, and parent materials are comparable are likely to reflect the impacts of past human activities.

Previous studies of landscape change in the Mediterranean region suggest that it is often possible to document past soil erosion to some degree through investigations of the strata deposited by fluvial systems. Geomorphic research shows that examinations of hillslope soils can provide important additional data concerning the degree and extent of that past erosion. Archaeological investigations pertinent to understanding demography and the subsistence economy provide a starting point for linking past ecological change to human activities. In addition, comparing the soils and strata in study areas in which the soil forming factors can be held constant, and where human activities were different in the past, should in many cases allow anthropogenic impacts to be separated from changes in climate or other external factors. This, in turn, facilitates stronger inferences regarding the causes of landscape change in the past.

Landscape Geoarchaeology in Iberia

To date, no geoarchaeological studies have been published that address anthropogenic landscape change during the post-Roman era in the Alentejo region of Portugal, aside from a brief summary of portions of this research presented in Boone and Worman (2007)[25]. Several scholars have, however, completed significant studies of land use and landscape evolution in other parts of Iberia, particularly in southeastern and eastern Spain. Notable among these are the works of Thornes and Gilman (1983; also Gilman and Thornes 1985), Castro *et al.* (2000), Barton *et al.* (1999, 2002) and Butzer (2005). Those investigations are relevant to the present study in that they attempt to

[25] Several studies focused on the Neolithic and earlier time periods in southern and central Portugal have incorporated geoarchaeological components. See, for example, Angelucci 2006, Angelucci *et al.* 2007, Bicho *et al.* 2003, Lillios 1997.

reconstruct human activities and soil erosion in circumscribed study areas where the archaeological record is reasonably well understood.

Bintliff (1992) asserts that Thornes and Gilman's research (1983; also Gilman and Thornes 1985) ushered in a new stage in the scientific understanding of diachronic relationships between human activities and soil erosion in the Mediterranean world. Bintliff lauds Thornes and Gilman for focusing on processes of geomorphic change, for recognizing that human activities may create a landscape particularly susceptible to erosion, and for highlighting the importance of extreme weather events in triggering major landscape change[26]. He also suggests that they were among the first to incorporate studies of hillslope processes into geoarchaeological research, as opposed to focusing solely on stream systems and fluvial stratigraphy. Given the groundbreaking nature of their research, and its relevance to the current study, a brief review is warranted.

In their 1983 article, Thornes (a geomorphologist) and Gilman (an archaeologist) open by stating that their goal is a close collaboration to assess erosion and to reconstruct the environment and economic potential of the site catchments, defined by a two hour walking radius, around 34 Neolithic, Copper Age, and Bronze Age archaeological sites in southeast Spain. It is the last time they mention archaeology or the sites. Introducing their work, they discuss the importance of understanding processes of soil erosion, and note the tradeoffs between detailed models, for which necessary data inputs are unavailable when studying the past, and overly-general models that do not produce valuable information about complex processes.

The remainder of the article presents a mathematical model and field data that are used to calculate the erosion potential of different areas within the study region; this information is repeated in slightly abbreviated form in Gilman and Thornes (1985: 48 – 83). The Thornes and Gilman model is based on a Musgrave type formula, $Y=kq^m s^n$ where Y is sediment yield and k is an empirically determined coefficient representing susceptibility to erosion for which they select a value of .02 that they assert is conservative. q is overland flow, and s is the tangent of the slope angle. m and n are empirically determined quasi-constants for which they use values borrowed from other

[26] Their conceptual scheme presages by almost two decades van der Leeuw's (2000) "fragilization with delayed response".

investigations, 2 and 1.66, respectively. The distinction between gullied and ungullied slopes is critical for determining erosive potential because the catchment area (which determines the value of q) for gullies increases as the distance downstream squared, while the catchment area for ungullied slopes is a linear function of slope length. Therefore, the authors present separate equations: for ungullied slopes, $Y=kp^2s^{1.66}$ and for gullied slopes, $Y=k(p*L)^2s^{1.66}$, where p is excess water (rainfall minus storage; storage is proportional to vegetation and infiltration) and L is slope length. Therefore, lithology (which affects infiltration) and topography are the two primary inputs that they measure from maps and in the field. In essence, this is a slightly more sophisticated version of the Universal Soil Loss Equation (USLE). It adds to the USLE in that it includes data derived from in-field measurements in specific locations but, because it is to be applied to the past, it excludes the factors in the USLE that represent current land use practices.

The authors then modify these two basic models to reflect average conditions and extreme storm events. The resulting equations are complicated, but basically the model for average conditions calculates a proxy for the average intensity and duration of storm events based on the years for which instrumental data exist. The extreme event model allows the authors to input precipitation events of various magnitudes and calculates excess water from changes in infiltration through time during a storm, as derived from field infiltrometer measurements. Both models use the difference between potential and actual evapotranspiration as a proxy for vegetation. The end result is an ostensibly "simple" model that is a full-page flow chart of equations.

In beginning to apply the model, Thornes and Gilman divide their study region into 8 classes of lithology and take multiple measurements of infiltration rates and bulk densities of surface sediments at five randomly selected sites within each. They repeat the procedure at an additional 15 sites in order to reduce the statistical variance in observations of infiltration and water storage on selected lithologies (at least three initially had coefficients of variation significantly higher than the mean values, suggesting strongly skewed distributions) and arrive at mean rates for each lithology. They use topographic maps, air photos, and unspecified field observations to calculate mean slope angles and mean slope lengths for each lithology. For climate data, they rely on recorded rainfall from provincial capitals and stream gauge data. They then calculate

predicted sediment yields for overland flow on rilled (gullied) and unrillled slopes that are vegetated and unvegetated, for each lithology and for each of the areas defined by provincial capitals for which rainfall data are available. They repeat the process using the models of both average conditions and extreme events. For the extreme events, they use both 60mm/hr and 120mm/hr storms, which have statistically estimated recurrence intervals ranging from 30 to 150 years at different places in the study region. The results are presented in several large data tables.

Briefly commenting on the results, the authors note that "the presence of vegetation sharply reduced erosion" and the results "represent the joint constraints provided by the assumptions of the model and by the parameter values recorded in the site territories studied" (1983: 108). Ultimately, they state that their model shows that vegetation is the most crucial variable affecting erosion, altering predicted sediment yield rates by as much as four orders of magnitude. For bare slopes, lithology is the strongest determinant of erosion for normal events but for extreme events that saturate surface deposits regardless of lithology, slope angle is the most important determinant.

Thornes and Gilman conclude by evaluating the performance of their model. Qualitatively, they note that the model fails to account for the relative lack of erosion in the chalk lithology class. They also note that it fails to account for variations in resistance to erosion related to grain size distribution and that it does not consider weathering-limited slopes. Quantitatively, they conclude that the model's predictions compare favorably to observed rates of erosion[27]. They note that for assessing erosion around archaeological sites the presence of gullying (channel formation) is highly significant, and that extreme events are crucial in determining overall geomorphic change. Finally, the authors consider the question of why, if predicted erosion rates are so low, the landscape is so evidently eroded and dissected. They contend that the general topography and drainage patterns are the result of major erosion prior to the Holocene and that the landscape has been stable at a large scale for at least the past six millennia.

Thornes and Gilman's (1983) article was, in many ways, innovative and it made several important contributions to landscape-scale geoarchaeological research. As noted

[27] This may be due, in no small part, to the fact that their model predicts these rates within a margin of error that spans as much as three orders of magnitude.

by Bintliff (1992), they highlight the importance of a process-based understanding of erosion and they refocus attention on hillslopes. In addition, they create a useful heuristic in which human activities are seen as increasing the potential for erosion while large storm events are responsible for triggering significant landscape change.

Despite these contributions, it is evident that the model is not applied to archaeological problems in the 1983 article. Gilman and Thornes' *Land-use and Prehistory in South-East Spain* (1985) promises to address this lacuna by presenting detailed examinations of the landscapes around archaeological sites. The fundamental thrust of the ambitious book is a site catchment analysis, informed by geomorphic studies, focused on the 34 Neolithic through Bronze Age sites in southeast Spain mentioned briefly in the 1983 article. The overall goal is to investigate agricultural intensification, particularly increases in irrigation agriculture through time, by comparing the availability of water and distribution of arable land around earlier vs. later sites. The book includes cogent discussions of the late prehistoric archaeological record from southeast Spain, site catchment analysis, traditional land use practices, and the relationships between agricultural intensification and social stratification (on the last, Gilman 1981 provides a compelling broader argument).

Although the Thornes and Gilman model of erosion is presented at length in the book, its actual application to archaeological problems is problematic. First, in order to use the model the authors exclude what they call "special cases" (1985: 15) where there is clear evidence for delta accretion or other major geomorphic change near an archaeological site. In addition, the only geomorphic field investigations they note (beyond measurements done to create the model) are a supposedly-detailed analysis of the site catchments in badland areas that they take as a worst case scenario for erosion. These detailed analyses appear to amount to noticing that the sites still exist despite the fact that their model suggests that they would have been destroyed had vegetation degradation or gullying (channel formation) exacerbated erosion in those areas. From this they conclude that erosion must not have been severe enough in any of their cases to impact significantly the spatial distributions of arable land they reconstruct from observations of current and historically recorded land use. The authors dismiss the idea of trying to measure or estimate erosion through additional fieldwork – or in any way

other than modeling – in a few lines in which they mention the problem of complex response in fluvial systems (*ibid.* 48 – 49; complex response is discussed further in Chapter 7, below). In the end, the erosion model contributes virtually nothing to the site catchment analyses beyond justifying the assertion that large-scale landscape change has been minimal since before the Neolithic.[28]

The evident difficulty in applying the model of erosion potential to archaeological questions begs the question of why it did not prove more useful. The model itself includes some questionable assumptions, such as the implicit assumption that rilling and vegetation are independent variables. Beyond such minor details, there are fundamental issues related to those encountered in most attempts to model complex processes. Specifically, modeling necessarily involves simplification and, depending on the scale of the questions and the relevant data, that simplification may be inappropriate for the questions the model is meant to address.

The Thornes and Gilman model assumes average slopes, average vegetation, spatially averaged rainfall, and average infiltration characteristics within the lithological zones they identify. The last assumption clearly is violated by their data, collected to calculate the averages; the data show higher variation in infiltration rates within many of their lithology classes than between the classes. Also, the model cannot account for the fact that people farmed, herded, and foraged on real slopes and no doubt focused their activities on favorable topographic features with specific hydrological and soil characteristics. Similarly, they ignore soils and base all of their calculations on bedrock lithology. Soils significantly alter many of the parameters in their model, such as infiltration rates and water storage capacity, and again, soil characteristics were no doubt important considerations taken into account by prehistoric farmers when selecting places to grow crops. The authors assume that rainfall is spatially constant around the provincial capitals despite working in a mountainous region where they recognize that "rainfall… is strongly relief dependent" (1983: 92). Finally, it seems transparently mistaken to base a model on hypothetical average vegetation when the fundamental archaeological question revolves around the ways in which anthropogenic alteration of

[28] By contrast, the far simpler model they use to estimate past stream flows is important in identifying differences in irrigation potential at different sites.

vegetation communities impacted the landscape (see Thornes 1987 on the central role of vegetation in mediating anthropogenic landscape change). It is because of parallel problems that Grove and Rackam assert flatly, “The Universal Soil Loss Equation does not work here [in the Mediterranean region].” They go on elaborate:

> we doubt whether it could be made to work by adding more variables: in the complex environment of Europe enough reliable data are difficult to collect. Modeling can be a means of understanding erosion, but it is still a long way from being predictive. (2001: 268)

These problems of oversimplification could be ameliorated by focusing on smaller areas, for example by modeling erosion on specific slopes or within small drainage basins (e.g., Wainwright 1994). Although labor intensive, modeling erosion at smaller scales and using data that were gathered at the specific location under study and not averaged over large areas could contribute to a more realistic understanding of the historical trajectory of landscape change around individual sites. It also would begin to address a fundamental problem of scale unacknowledged in Thornes and Gilman’s research: soil erosion is not the same thing as dramatic changes in landforms and drainage patterns (see Grove and Rackham 2001: 246). The former is relevant to understanding agrarian land use, while their model really addresses the latter.

More detailed approaches inevitably would result in an exponential increase in the complexity of the modeling endeavor. Beyond this, even a perfect model (or set of models) would have to be used by the authors in particular ways so as to overcome additional shortcomings. First, they actually would have to evaluate the magnitude and timing of past erosion in individual site catchments in order to address archaeological questions relating to the economic potential of those areas in the past. Second, they would have to attempt to apply their models in a historical way; the model as it is does not account in any way for changes through time. It provides estimations of sediment yield under various conditions, but does not begin to approach the complex problems of how the dynamics of erosion would change through time as sediments moved across the landscape, let alone tackling the additional complexities of tracking human inputs and diachronic responses to a changing landscape. Finally, while the model successfully highlights the importance of channel formation, changes in vegetative cover, and extreme

storm events, the authors fail to show how any of these parameters could be measured for archaeological cases.

Their work makes many important theoretical contributions, but Thornes and Gilman's model and the associated fieldwork fall short of answering the basic question of what is likely to have happened in the past in any particular location. Put another way, Gilman and Thornes use their model to argue that landscape change since the Neolithic has not been great enough to impact significantly the distributions of arable land around selected archaeological sites in their study area. To the extent that they may be correct, this is an important part of their larger arguments (otherwise generally successful) concerning the relationships between irrigation agriculture and social stratification. Their model, however, apparently is not useful for evaluating other aspects of human-environment interactions in the past such as when, where, or to what degree people caused soil erosion, whether people impacted the landscape differently in different time periods, whether landscape change can, in fact, be attributed to human activities, or how people responded to changes in the environment.

Castro *et al.'s* (2000) article considers broadly similar questions of land use and landscape change since the Neolithic in the Vera basin, part of Gilman and Thornes' study area[29]. In the context of recent concerns with global warming and desertification, the European Union has funded several research projects directed at building predictive models of human-landscape-climate interactions. Castro and colleagues present the results of archaeological research associated with two of these, the Aguas and Archaeomedes projects. They highlight archaeology's contributions to the general goal of understanding human-environment interactions, and they emphasize the importance of a long-term perspective on recent desertification and ecological degradation (cf. Van der Leeuw 2000).

Beginning with a review of more than a century of archaeological investigations, Castro *et al.* (2000) reconstruct the demographic history of their study area since the start of the Neolithic (locally ca. 4500 BCE). They incorporate data from relevant historical documents to refine their population estimates for the past five centuries. Wherever it is available, the authors include information on subsistence economy and political

[29] Curiously, the authors cite neither Thornes and Gilman (1983) nor Gilman and Thornes (1985).

organization, focusing particularly on the area's incorporation into regional political and economic systems beginning with Phoenician colonization at roughly 900 BCE. They note that, after the Bronze Age, population changes were related primarily to exploitation of the area's mineral and agricultural resources by state-level polities and empires that ruled from afar.

Turning to the long-term record of ecological change, Castro and colleagues describe a repeating pattern of population growth followed by population decline, political instability, environmental degradation, and eventual regeneration. Moreover, they argue that population declines were increasingly precipitous and ecological degradation more severe with each iteration of the cycle. They suggest that intensive agricultural production and deforestation related to mining have caused soil erosion and vegetation degradation at least since the Bronze Age. Interestingly, the single exception to this trend is the Islamic period, which they state was characterized by "'environmentally friendly' cultivation systems… in the hands of more or less self-sufficient, autonomous farmers" (159). They conclude that the most severe soil erosion during the Holocene was due to the abandonment of those cultivation and land-tenure systems following the *reconquista*. Ending the article with a series of policy recommendations, Castro *et al.* (2000) propose returning much of the landscape to traditional forms of agricultural production focused on the surface-water irrigated valley bottoms and terraced uplands.

This article is, in many ways, strikingly different from Gilman and Thornes' work. It is focused on a much smaller area, a basin measuring roughly 15 by 25 km, which the authors further subdivide by drainage. At the same time, it considers a longer period of time, tracing socio-environmental developments from the beginnings of agriculture to the current system of greenhouses and groundwater irrigation. It is more properly speaking diachronic in that it traces changes through time within an area as opposed to inferring changes by comparing different areas occupied at different times. Finally, in part because of the restricted size of their study area, the authors reject geomorphic modeling in favor of field studies aimed at determining the degree and timing of erosion in the past.

These differences imply that the work by Castro *et al.* (2000) might overcome some of the shortcomings noted above for the work of Gilman and Thornes. Castro and colleagues provide data on changes in plant communities derived from palynological and macrobotanical studies, highlighting an important interface between people, soil, and landscape. They consider the possibility that climate shifts might have impacted landscape change, particularly before roughly 3000 BCE. In addition, detailed demographic reconstructions allow them to investigate human-environment interactions within their study area without having to focus on one or a handful of individual sites as exemplary of the range of land use systems in any given time period. Finally, their focus on a smaller area allows them to investigate empirical evidence for trajectories of landscape change through time.

Despite these strengths, the work of Castro *et al.* (2000) has shortcomings of its own, primarily because their inferences about landscape change are drawn from a relatively brief study of the area's geomorphology published by French *et al.* (1998). The geomorphic study is based on the sediments associated with the Río Aguas and its tributaries, including examinations of the river terraces, limited coring of alluvial deposits, and detailed stratigraphic recording of fewer than a dozen exposures of fluvial sediments. French and colleagues report only two radiocarbon dates, one infrared luminescence (IRSL) date and two uranium/ thorium series dates. In addition, the ages of strata in one profile and several of the terrace surfaces are constrained by temporally diagnostic artifacts.

Compounding the overall lack of well-dated strata, the authors note that their focus on fluvial systems is limiting because of the problem of complex response: "The major problem with these interpretations is that the amount of reworking of earlier channel infills and alluvial terrace deposits is unknown" (French *et al.* 1998: 49). Given the relatively poor chronological control and the complications introduced by complex response, it is perhaps unsurprising that their results are somewhat underwhelming: the data "imply an intensification of erosion/ sedimentation processes during the last 500 or 600 years. These higher sedimentation rates seem to be induced by anthropogenic factors…" (*ibid.*: 52). Castro and colleagues note that the recent increase in

sedimentation also is reflected in studies of coastal formation at the mouths of the rivers that drain the Vera basin.

Because French and colleagues (1998) provide only a relatively general sketch of large-scale landscape change, it is necessarily somewhat difficult for Castro *et al.* (2000) to generate a detailed study of the relationships between human land use and that landscape change. They marshal a considerable amount of evidence concerning agrarian practices and changes in plant communities throughout their study area. They are, however, not able to tie these to a detailed chronology of erosion and sedimentation, making it impossible for them to proceed beyond noting a probable correlation between population decline, political unrest, and ecological degradation. They are unable to determine for any particular instance the causal links between these processes because they cannot establish the chronological relationships. Their assertion that local control fosters more ecologically stable agrarian land use may be true but fundamentally is based on a second assertion, that farmers were relatively independent and practiced 'environmentally friendly' production techniques during the Islamic period.

Working farther to the north, Barton and colleagues have published the results of a long-term program of archaeological survey, collection, and excavation focused on "changing prehistoric landuse in this region… [and] the dynamics of Mediterranean landscapes, including their role in human settlement and in the creation and alteration of the archaeological record" (Barton *et al.* 2002: 156; see also Barton *et al.* 1999, 2004). In their surveys, the investigators applied patch-based sampling and used resurveys to evaluate visibility, recovery rates, and other variables. They recorded such pertinent variables as vegetation cover, surface visibility, modern land use, and landform context. They also refer to a handful of geomorphic studies that documented significant landscape change, such as a major episode of stream capture in the mid-Holocene and more recent widespread sheet erosion.

The work of Barton and colleagues contributes in valuable ways to survey methodologies, particularly for areas that have been significantly modified by human activities for millennia. Their application of a "taphonomic approach to integrate the study of formation processes and archaeological residues" (2002: 156) facilitates reliable reconstruction of broad patterns of changing land use from the Paleolithic to the present.

In the 1999 and 2002 articles, however, their focus is almost exclusively on post-depositional processes that affect the archaeological record in various ways (Schiffer's [1987] "N-transforms"). They argue persuasively that this is a necessary first step towards reconstructing change through time in past socioecosystems. In those publications, however, they do not investigate in any detail the recursive relationships between human activity and landscape change, nor do they claim to.

In their longer 2004 article, Barton *et al.* begin to examine in greater detail the implications of their results for understanding past human-landscape interactions. As in the earlier articles, they use the distribution of archaeological materials as a proxy for the spatial extent of land use, and develop a means of calculating a measure of land use intensity from artifact abundance. They then go on to compare the extent, locations, and intensity of inferred land use for the Middle Paleolithic, Upper Paleolithic, Late Upper Paleolithic/ Epipaleolithic, Early Neolithic, and Late Neolithic periods in the four valleys that comprise their study area. Ultimately, they are able to build a strong argument that the transition from foraging to agriculture played out differently in the different valleys because each had a unique history of land use and anthropogenic landscape change reaching back into the Pleistocene. Moreover, they trace the persistent ecological effects of erosion related to Early Neolithic forest clearance forward through time, documenting the shift in the Late Neolithic to a focus on upland environments and, ultimately, to current variability in agricultural systems in the four valleys.

Barton and colleagues conclude that "An important goal of this paper has been to outline a systematic framework in which archaeologists can undertake long-term studies of human socioecosystems at regional scales." (2004: 288). They have taken important steps toward that goal, elaborating a sophisticated approach to regional survey informed by taphonomic considerations. In addition, they make non-trivial contributions to understanding the shift to agriculture in their study region and to emphasizing the importance of historical contingency in studying human-landscape interactions in general.

For all of their sophistication in untangling taphonomic processes, however, the overall lack of pedological and geomorphic data presented by Barton and colleagues is startling. They do not refer to any comprehensive or large-scale studies of the soils and

geomorphology of the region; likely none exist. They rely to a large extent on visible indications of recent surficial erosion to understand patterns in the archaeological record. Where past erosion is concerned, they develop a clever means of inferring whether significant portions of the archaeological record were removed by examining which time periods are represented in any given location. This technique, however, relies on the assumptions that people must reliably return to the same locales through time, that they must always discard non-perishable, temporally diagnostic artifacts in those locations, and that archaeologists will then recover and recognize those artifacts. Finally, their conclusions regarding erosion during the Neolithic are largely based on a model of land use, erosion, and subsequent changes in land use that is theoretically well grounded, but which itself is based almost entirely on inferences regarding the likely impacts of probable agricultural strategies (McClure *et al.* 2006). At large spatial and temporal scales, the conclusions of Barton *et al.* (2004) are interesting and very likely correct. However, they rely almost exclusively on archaeological data to infer past landscape change (see Hill 2004 for a similar approach). Actual geological and pedological information documenting that the landscape changed in the past in the ways that they infer would add considerable weight to their arguments.

In his recent article, discussed at some length in chapter 2, Butzer (2005) summarizes relevant research in Greece and eastern Spain. The case studies are discussed here, in particular focusing on his contributions to the problems of isolating human impacts, the roles of human perceptions, and the problems of conceptualizing and measuring degradation. Setting the stage for his case studies, Butzer discusses the growth of large-scale social systems since the Neolithic and places the associated agricultural intensification in the context of the Mediterranean agrosystem.

Butzer maintains that the Mediterranean agrosystem, which combines arboriculture (olives, various nuts in some locations) and viticulture with extensive grain farming (usually wheat) and pastoralism, successfully reduces risk through diversification while also generally being ecologically sustainable (see also Butzer 1996). In addition, he notes that several aspects of the agrosystem, including arboriculture, viticulture, and terracing, require significant long term investments in the landscape, presupposing recognized property rights and facilitating the growth of social stratification. Moreover,

he argues that it was the production of olive oil, wine, and other high-value storable goods that facilitated the growth of long-distance trade networks. These networks, in turn, fostered economic integration that averaged spatial and temporal variability in production throughout the system, further minimizing risk and creating systemic links between ecology, agrarian intensification, demography, and political-economic regional integration[30]. Given their diversity and ecological sustainability, Butzer argues that regional agrosystems in the Mediterranean were inherently more vulnerable to social than to environmental disruption (*contra* e.g., Chew 2001, Redman 1999).

Butzer makes a salient point that "degradation" is an ill-defined term, particularly for the Mediterranean world. He notes that many observers, from the classical writers to the present, have described ruined agrarian landscapes in the region (see also Grove and Rackham 2001: Chapter 1). Because of problems in determining cause and effect relationships, they have attributed ecological destruction to numerous agents, including climate change, populations of semi-nomadic pastoralists, the growth of intensive agriculture, warfare and abandonment, or to the existence of state-level polities themselves. At the same time, the region has supported productive agriculture and pastoralism for at least eight millennia and continues to do so today, leading him to suggest that many disturbances should be considered transformations as opposed to degradation. The key issue, then, is determining when the inevitable anthropogenic and climatic disturbances qualify as significant ecological damage

Butzer proposes two measurable indications that disturbance has progressed to the point where it reasonably can be considered degradation. The first is the long-term conversion of woodland ecosystems to degraded scrubland (phrygana, from the Greek, in his terminology; also garrigue [French], tomillares [Spanish], matagal [Portuguese], and broadly similar to chaparral or desert scrub in the American west). This can be measured through pollen cores, as he recounts for the case study from Greece. Importantly, the pollen core not only traces the change to scrubland, but also establishes the pre-Neolithic – inferred to be before significant anthropogenic disturbance – presence of a woodland biome in the Greek study area.

[30] Although he criticizes world systems theory, Butzer's argument to this point generally parallels those of world systems theorists who have considered pre-industrial systems (e.g., Peregrine 2000, with references).

Butzer terms the second indication of significant ecological damage "soil, slope and stream disequilibrium" (2005: 1786). Some amount of erosion occurs in virtually every terrestrial setting and under almost any land use system. There are, however, thresholds beyond which erosion changes the nature of the hillslope and fluvial geomorphic systems by altering the patterns of runoff following storm events and by increasing sediment loads. The ensuing geomorphic disequilibrium can persist for centuries. The crossing of these thresholds of disequilibrium at a regional scale can be identified when a major river with a meandering channel morphology, typical in the Mediterranean setting, becomes a braided stream due to dramatic increases in sediment load. This occurred in one of his case studies from Greece.

It is somewhat more difficult to determine whether biotic and geomorphic transformations qualify as ecological damage at smaller scales. Studies of sediments and soils on slopes paired with investigations of fluvial stratigraphy are necessary to generate insights into the timing, extent, and ecological impacts of past erosion. Where that erosion is severe enough to reduce the productive potential of the landscape significantly for a period of time on the order of centuries, it qualifies as an ecological "crash" (*ibid.*: 1795). Butzer also notes that the formation of dense, deep gully networks is highly detrimental to agriculture, implying that the presence of such networks would indicate significant ecological damage.

Butzer emphasizes that thresholds of disequilibrium are determined by local conditions such as topography, soil types, bedrock geology, and others. In addition, human activities destabilize the landscape in various ways, but major geomorphic change usually is triggered by extreme precipitation events. Finally, crossing these thresholds leads to immediate changes in the fluvial system, but it also can cause secondary disequilibria and cascading feedbacks (i.e., Schumm's [1977] complex response) as the geomorphic system continually adjusts to new conditions over the course of the following centuries. Because of these attributes, detailed long-term reconstructions of landscape change based on empirical research in small study areas are necessary in order to understand the state of the system at any one time in the past or present.

Butzer's case studies provide examples of local and regional reconstructions of human activities and ecological change. As noted above, he presents palynological data

from Greece showing the long-term degradation of woodlands to phrygana. He also discusses the conversion of a major river, the Alpheios, to a braided channel over the course of a 1200 year cycle of disturbance and disequilibrium. Importantly, in each case he compares geomorphic studies from multiple areas in order to differentiate anthropogenic impacts from erosion caused by climate shifts. Comparing the geomorphic, archaeological, and historical data, he concludes that ecological degradation in the study areas in Greece initially was related to the spread of farming, particularly to steep upland areas. All subsequent cycles of erosion and degradation, however, appear to be closely associated with periods of political unrest when large portions of the landscape were depopulated and terrace systems, orchards, and vineyards were left to decay.

In his case study from the Sierra de Espanán in eastern Spain, Butzer considers whether significant ecological degradation can be attributed to agropastoral exploitation of upland areas during the Islamic period (locally 711 – 1242 CE). He begins with an ethnographic and ethnohistoric study of the Christian village of Aín from 1612 CE to the present. He documents a shared community ethic of ecologically responsible agrarian production and chronicles numerous local adjustments to changes in regional and global markets. He notes that, despite the necessary adjustments to changing conditions, "there has been no discernible soil erosion since the 17th Century" and concludes that the community exemplifies "a traditional, practicable sustainability, closely tailored to a fragile Mediterranean environment" (1790).

Moving farther back in time, Butzer combines data from geomorphic studies and archaeological excavations to trace a local history of phases of landscape stability and disequilibria since the Neolithic. He suggests that there was an important episode of hillslope erosion and disruption of the fluvial system during the Chalcolithic, a second during the Late Bronze Age and a third related to the Islamic period expansion of settlements in the area. Pollen and macrobotanical data suggest significant changes in plant communities linked to each of these episodes. Butzer presents geomorphic, stratigraphic, and pedological data from hillslopes, from the floodplain of the axial stream draining the mountains, and from the coastal floodplains of two additional large rivers in the region, building a strong case for his three cycles of disequilibrium.

Differences in the timing of landscape change in the mountains and along the coastal floodplains are associated with different settlement histories in each area, strongly suggesting that the disequilibrium during the Islamic period was anthropogenic. Data from excavations at two montane Muslim fortresses, along with the geomorphic data, show that significant degradation did not begin in the sierra until the later Islamic period, after approximately 1100 CE. Major transformations of vegetation communities occurred primarily after the Christian *reconquista* in 1242 and in particular during the 16th century when there was widespread deforestation. Butzer suggests that settlement of upland areas was sparse prior to approximately 1000 CE, and that erosion was localized and relatively minor prior to the *reconquista*. From this, he concludes that the Muslim agropastoral system was not, in and of itself, ecologically destructive.

Having documented a cycle of erosion and disequilibrium in the Sierra de Espadán associated with the Islamic period while rejecting the idea that it was directly associated with a specific agropastoral land use pattern, Butzer highlights the importance of humanistic research in attempting to unravel the cause(s) of ecological degradation. He asserts that Islamic Iberia shared and, in fact, was instrumental in translating, developing, and dispersing, the tradition of ecologically responsible Mediterranean agriculture that originated with the agronomic literature of the Greeks and continued in the Latin and Arabic literature (see also Butzer 1994); the cycle of disequilibrium cannot be attributed to perceptions of or attitudes towards the environment that were peculiar to the Moors in Iberia.

Drawing on documentary evidence, Butzer traces the history of the Muslim communities in the sierra from the *reconquista* to their final expulsion in 1609. He chronicles repeated food stress, exorbitant taxation, and chronic political instability due to conflicts with Christians. These conditions undermined community solidarity and subverted the ethos of ecologically responsible production. Ultimately, the Muslim population focused on short-term maximization in the face of insecurity, triggering widespread ecological degradation. Butzer concludes that fear, insecurity, and disruption of rural communities are the common threads in the cases of ecological degradation recounted in his case studies in Greece and Spain.

Butzer's work highlights several important theoretical and methodological advances in reconstructing human-landscape interactions. It is explicitly cross-disciplinary, incorporating contributions from archaeology, paleoethnobotany, palynology, geomorphology, hydrology, history, ethnography, sociology, and others. He creates a useful conceptual distinction between biophysical and humanistic research. The first is directed at determining the impacts of human activities in the past and the history of changes to the landscape and ecology. Humanistic research, on the other hand, is more interpretive, focused on the roles of human perceptions and attitudes in determining why people made the choices that they did. In addition, the realization that socio-natural systems are truly complex and historical leads directly to his emphasis on detailed, empirical research in relatively small areas and his rejection of generalizing models.

Methodologically, Butzer implicitly recognizes that comparing historical trajectories of human activity and landscape change in multiple areas is a useful way of isolating anthropogenic impacts on the environment. He creates sound criteria for identifying when human and climatic disturbance to the biophysical landscape can be considered degradation. Finally, he includes investigations of hillslope soils and sediments alongside stratigraphic studies of fluvial deposits in stream systems of various sizes. This multi-scalar inductive approach to investigating geomorphic change in several settings provides a solid basis for elucidating when and where erosion occurred and the degree to which it was detrimental to production.

Of the research in Iberia considered here, Butzer's is the most sophisticated in terms of reconstructing with some degree of certainty the history of ecological change in circumscribed areas and the complicated environmental and human causes of that change. He does, however, document a significant pulse of erosion at approximately 1100 CE that cannot be explained by friction between ruling Christians and conquered Muslims. In addition, he provides few details concerning soils and the history of erosion and deposition in upland environments. Finally, his interpretations of the causes of ecological degradation run the risk of romanticizing rural communities by assuming *a priori* that their activities cannot be detrimental without some outside influence.

Each of the geoarchaeological studies summarized above contributes something valuable to the current study of long term human-environment interactions. The work of

Thornes and Gilman identifies the importance of vegetation, channel formation, hillslope processes, and extreme precipitation events in landscape change. The work by Castro and colleagues is exemplary in its presentation of the "socio" portion of the socio-natural system, with detailed reconstructions of demographic change, land use patterns, human impacts on vegetation communities, and the dynamics of local interactions with regional polities. Weaknesses in the two studies highlight the importance of detailed empirical investigations of landscape change with a particular emphasis on chronological control. Barton and his collaborators focused on the different but related question of how landscape change affects the archaeological record itself; this is, if anything, a more basic question that must be considered before any attempts are made to reconstruct aspects of human-environment interactions from that record. Finally, Butzer's work also illuminates the importance of detailed empirical research in circumscribed areas. Geomorphic and pedological research in upland environments is crucial to identifying ecological degradation. He also emphasizes a multi-disciplinary approach to untangling the complex causes of ecological change.

Previous Geomorphic Research – Southern Portugal

As with geoarchaeological studies of the Islamic period, there are as yet no published geomorphic investigations of long-term landscape evolution in the Alentejo region of Portugal. Chester and James (1991, 1999) have, however, investigated the fluvial stratigraphy of river systems in the adjacent Algarve region. Their research is relevant because of geographic proximity and because agricultural and pastoral practices have been similar in the two regions at least since the Roman era. In addition, the bedrock geology is comparable in both areas and some of the river systems studied by Chester and James, including the Guadiana, drain the Alentejo. Some of the sediments deposited along the floodplains of rivers in the Algarve likely originated in and around the study area.

In their 1991 article, and in more detail in the 1999 publication, Chester and James argue that significant erosion in the Algarve region during the later Holocene has been caused primarily by human activity. They use stratigraphic and pedological data from the floodplains of several rivers along the south coast of Portugal to identify widespread upper and lower fills analogous to those of Vita-Finzi. Radiocarbon dates

and, occasionally, diagnostic artifacts allow them to estimate the ages of these units and to identify correlations between different river valleys. Their data suggest that the upper fill was deposited during the late Pleistocene and early Holocene prior to 7400 BP. After a period of landscape stability, renewed hillslope erosion led to floodplain deposition after 3000 BP. Major erosive events during the later Roman and Islamic periods created the extensive lower fill and made many rivers too shallow for navigation by oceangoing vessels.

After presenting the evidence for two cycles of deposition (and inferred upland erosion) during the latest Pleistocene and Holocene, the authors compare the timing of floodplain deposition to patterns of occupation and land use inferred primarily from historical sources. They attribute hillslope erosion and valley alluviation prior to 7400 BP to climatic change at the end of the Pleistocene. They suggest that the apparent landscape stability from 7400 to 3000 BP was due to the growth of pine and oak forests on the hillslopes, associated with what they call "stable brown topsoils" (1999: 177). Beginning with the introduction of the Mediterranean agrosystem at approximately 3000 BP, they suggest that anthropogenic influences became increasingly important, overshadowing landscape responses to climate fluctuations. Although the lower fill is approximately contemporaneous throughout the Algarve, they argue against Vita-Finzi's conclusion that analogous deposits are present throughout the circum-Mediterranean region. Therefore, they infer that hillslope erosion was not due to regional climate change. Chester and James suggest that the lower fill in the Algarve was deposited because timber harvesting and land clearance for agriculture caused massive hillslope erosion during the Roman and Islamic periods.

Farther to the north, recent research conducted near Lisboa (Lisbon) has revealed similar patterns in the timing of alluviation in the lower Tejo (Tagus) river valley[31]. There are significant differences between southern Portugal and the Tagus river drainage basin in terms of bedrock geology, river valley and adjacent bathymetric morphology, climate patterns, and other variables. While these imply that the recent studies are probably less relevant to understanding the history of the Alentejo region than the work

[31] The authors of these articles use Portuguese place name rather than the anglicized versions.

of Chester and James, the studies nonetheless do help to provide insight into human impacts on the landscape at a larger scale.

Vis *et al.* (2008) suggest that rapid sea level rise between ~20,000 and 7000 BP caused deposition of alluvium within the lower Tagus valley. Since the stabilization of sea level at approximately 7000 BP, rates of deposition have been driven primarily by changes in sediment supply. Van der Schriek *et al.* (2007) attribute increased alluviation after 2200 BP to human activity. Similarly, Vis *et al.* (2008) document a threefold increase in sedimentation rates beginning at approximately 1000 BP. They note, "From the Middle Ages and mainly from ~ 1000 cal PB onwards, natural vegetation virtually disappeared and grazing, burning, agriculture and deforestation increased dramatically, leading to the disappearance of forests and strong erosion of soils" (p. 1706). That the dramatic increase in rates of alluviation began during the Islamic period suggests that the patterns of land use and soil erosion inferred for the southern portion of Portugal also affected the Tagus drainage in central Portugal and east to the central meseta of Spain. During the Islamic period, human activity seems to have become a more important factor than differences in the physical environment in determining the trajectory of landscape change in the two areas.

After the Christian *reconquista*, southern Portugal (including the Alentejo and the Algarve, but not the Tagus drainage) went into a severe economic decline. The alleviation of human pressure on the landscape allowed hillslopes to restabilize. Chester and James note that erosion, as measured by deposition on the floodplains of large river systems, was minimal from the end of the Islamic period until the Salazar regime attempted to modernize the area beginning in the 1930's. The ministry of agriculture encouraged commercial forestry and launched the *campanha do trigo* (wheat campaign) to promote extensive dryland hillslope farming, which caused rapid, widespread erosion[32]. The 1999 Chester and James article concludes with a consideration of the attributes of the region that make it particularly sensitive to human impacts, specifically the high slope angles and the high erosion potential of the thin soils and the

[32] The first campaign promoting cereal cultivation actually occurred in 1899 (Salgueiro 1987: 66 – 67, cited in Dinsmore 1994: 47)

metasedimentary bedrock. These are characteristics common to both the Algarve and the Alentejo.

These articles present valuable data generated during long-term programs of research, and their inferences regarding regional processes appear reasonably secure. Their data remain, however, somewhat coarse-grained. Rather than documenting specific cycles of erosion associated with specific land use patterns, they have identified periods of centuries or millennia in which erosion or stability were generally dominant and correlated these with generalized sketches of land use (i.e. Mediterranean agrosystem vs. scattered Neolithic farmsteads). Little archaeological research has been conducted and published (at least in English) that would allow the authors to explore more fully the human aspects of the socio-natural system. In a few instances, Chester and James in particular note the presence of charcoal and artifacts that likely originated on archaeological sites within strata indicative of erosion. This association is the only part of their argument that uses specifically archaeological evidence. As they recognize, their arguments regarding causation remain largely dependent on temporal correlation (Chester and James 1991: 83). Their data do, however, suggest that regional erosion during the late Roman or Islamic period was significant enough to qualify as degradation according to Butzer's (2005) soil, slope, and stream disequilibrium criteria.

The current research does not imply a rejection of the work of the geomorphologists working in the region. As the authors hoped, their research "provide[s] a framework for subsequent archaeological and historical studies" (Chester and James 1999: 170). This study is intended to build on their research in several ways, primarily by approaching similar questions at finer spatial and temporal scales. The information generated in the current study hopefully will allow a more detailed exploration of the long term recursive interactions between humans and the landscape in the study area.

The Problem of Climate

Although their work is not focused explicitly on paleoclimate reconstructions, geomorphologists working in central and southern Portugal argue that climate change has not been a significant driver of large scale landscape change during the past two to three thousand years at the very least (Chester and James 1991, 1999; van der Schreik *et al.* 2007; Vis *et al.* 2008). Similarly, Stevenson and Harrison (1992) assert that climate

patterns have been stable in adjacent parts of Spain for more than two millennia. Grove and Rackham (2001: 145 – 150) suggest that the climate in Iberia and across the Mediterranean has been stable within modern parameters for well over 2000 years. Gilman and Thornes (1985) and Delano-Smith (1979) conclude that climate change has been minimal in Iberia since the advent of the Neolithic some 6000 years ago. Castro *et al.* (2000) suggest that climate shifts probably have not impacted the landscape in any significant way for at least three millennia, and Butzer (2005) asserts that erosion in Iberia during and after the Islamic period cannot be attributed to climate change.

Despite the general agreement that climate change has not been significant enough to cause regional landscape change at least since the Roman era, it is possible that minor changes in rainfall, effective moisture (precipitation minus evapotranspiration), or the frequency of extreme precipitation events impacted the landscape in the study area in important ways. This is particularly true of locations where human activities had already increased susceptibility to erosion (Thornes and Gilman 1983; see also van der Leeuw 2000 on the concept of "fragilization"). Ideally, it would be possible to investigate the potential contributions of climate change by reconstructing the paleoclimate and paleoecology of the study area in detail. This could be accomplished using dendroclimatology, micro- and macro-botanical remains, the remains of other biota or, for more general reconstructions, relevant sea core data or paleoclimate modeling.

Publications concerning the potential of tree rings to provide high-resolution data about past climates go back at least to the early 19th century (e.g., Twining 1833). A. E. Douglass, however, generally is credited with recognizing in the early decades of the 20th century that studies of tree rings could lead to both long-term records of climate variation and a dating method for wood recovered from archaeological contexts (Bradley 1999: 397 – 438 provides a useful overview of history and techniques with numerous references). A century of research now has shown that tree ring studies are exceptionally useful for fine-grained investigations of past precipitation, temperature, hydrology, and geomorphic change, in addition to archaeological chronology.

In the 1970's, Stockton (1975) compared recorded flows in the Colorado River to tree ring widths in samples from sites within its drainage basin. He then developed a statistical method for reconstructing stream flow back to 1564 C.E. using the longest tree

ring series for the basin. Building on this work, scientists at the Arizona State Museum developed techniques that allowed them to reconstruct flows in the Salt River by statistically comparing recorded flows, tree ring widths from sites within the drainage basin, and tree ring series that came from other drainage basins in the region and extended over longer time periods (Nials *et al.* 1989, Graybill 1989). The implication of this pioneering work is that it should be possible to generate long-term reconstructions of climatic parameters such as rainfall in any relatively small region, provided that there are relevant local instrumental data, a local tree ring record covering at least several decades and based on trees sensitive to that parameter, and that a long-term tree ring record is available for a location within the region that experienced a similar climate regime.

In order to pursue this line of investigation, tree ring samples were collected from Mediterranean oaks (*Quercus spp.*) in the study area[33] and a source of instrumental data on temperature and rainfall was identified in the nearby town of Beja. Finding an appropriate long-term tree ring record useful for reconstructing past climate in the study area proved more problematic. No tree ring series have been published for the country of Portugal (all tree ring data are from the International Tree Ring Data Bank, NOAA 2008). Due primarily to deforestation during the early modern period, there are to date no tree ring series from Spain that extend back beyond 1485 C.E. For similar reasons, no series from Italy cover the period before 1441 C.E. Two series from France cover more than the past 1000 years: the Bourgogne 29 Master series (Lambert *et al.* 2008) and the Les Merveilles Mixed Source (Live and Dead) series (Serre-Bachet 2008). There are, however, significant problems with using either of these long-term tree ring series from France to create a climate reconstruction for the study area.

The Bourgogne series was created from oaks (*Quercus spp.*) and includes the years 618 – 1991 C.E. The time depth and use of the same genus make it seem a likely candidate for statistical correlation with a modern tree ring series from the study area. The Bourgogne series was, however, built using trees that grew in central France near the town of Roanne, more than 1300 km from the study area. Instrumental data for Roanne

[33] As an aside, these trees produce exceptionally hard wood and two increment borers broke during collection of only four samples. The remaining 10 samples were collected using a bow saw and several quickly-dulled blades to cut wedges out of down, dead oaks. There was no shortage of blood, sweat and bile in the process. Special thanks are due to Erin Hudson for assistance with this part of the fieldwork.

covering the period of 1851 – 1973 C.E. (WorldClimate 2008) show that the area is dominated by the continental climate regime, with warm, wet summers and cold, dry winters. The majority of precipitation falls in the summer months. This climate regime is dramatically different from that in the study area where the typical Mediterranean climate prevails: hot, dry summers, mild, wet winters and virtually all precipitation during the winter months.

While the different climate regimes pose serious problems for correlating the Bourgogne series with that in the study area, they probably are not insurmountable in and of themselves; very general patterns of climate change might be revealed for the study area by a statistical correlation. There is, however, an additional and significant problem: Roanne today is to the north of the average boundary between the Mediterranean and continental air masses, but that boundary has moved northward across central France several times in the past few thousand years (Crumley 1994b; see also Lamb 1965). The boundary moved significantly northward during the Medieval Climate Optimum (approximately 10th to 14th Centuries C.E.), allowing large vineyards to flourish and produce wine as far north as southern England and Wales. Very likely the Roanne area was at least strongly influenced by the Mediterranean climate during that period. The statistical transfer function that would be used to reconstruct the climate in the study area from the Bourgogne series is necessarily based on current conditions and would be unreliable for reconstructing climate during periods when different average conditions prevailed in either area. The climate reconstruction, then, would be the least reliable for precisely the time period that is of interest in this study.

The Les Merveilles series was created from European Larch (*Latrix decidua*) and includes the years 988 – 1974 C.E. The sample site is more than 1400 km from the study area, near the village of Lieuche along the French border with Italy. A more significant problem than the distance is that the sample site is at an elevation of more than 800 m in the Maritime Alps, in a high valley surrounded by peaks that reach more than 2000 m. That *département* of France is relatively sparsely populated away from the coast, and an extensive search did not reveal any long-term (~ 100 years) instrumental climate records anywhere in France within 100 km and at a similar elevation. Climate data covering 1961 – 1990 are available for the town of Cuneo, located in Italy, 60 km to the northeast

and at an elevation of 720 m. The data show a bimodal distribution pattern in precipitation, with the majority occurring in spring and fall (EuroWeather 2008). This pattern is corroborated by summaries of the climate in the area of Lieuche published in the travel literature.

The Les Merveilles series therefore poses two major problems. First, modern climate data show that the area experiences a montane climate regime, with substantial snowfall in the winter months. As with the Bourgogne series, modern differences in climate suggest that the series is likely to provide a poor predictor of climate changes in the study area; a few cm of snowfall in Mértola are talked about enthusiastically for years by local residents. Second, because of the differences in elevation and climate, the tree ring records themselves reflect different climate parameters in the two areas. In the study area, water availability is the main natural stressor impacting tree growth and therefore ring width. In the wetter mountains of southeast France, snowfall and snowmelt significantly alter the seasonal availability of water. The length and severity of winter cold are stressors that are likely to significantly impact ring width there. The Bourgogne and Les Merveilles series are therefore inadequate to create a dendroclimatological reconstruction of past conditions in the study area[34]. If a more appropriate comparative series is published in the future, it might be possible to build a high-resolution reconstruction of the climate in the study area using the collected samples.

Based on a long-term tree ring series from Finland, Helama *et al.* (2009) have argued that the late 12th and early 13th Centuries C.E. were characterized by a prolonged dry period – a "megadrought" – in Northern Europe. In addition, by comparing their evidence to data sets from Western North America, Peru, and Eastern Africa, they suggest that their megadrought was part of a temporary worldwide shift in climate patterns related to the El Niño – Southern Oscillation (ENSO) system in the Pacific Ocean. The implications of this climate shift for southern Iberia, however, remain opaque. Southern Iberia, including the study area, is located in the Mediterranean climate zone. Helama *et al.* rely almost exclusively on data generated in the northern parts of Europe to reconstruct the climate there; it is dominated by a continental climate. Their

[34] For the same reasons, the master chronologies based on German and Irish oaks are not useful for the current study.

data are consistent with Crumley's (1994b) and Lamb's (1965) characterizations of the Medieval Climate Anomaly (also the Medieval Warm Period) as a period during which the boundary between the Mediterranean and Continental air masses moved northward, bringing drier summers and wetter winters to Northern Europe.

The authors do not, however, present data that necessarily imply desiccation in the Mediterranean region or in the study area. Lamb's classic study of the Medieval Warm Period is restricted to "Europe between about 45 and 55° N, from Ireland to Russia" (1965:19), and his few passing references to southern Europe and North Africa suggest that the Mediterranean world was, if anything, wetter on average during that interval (see also Lamb 1995: 182 – 185). Similarly, the only mention of Iberia made by Helama and colleagues is a reference to a paleoflood analysis that documented increased winter precipitation in the Tagus drainage in what is now central Spain during the period between 1160 and 1210 C.E. (G. Benito *et al.* 2003).

Beyond tree rings, other types of botanical remains are potential sources of information frequently used by archaeologists to infer past climatic conditions. Initially developed as a tool for correlating stratified lacustrine and terrestrial deposits, palynology has played a major role in paleoenvironmental studies for over a century (see overviews in Bradley 1999: 357 – 396, Dincauze 2000: 343 – 362, Rapp and Hill 1998: 90 – 92). While lacking the temporal precision of dendroclimatology, studies of pollen from dated contexts are used widely to provide insight into past plant communities in an area or region.

Pollen data can reveal climate shifts, for example by documenting the appearance or disappearance of certain indicator species that have relatively narrow climatic tolerances. Palynological studies also can provide a great deal of insight into human impacts on the environment by showing relative increases or decreases in tree cover or crop plants and weedy species associated with agriculture or other significant changes in the pollen rain; isolating climatic and anthropogenic factors remains a challenge in palynological studies. Important developments in the past several decades include more sophisticated quantification techniques and an increasing awareness of the physical and ecological parameters that affect pollen rain and therefore the number of pollen grains of different types recovered from sediment samples. These parameters include pollen grain

size, average travel distance, resistance to decay, and the variable quantities of pollen produced by different plants, among others. Recognition of the importance of pollen grain size and average travel distance in particular are improving awareness of the spatial resolution of change revealed by changes in the abundance of pollen produced by different genera.

Pollen tends to be best preserved in anaerobic waterlogged environments or in extremely dry sediments, but most grains are surprisingly resistant to decay in a wide range of conditions. In a pilot study conducted during the summer of 2003, sediment samples were collected from several locations in the study area for pollen analyses. Sampled loci included layered floodplain deposits as well as sediments adjacent to small springs that likely have remained wet at least for the majority of the past several hundred years. The samples were submitted to Dr. Vaughn Bryant at Texas A&M for analyses. Unfortunately, none of the eight samples yielded enough preserved grains to indicate that a statistically valid sample of the pollen rain was preserved and recoverable. The apparent rapid degradation of pollen in the study area is attributable to seasonal variability in precipitation; the annual alternation between wet winters and dry summers causes repeated wetting and drying of sediments, the single condition most likely to lead to decay of the pollen grains (Bryant and Hall 1993). The generally alkaline soils probably also contribute to poor preservation (Dincauze 2000: 346).

Several pollen studies have been completed in montane settings in western Iberia and in low-lying marshes or lagoons in protected locations along the Atlantic coast (Janssen 1994 summarizes palynological studies in the region). Although chronological control is almost universally poor, these investigations reveal a regional pattern of significant anthropogenic impacts on plant communities beginning as much as 3000 to 6000 years BP, associated with the megalithic bronze age and iron age cultures that practiced the first large scale agriculture in the region. More dramatic changes in vegetation are documented for the Roman era, followed by a period of forest regeneration coinciding with the Late Roman period. Finally, the pollen data suggest that “natural” vegetation virtually disappeared during the Islamic and Christian Medieval periods, replaced by plant communities reflecting agriculture, pastoralism, and widespread

ecological transformation. Importantly, none of the authors attribute changes in vegetation after the mid-Holocene (~ 7000 – 5000 BP) to changes in climate.

The most intensive pollen research, yielding by far the best-dated sequences for the region, has been conducted in the Serra da Estrela of north-central Portugal. Glacial cirques at elevations between 1400 and 1900 masl contain lakes, ponds, and bogs from which multiple cores have been taken and analyzed (Van den Brink and Janssen 1985, Van der Knapp and Van Leeuwen 1995). The results generally mirror those for the region, but reflect a particular emphasis on pastoralism at the high elevations. Specifically, the research documents the establishment of oak (*Quercus spp.*) forests during the early Holocene, following the amelioration of glacial conditions. Minor changes in pollen spectra appear to track minor climate shifts for several thousand years. By approximately 7000 BP, there is weak evidence for scattered grazing and possibly cultivation of cereals in the region. The authors note rapid sedimentation before approximately 8000 BP, presumably related to landscape adjustment to post-glacial climate conditions.

Van der Knapp and Van Leeuwen (1995: 191) suggest that increasing anthropogenic impacts permanently overshadow climate shifts by the beginning of their pollen zone C at circa 5670 BP, when there is increased evidence for grazing and small scale deforestation. For roughly the next four millennia, the pollen data show increasing human activity resulting in large-scale deforestation by about 3200 BP, along with growing indications of overgrazing and soil erosion and some evidence for episodic changes in emphasis on agriculture vs. pastoralism. Deforestation increased significantly during the Roman era, coincident with the introduction of *Castanea sativa* (chestnut) and increases in *Olea europea* (olive). The late Roman era saw a regeneration of the forests and reduced cultivation and grazing in the Serra da Estrela. Van der Knapp and Van Leeuwen (1995: 202) identify their pollen zone E, beginning circa 955 BP, as "Anthropogenic forest destruction and landscape degradation… [with] irreversible destruction of forests, heathlands, and soils, resulting in present-day's barren landscape… natural forests virtually disappeared, and organic soils were for the greater part eroded and washed away." The authors of the studies suggest near-complete replacement of the

original mid-Holocene montane woodland by degraded heath some time between 1050 and 850 BP.

In concert with the other pollen studies in the region, the data from the Serra da Estrela suggest a general trajectory of increasing anthropogenic impacts on plant communities during the past 3000 – 4000 years, with relatively brief periods of forest regeneration before and after the Roman era. This trend culminated during the Islamic period in the appearance of plant communities the composition of which was almost completely determined by human activities. No study suggests that these changes were driven by climate shifts. The Serra da Estrela, however, are over 300 km north of the study area and well over 1000 meters higher in elevation. Only a few types of arboreal pollen (notably *Pinus spp.*) travel sufficient distances to provide insights into vegetation changes more than a few 10's of km from the center of the mountain range (Van der Knapp and Van Leeuwen 1995: 169). The three pollen sequences recovered closer to the Alentejo are all poorly dated and in lagoon settings more than 100 km from the study area where coastal flora dominate the pollen diagrams. These pollen data provide only very general insight into changes in plant communities at a significant distance from the locations of the studies themselves and they do not provide the resolution necessary for identifying decadal-scale changes in plant communities or climate in the study area during the Islamic period.

Phytoliths, microscopic structures present in plants and usually consisting of opaline silica, are another potential source of information about past plant communities (Dincauze 2000: 362 – 365 and Rapp and Hill 1998: 93 – 95 provide overviews). Phytoliths appear to be resistant to decay in a wide range of environments and many can be identified at least at the genus level. In addition, they are not as susceptible as pollen to problems of wind transport; in general phytoliths are deposited where a plant decays and they therefore provide a more direct window on local plant communities. Because the phytoliths are so small, assemblages tend to be affected by bioturbation and other post-depositional mixing processes, but statistical analyses offer a means of reconstructing general trends in vegetation change through time at a particular site (Grave and Kealhoffer 1999).

There are several drawbacks to using phytolith analyses in this study. To date, phytoliths mostly have been used to identify the presence of specific plants at individual sites or in particular contexts (e.g., in garden sediments, adhering to tooth enamel, or on ground stone tools). There have been few, if any, attempts to reconstruct regional changes in plant communities from phytolith data and protocols for doing so have not been established. In addition, contexts with deep, well-stratified deposits dating to the period of interest are rare in the study area, exacerbating problems associated with bioturbation. At present, phytolith studies are not well established, they are expensive, and they generally are considered most useful in concert with pollen studies. Given these problems, no attempt was made to recover or study phytoliths. In the future, such studies carried out at individual sites may provide some insight into the changing ways people used plants in the past.

Like the microscopic remains, macrobotanical remains can reveal something of the suite of plants present in a given area in the past (see overviews in Dincauze 2000: 332 – 343, Rapp and Hill 1998: 92 – 93). Partial burning increases the likelihood that plant remains, particularly wood and seeds, will be preserved. The resulting charcoal fragments can be identified, often to the genus or species level, providing a window on the suite of plants present. Radiocarbon dating of the same materials offers a convenient way to constrain the age of an assemblage. The presence or absence of certain indicator species may provide some insight into past climate change. In general, however, assemblages recovered from archaeological contexts represent a biased sample of the plant communities on the nearby landscape; the plants at the site are primarily those collected and brought there by the occupants. Changes in assemblages through time, then, usually reveal at least as much about human activity as they do about climate shifts.

As discussed above (Chapter 3), Dr. Boone organized a study of macrobotanical remains recovered from several Late Roman/ Transitional and Islamic period sites he excavated in the study area (Carrión 2006). The results reveal significant changes through time in the proportions of different types of plants recovered from sites. The suite of plants, however, remains constant, suggesting that any climate changes that may have occurred during the Late Roman and Islamic periods were not severe enough by themselves to impact significantly the composition of local plant communities. Carrión's

data for the most part appear to reflect changing human impacts on those plant communities, including progressive deforestation and possibly the emergence of a managed woodland.

In order to add to the macrobotanical data from archaeological sites, and to produce samples perhaps more representative of the local plant communities, several attempts were made to recover charred plant remains from non-site contexts during the present study. A total of 180 liters of sediment from 2 soil test pits and 3 fluvial study units was collected and processed by flotation. Although sampling loci were chosen based on the presence of visible charcoal fragments and dark staining of the strata, only one locus (1992 survey area, Fluvial Study Unit 5) produced more than a gram of charred organic material. None produced an assemblage that would have rewarded further study.

The final proxy indicator of past climate conditions in the study area that profitably could be analyzed is faunal remains of various types. Dr. Boone's research has shown, however, that osseous materials are poorly preserved in the alkaline soils of the region; human skeletal material generally is preserved only where individuals are interred in crypts or cysts excavated into bedrock and covered with stone slabs. There is little probability that the remains of indicator species such as small mammals with relatively narrow environmental tolerances could be recovered from dated deposits. Because they are affected differently by soil chemistry, and because many species survive only in relatively narrow ecological conditions, the remains of insects and snails might provide some insight into past climate conditions (Bradley 1999: 348 – 354, Reitz and Wing 1999:307 – 312). If appropriate deep, stratified contexts were encountered, and if the remains were preserved, this might be a productive avenue for future research.

For the present, then, no commonly used proxy records are available that allow for a detailed reconstruction of climate change in the study area during the past two millennia. Absent those records, it is possible to gain some more general insight into the regional paleoclimate using sea floor coring. Abrantes and colleagues (2005) recently published a detailed analysis of marine sediment cores recovered from shallow, near-shore contexts at the mouth of the Tagus River near Lisbon. They correlated cores taken at four locations using nine accelerator mass spectrometer (AMS) radiocarbon dates, 18 analyses of lead isotope (^{210}Pb) activity, and hundreds of measurements of magnetic

susceptibility and then analyzed a range of proxy indicators of past climate parameters in each core.

In addition to identifying deposits associated with the Lisbon earthquake of 1755 C.E., Abrantes and colleagues generated high resolution (approximately decadal scale[35]) reconstructions of sea surface temperature (SST). They also produced proxy measures of variability in discharge from the Tagus River and biological productivity related to changing relationships between upwelling and river discharge at the same resolution. Their composite record covers most of the past two millennia. They suggest that their data show regional climate change (i.e. at the scale of the Tagus River basin) related to changes in the North Atlantic Oscillation (NAO) index. In general, their data suggest "dryer [sic] continental conditions and increased coastal upwelling conditions during MWP, and indicate increased river influx and river induced marine productivity during LIA" (Abrantes *et al.* 2005: 2491). In other words, they contend that conditions were generally warmer and drier from roughly 550 to 1300 C.E. (the Medieval Warm Period, also called the Medieval Climate Optimum or Medieval Climate Anomaly; the time range more commonly used is ca. 950 – 1250 C.E.) and then cooler and wetter from about 1300 to 1900 (the Little Ice Age; the time range more commonly used is ca. 1550 – 1850 C.E.). Given its proximity to the Tagus River basin, it seems reasonable to assume that the paleoclimate reconstruction derived by Abrantes and colleagues provides a useful proxy for changes in the study area.

Looking more closely at the data they present, there are several observations that indicate finer-grained variability within that general pattern that potentially is important here. The sea surface temperatures they calculated from alkenones extracted from foraminifera reflect mainly winter to early spring temperatures, and show "a rise to 18 °C at 630 AD. After this date, SST decreases to ~ 17 °C at 1080 AD. A period of relatively stable temperatures (17 °C) between 1060 and 1200 AD is followed by a minimum at 1365 AD and a new rapid and sharp decrease of 2 °C to ~ 15 °C by 1600 AD" (Abrantes *et al.* 2005: 2485, see also their figures 7 and 9 – 11). This suggests a minor change in conditions in the late 11th century.

[35] Although most of their figures show data points by decade, dating uncertainties, sediment mixing, the resolution of their magnetic susceptibility measurements, and other potential sources of error suggest that some caution is warranted in interpretation.

The data also show significant increases in iron content, and the "mud" (silt + clay) fraction in the sediments beginning at approximately 1080 and in magnetic susceptibility beginning at roughly 1140 (Abrantes *et al.* 2005: figure 9). These changes reflect increased deposition of terrestrial sediments carried by the Tagus River. Although the authors emphasize the more significant changes between the aggregated records from the MWP vs. the LIA, these data suggest increased flows in the Tagus, again hinting at a shift to a slightly wetter climate in the late 11th to 12th centuries. There were not, however, pronounced, patterned changes in marine productivity (abundance of foraminifera) or the abundance of freshwater diatoms (*ibid.* figure 10) or particularly large decreases in salinity (as calculated from oxygen isotopes extracted from foraminifera; *ibid.* figure 11) at the same time.

Interestingly, the time lag between increased sediment supply and changes in marine productivity and salinity imply that suspended sediment load in the Tagus River increased more rapidly than total discharge. In other words, during this earlier phase of somewhat increased flows the river was relatively muddier than during the LIA when increased sediment supply was coupled with consistently higher flows. This, in turn, implies relatively high rates of erosion in the drainage basin beginning in the 11th to 12th centuries. While it does not bear directly on erosion in the study area (i.e., in the drainage of the Rio Guadiana), it may indicate regional landscape change in response to minor climate change, widespread changes in land use patterns, or some combination of the two.

Although it is much less sensitive as an indicator of local conditions, another means of reconstructing regional climate changes is through computer generated models (Bradley 1999: 471 – 505 provides a useful overview with references). General circulation models (GCMs, also called global climate models) have been developed that track changes in climate in "cells" of varying spatial resolution based on simulations of atmospheric and oceanic circulation. Where possible, these models are calibrated against paleoclimate proxy data sets such as glacial ice cores, sea floor cores, corals, and tree ring series. The resulting calibrated models show the locations of major air masses, fronts, and oceanic currents – the climate drivers – and their movements through time since the last glacial maximum or longer. The models can be calibrated further for a particular

area by comparing the movements of the regional climate drivers to an instrumental record of climate; such a model is presented below. It is based on a grid spacing (cell size) of somewhat less than 2° latitude by 2° longitude, or less than about 200 km by 200 km, with the cell centered on Beja. It therefore covers roughly the southern 1/3 of Portugal. The resulting data also are fairly coarse-grained temporally, tracking changes at the scale of centuries, but they do provide insight into general trends.

As noted in the introductory chapter, rainfall in the study area is highly variable from year to year. It also is likely that there have been decadal-scale fluctuations in total rainfall during the past millennia, and changes at those scales are not detected in GCM-based reconstructions. As shown in figures 5.1 and 5.2, the regional scale paleoclimate model does not suggest major changes in total rainfall at the scale of centuries during the Islamic period.

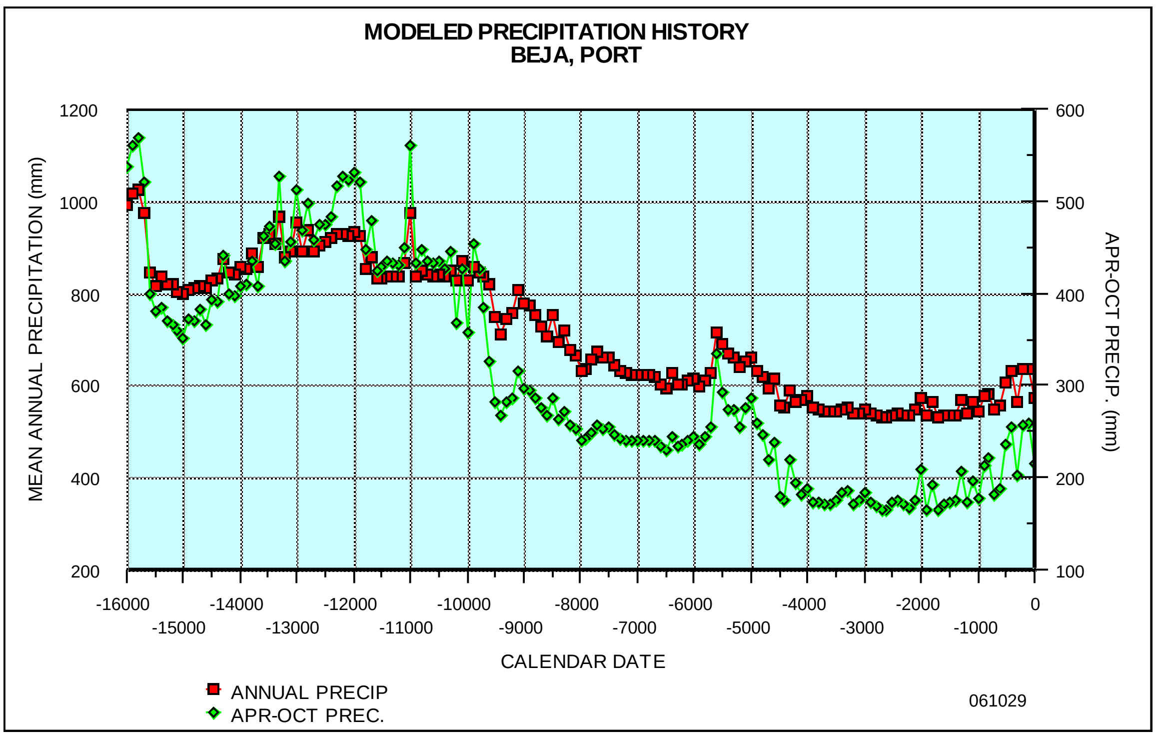

Figure 5.1: Modeled precipitation history in the study area for the past 16 millennia based on Global Circulation Models and instrumental data from Beja, Portugal (Courtesy of Dr. R. Bryson)

The reconstructed average annual precipitation during the 8th through the 14th Centuries fluctuates between approximately 550 and 590 mm/ yr. and it consistently is slightly below the average annual potential evapotranspiration. This is a far smaller

fluctuation than the average variability from year to year during the period for which records are available. During the water years 1925 – 1994, the average annual rainfall was 567 mm, with a standard deviation of 164.3 mm. The range of variability during the same period was significantly larger, with recorded annual precipitation varying from 207 to 972 mm. Given the relatively small differences in average rainfall between centuries and the much larger differences from year to year, it seems reasonable to suggest that the GCM reconstruction does not indicate conditions significantly different from those that pertain today.

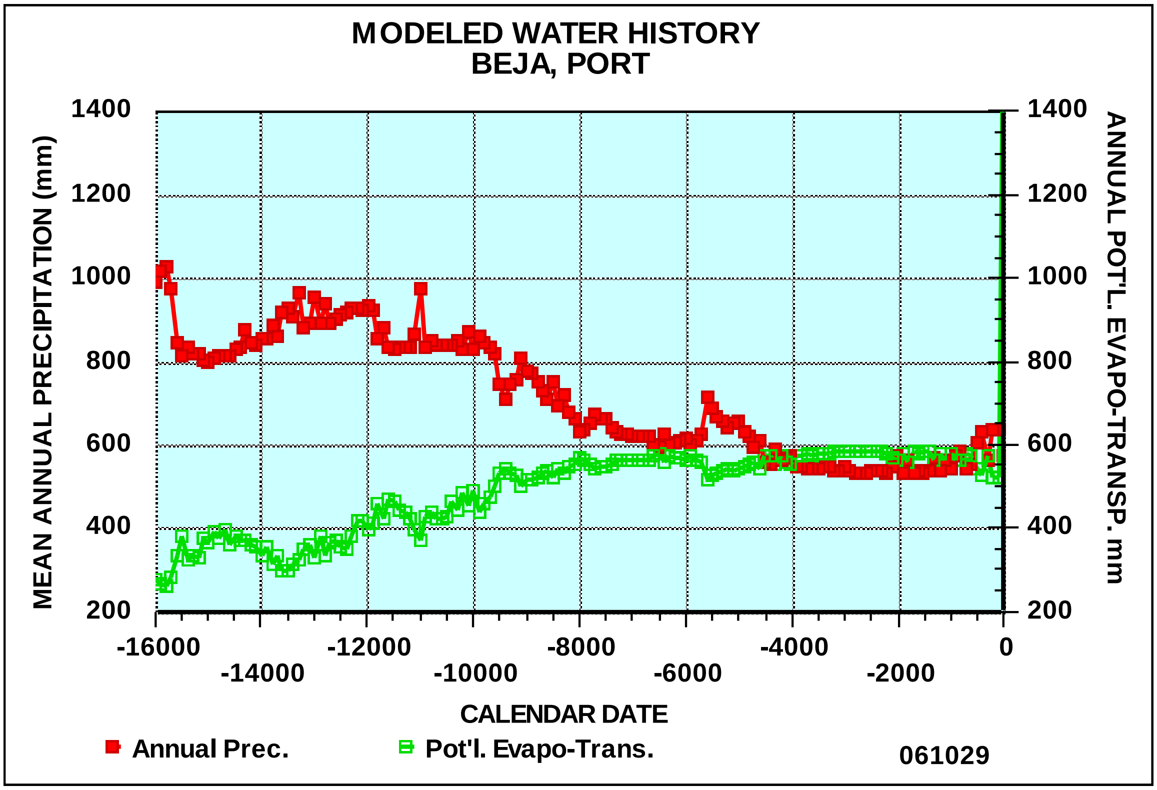

Figure 5.2: Modeled water history in the study area for the past 16 millennia based on Global Circulation Models and instrumental data from Beja, Portugal (Courtesy of Dr. R. Bryson)

Total rainfall, however, is not the only important parameter determining erosive force on hillslopes, stream discharge, or the ability of fluvial systems to move sediments. The timing of precipitation and severity of storms also are significant (e.g., Bull 1991, Ely 1997), and rare, large events can dramatically impact landscapes (e.g., Thornes and Gilman 1983; see also Klemes 1989 on rare events). The climate model does suggest a

slight increase in total precipitation and in summer rainfall, in particular in the 12th and 13th centuries relative to the preceding and succeeding centuries. Given the typical timing of rainfall in the study area, most of the summer rain probably fell in the late spring months (April – June). The majority of large storms associated with flooding in the study area are caused by winter precipitation, but it is possible that large storm events were more common overall during those centuries, increasing the potential for erosion in the study area. Paleoflood analyses are one way to identify the relative frequency of large storm events in the past.

Although paleoflood analyses have not been done in the study area, and climate models do not have the resolution to detect individual events, paleoflood analyses based on dated fluvial deposits from locations across Spain including the upper reaches of the Tagus and Guadiana rivers suggest increases in flood frequency and intensity at 2850 – 2500, 1000 – 800, and 520 – 250 cal. BP (Thorndycraft and Benito 2006; see also Uribelarrea and Benito 2008 for a detailed study of the Guadalquivir at Córdoba). The pattern implies that there may have been unusually large or numerous precipitation events during those periods, one of which corresponds to the later Islamic period.

Comparisons of the distribution of dates for slackwater flood deposits to the distribution of dates for alluvial sequences, however, shows increased overall alluviation beginning during the Roman period and continuing through the period of low flood frequencies in the 14th and 15th Centuries CE. Although flood events undoubtedly are important, total alluviation is a more reasonable proxy for the total amount of soil entering the fluvial system, in turn a better proxy measure of soil erosion. In addition, the authors note that anthropogenic erosion and deforestation likely contributed to increased flood frequency and severity for at least the latest two periods of increased flooding. Based on these observations, they conclude that erosion and alluviation have primarily been caused by human activities and not extreme precipitation events since the Roman era or before, although they acknowledge the need for additional data.

Similarly, an analysis of historical records from sites along the Tagus River indicates a period of increased flooding in the late 12th and early 13th Centuries C.E. (G. Benito *et al.* 2003; Lamb 1995: 163 also documents increased flood frequency in Italy from 1150 – 1300 C.E.). The authors identify seven periods of severe flooding recorded

during the past millennium in various historical documents. The first of these, reflected in only 3% of those documents, encompasses the period from 1160 – 1210 C.E., with particularly large floods recorded between 1168 and 1207. They suggest that the floods were caused by heavy winter rainfall, and their comparison to other large Iberian rivers[36] implies a period of increased winter precipitation between approximately 1150 and 1300 C.E. They suggest that large storm events during the late 12th and early 13th Centuries might be related to larger-scale climate shifts between the Medieval Climate Anomaly and the Little Ice Age. Working in the American Southwest, Ely (1997) also found that extreme storm events and the resulting floods clustered in transition periods, when the climate at large scales was shifting between periods generally characterized as wetter, drier, warmer, or cooler. Taken together, the data imply that large storms might have become more common in Iberia as early as the 11th and through the 12th and 13th centuries, at the beginning of a larger climate shift.

Although suggestive of possible climate change and perhaps an increase in the frequency of large storms, there are some problems in applying the paleoflood data to the study area. Specifically, floods on the larger rivers are caused primarily by extreme precipitation events in the mountainous headwaters which are both far from the study area and for the most part outside the area typically dominated by Mediterranean weather patterns. Whether those storms could have triggered hillslope erosion in the study area is questionable, particularly as isopleths maps of rainfall intensity across Iberia based on the highest recorded rainfall in one hour and in any 24 hour period show the study area in the lowest and second-lowest categories, respectively (Grove and Rackham 2001: Fig. 2.7). Outside of the deeply-incised valley of the Rio Guadiana, which represents a miniscule proportion of the study area, it seems unlikely that significant landscape change there can be attributed specifically to the storm events that caused the historically recorded floods.

Fortunately, a proxy measure currently is being developed that has the potential to provide data concerning effective moisture in the past at relatively high spatial and temporal resolutions, and one of the first applications of the technique is to samples from the study area (Drake *et al.* n.d.). Building from the observation that in arid environments water stress affects the rate at which plants discriminate against ^{13}C during

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[36] Notably absent are any references to the Rio Guadiana.

photosynthesis ($\Delta^{13}C$), Drake and colleagues reasoned that the ratio of ^{13}C to ^{12}C in plant material ($\delta^{13}C$) reflects water stress on the plant. Using known atmospheric concentrations of ^{13}C and fractionation rates related to the chemistry of photosynthesis, it is possible to compute the value of $\Delta^{13}C$ from $\delta^{13}C$. Moreover, $\delta^{13}C$ values routinely are reported with radiocarbon assays, providing a trove of potential paleoclimate data.

Drake and colleagues then used reconstructed past values of atmospheric $\delta^{13}C$ to calculate $\Delta^{13}C$ values for 41 samples of radiocarbon dated burned plant material from archaeological sites in Mértola and the area surveyed by Boone in 1992. By comparing the $\Delta^{13}C$ values to the observed ranges of $\Delta^{13}C$ values in modern plants of the three genera most common in the archaeobotanical assemblage analyzed by Carrión (2006; i.e., *Cistus, Quercus,* and *Olea*), they reconstruct a history of increased and decreased water stress in plants in the study area that covers the past 1500 years. Clusters of lower and higher $\Delta^{13}C$ values reflect more and less water stress, indicating drier and wetter conditions, respectively. They note a cluster of lower $\Delta^{13}C$ values in the period from 1029 – 1106 AD, half of them falling within the range of minimum $\Delta^{13}C$ values observed for living *Olea, Quercus,* and *Cistus* plants during drought conditions. The authors suggest that this is evidence for an extended dry period in the study area bracketed by periods where conditions were, on average, more mesic.

The technique pioneered by Drake and colleagues is ingenious and shows great promise for future paleoclimatology studies. Their results strongly suggest drought in the study area during the 11th and early 12th centuries followed by a return to more mesic conditions. The work is not, however, entirely without problems. One that they note is that their samples had not been identified taxonomically prior to the radiocarbon assays. Different species exhibit different ranges of $\Delta^{13}C$ values in wet and dry conditions; some of the patterning they perceive in the data may be driven by variability between species. However, because $\Delta^{13}C$ values in *Olea, Quercus,* and *Cistus* all have been shown to respond to changes in available moisture, because those genera dominate the archaeobotanical assemblages, and because the $\Delta^{13}C$ values fall within an overlapping range during drought conditions, this probably is not a major problem in this particular case. A second problem is that water stress in plants is an indirect measure of precipitation. Water stress can be triggered by competition between plants, by soil loss,

or by other conditions; work presented in the following chapters indicates severe and widespread erosion in the study area during the period they identify as a drought. Beyond including samples identified prior to the radiocarbon assays, both of these problems could be ameliorated by repeating the analysis with a greater number of samples in order to reduce the influence of outliers and to reduce statistical uncertainties. Drake and colleagues hopefully will expand on their research in that and other ways in the future.

Numerous proxies and models suggest that the Medieval Warm Period was, on average, warmer and somewhat drier than current conditions across much of Europe. Data from sea cores recovered near Lisbon suggest that this was the case in central and southern Portugal as well. Within that generally warmer period, however, the sea core data, climate models, paleoflood analyses, and the radiocarbon-derived $\Delta^{13}C$ values all point toward a shift to wetter conditions and hint at increased storm frequency in the study area in the 12th century. The sea core data also imply a contemporaneous increase in erosion, and general principles of geomorphology suggest that the transition to a wetter climate after an extended period of aridity initially will be accompanied by increased erosion before the density of plants on the landscape increases (e.g., Bull 1991). Even though none of these analyses is conclusive on its own merits, that each one detects changes of the same type at approximately the same time implies that increased precipitation and/ or extreme weather events could have contributed to soil erosion and arroyo formation in the study area during the later Islamic period.

Summary and Overview of Research

The geoarchaeological research presented here builds on the techniques and perspectives developed in the studies cited above. The majority of the author's work focuses on determining when and how the landscape changed in the study area in the past and whether those changes were anthropogenic. The study considers human activities and geomorphic change at the landscape scale, specifically focusing on low-order stream systems and small drainage basins in two areas in which systematic archaeological surveys and previous excavations have been completed.

The geomorphologic component of the research combines two complementary approaches to determining the history of landscape change. First, stratified fluvial

deposits were examined and recorded in order to determine the geographic extent and timing of significant episodes of erosion in the past. Second, detailed studies of the soils and sediments on and at the base of hillslopes were completed to ascertain the severity of past erosion and to provide additional data relevant to determining the timing of those landscape changes. Bringing together these studies from different geomorphic contexts allows each to inform the other, creating stronger inferences regarding landscape change. In addition, it facilitates a historical reconstruction of landscape evolution based on an understanding of geomorphic processes.

Beyond generating empirical evidence concerning the nature and timing of landscape change, the research reported here includes a comparison of two areas with different histories of occupation and land use. The climate, biotic communities and topography are comparable in the areas. In addition, the 1992 survey area and the southern half of the 2004 – 05 survey area are similar in terms of bedrock geology (Oliveira 1989) and soil types (SRAO 1959). This comparison, then, provides one line of evidence relevant to determining whether any documented environmental changes can be attributed by human activities. In addition, archaeological and macrobotanical data from the study area, in the context of the paleoclimatic data that are available for the region, provide the foundation for parallel arguments concerning whether landscape change during the Islamic period was anthropogenic.

Butzer's (2005) work suggests that the causes of ecological change are complicated; answers to the question of why the biophysical landscape changed can be sought at levels deeper than simply identifying the different contributions of human activities and changes in external conditions. After documenting the history of landscape change in the study area, relevant historical and archaeological data are employed to examine changes in land use and to identify the probable reasons for those changes, which ultimately played a decisive role in determining the observed trajectory of change in the socio-natural system.

Chapter 6:
Geoarchaeological Methods

The geoarchaeological research reported here was designed with two related goals in mind: elucidating the history of landscape change in the two surveyed areas and generating the data necessary to determine whether those changes can be attributed to human activities. Geological fieldwork was conducted to identify evidence for past episodes of hillslope erosion, floodplain deposition, and channel formation and to constrain the timing of past landscape change. Changes through time in agrarian land use are inferred from archaeological data generated by pedestrian surveys and previous excavations. Temporal correlations of changes in land use with episodes of erosion suggest that past landscape change may be anthropogenic. In addition, contrasts between the histories of landscape change in the two surveyed areas, where settlement density and land use patterns were different in the past, provide additional information relevant to linking environmental change to human activities.

The geomorphic component of this research combines complementary investigations in floodplain and upland contexts in order to reconstruct the timing, extent, and severity of past erosion in the study area. Increases in the extensive cultivation of wheat and other cereal crops led to significant erosion throughout the Alentejo region during the 20th century. In recent decades, and especially since tractors came into common use for cultivating hillslopes in the 1980s, this ongoing erosion has caused the formation of incised ephemeral stream channels (arroyos) that expose stratified floodplain deposits throughout much of the study area. These floodplain strata are easily accessible for study and record a history of episodes of hillslope erosion, floodplain deposition, relative landscape stability, and channel formation that can be illuminated through careful interpretation. Included artifacts, soil-stratigraphic relationships, radiocarbon dated charcoal, and optically stimulated luminescence (OSL) dating of sediments provide means of chronological control. In addition to constraining the timing of landscape change, the fluvial stratigraphic studies generate insight into the areal extent of past erosion.

Inferred histories of landscape change based solely on fluvial data are, however, arguably incomplete. Studies of hillslope deposits and soils address several lacunae. The information they produce is important for interpreting fluvial stratigraphy correctly. In addition, unlike studies in fluvial contexts where strata indirectly reflect the movement of water and sediments through the drainage basin, examination of upland deposits illuminates the history of erosion on individual hillslopes. Hillslope studies directly demonstrate the severity and geographic extent of erosion in the past; by investigating the setting where a significant proportion of human activities occur, they can yield additional insights into human-landscape interactions. Finally, by applying the same suite of chronometric techniques employed in fluvial contexts, studies of hillslope deposits can provide additional data relevant to constraining the timing of landscape change in the past. A detailed reconstruction of the timing and trajectory of landscape change is a necessary prerequisite to building strong arguments regarding whether that landscape change was anthropogenic. The studies in both fluvial and upland contexts can be divided into three phases: choosing loci for study, completing and interpreting formal in-field soil-stratigraphic descriptions, and conducting additional laboratory analyses.

Sample Loci

Prior to choosing locations for formal pedostratigraphic (soil-stratigraphic) descriptions, it was necessary to obtain a basic knowledge of the overall landscape context and the range of variability in landforms and fluvial systems in the study area. For the 1992 survey area, this was accomplished through reconnaissance with Dr. Boone, who had gained an intimate knowledge of the landscape during the systematic pedestrian survey. At the beginning of the 2003 field season we visited numerous loci throughout the surveyed area and made preliminary observations. For the 2004 – 05 survey area, the author made preliminary observations and identified potential loci for formal soil descriptions during the pedestrian archaeological survey.

In addition, soil and geologic maps provided baseline information concerning which parts of the surveyed areas were most similar and were therefore likely to yield comparable information concerning landscape evolution. The bedrock in the 1992 survey area is mapped as the Mértola formation, part of a larger group classified as the flysch of the Lower Alentejo. The Mértola formation includes turbidites (greywackes, siltites, and

pellites) and conglomerates. The bedrock in the southern portion of the 2004 – 05 survey area, north of an area of folding and volcanic intrusions, is dominated by the Gafo formation, also consisting of turbidites (pellites, grawackes, and silicious siltites) with some red schist and metavolcanics. In the northern portion of that survey area, the bedrock transitions to the Atalaia formation, quartzowackes, arenites and filites, and then to the Pulo do Lobo formation, filites and quartzites with extruded quartz and rare acidic metavolcanics and metabasalts (Oliveira 1989; translated from the Portuguese).

Almost all of the soils across the 1992 survey area are classified as unsuitable for agriculture with limitations due to erosion and surface scouring. More specifically, they are characterized as lithosols or skeletal soils forming on schist or greywacke, as thin, brown Mediterranean soils[37], and as areas of bedrock outcrops of schist or greywacke. Small pockets of more productive soils are present, most of which are listed as having agricultural limitations in the root zone (presumably soil depth) or due to erosion. Average slope angles for the mapped soil types vary from 3 to 25%.

Similarly, soils in the 2004 – 05 survey area are classified as unsuitable or poorly suited to agriculture with limitations due to erosion and surface scouring or limitations in the root zone. The southern portion of the 2004 – 05 survey area, corresponding to the portion with turbidite bedrock, is dominated by soils that are described in the same ways as those in the 1992 survey area: thin, brown Mediterranean soils and lithosols or skeletal soils forming on schist or greywacke, with some small areas of bedrock outcrops of schist or greywacke. To the north, thin red or yellow Mediterranean soils and lithosols or skeletal soils forming on schist or greywacke are common. The few small areas of better soils in the 2004 – 05 survey area are mostly present in the southern portion and these also are limited by depth and/ or erosion. Average slope angles are similar to those in the 1992 survey area, with the exception of a few steeper areas (> 25%) near the river at the eastern border of the 2004 – 05 survey area (SRAO 1959 maps 46B and 46C; translated from the Portuguese). Because the soil and geological maps show the greatest similarities between the 1992 survey area and the southern half of the 2004 – 05 survey area, all but one of the catenary (hillslope) studies in the 2004 – 05 survey area were

[37] Butzer (1994: 31 – 32) tentatively identifies the brown Mediterranean soils as haploxeralfs or xerocrepts in the USDA soil taxonomy nomenclature. He suggests that the red soils (terras rosas) probably are rhodoxeralfs.

conducted in the southern portion. All of the fluvial study units were in the southern area with similar soils or immediately to the north in the transitional zone.

Locations for formal soil-stratigraphic descriptions in fluvial contexts were selected for their potential to produce several kinds of relevant data. Modern channels had to cut through visibly stratified deposits that appeared broadly representative of the fluvial stratigraphy in each surveyed area. In addition, the majority of the profiles were situated near archaeological sites in order to maximize the likelihood of encountering temporally diagnostic artifacts and other dateable materials eroded from settlement areas. A final consideration in selecting study loci was the desire to focus primarily on small drainage basins, with catchments of less than one km^2, in order to minimize some of the interpretive problems created by complex response[38]. Essentially, complex response should be less significant and interpretation more straightforward where the stream system interacts directly with more hillslope deposits and fewer redeposited floodplain materials, as would be expected at higher elevations in the system.

Loci for catenary studies were selected judgmentally based on several criteria. As was the case for studies of floodplain deposits, a basic knowledge of the overall landscape was necessary in order to identify locations that were likely to be representative of hillslope deposits in the surveyed areas. Proximity to sites was desirable for a portion of the sample in order to increase the likelihood of recovering temporally diagnostic artifacts and other dateable materials. Two of the hillslope studies in the 1992 survey area and one in the 2004 – 05 survey area were undertaken on slopes immediately below hilltop archaeological sites. One of the hillslopes in the 2004 – 05 survey area was located adjacent to and above an archaeological site. The remaining study loci were chosen to provide a sample of slopes with different aspects. They also were located at varying distances from archaeological sites so that they could provide insight into the geographic extent of landscape change in the past. The variable distance from sites should minimize the bias that would be introduced by examining only loci adjacent to settlements, where any localized anthropogenic erosion that occurred during the occupation of those sites likely would be most severe. Once locations were selected for study, soil test pits were excavated in the five geomorphic sections of the slope in

[38] The problem of complex response is considered in detail in the next chapter.

order to characterize the variability of deposits along that slope. The five sections are the summit, shoulder, backslope, foot of the slope, and toe of the slope (Birkeland 1999: 231, Holliday 2004: 25).

Field Observations

At each study location, the author described the strata and soils using standard field techniques (Birkeland 1999: Appendix 1, 347 – 359; Buol *et al.* 1997; Soil Survey Division Staff 1975, 1993, 1999[39]). Each profile was excavated to bedrock or, for several of the hillslope soil test pits, several 10s of cm into deposits that clearly were decomposing bedrock and soil parent material. The face of each profile was cleaned with a trowel. Strata were identified visually and by comparing the color and structure of peds removed from the profile at different depths. The following characteristics of each stratum were evaluated in the field and recorded: color, structure, consistence, texture, clay films, carbonate accumulation, boundary characteristics, and the presence, abundance, size, and orientation of clasts. Boundary morphology and the size and orientation of larger clasts were evaluated visually while sediments were *in situ* in the profile. Carbonate accumulation was measured by testing reactivity to a 10% solution of hydrochloric acid (HCl) applied to the vertical column.

Sediments removed from each stratum were placed in a 2 mm soil sieve. The author examined peds (natural soil aggregates) macroscopically to characterize structure and used a 10x hand lens to aid in the identification and description of clay films. After evaluating dry consistence, the remaining peds were crushed through the soil screen. The gravel content was estimated by comparing the amount of screened sediment to the clasts remaining in the sieve. The size and degree of rounding of those clasts were recorded. Color was measured by comparing a sample of dry, screened sediments to a Munsell Soil Color Chart (1994). Finally, the texture class of the soil was estimated by wetting a sample of screened sediments and observing characteristics such as stickiness, plasticity, grittiness, etc. While many of these observations (especially color) potentially can be

[39] *The Field Book for Describing and Sampling Soils* edited by Schoenberger *et al.* (2002) also provides a useful guide to field techniques. It was unavailable when I started fieldwork, so was not used here. The changes it makes to nomenclature and recording conventions are minor and not highly relevant here.

affected by inter-observer error, the author completed all of the formal soil descriptions for this research; the observations should be comparable between sample loci.

The depth and thickness of each stratum and/ or soil horizon were measured and recorded. In addition, the location(s) and type(s) of any artifacts present were noted. In cases where artifact type was not readily discernable, samples were collected and types and time ranges were determined in consultation with Dr. Boone or Dr. Gómez of the Campo Arqueológico de Mértola. Where visible, charcoal was collected from appropriate strata for radiocarbon dating. Finally, each profile was photographed and their locations were measured and recorded with a handheld GPS unit (Garmin GPSmap 76S) using the averaging function and a minimum of 300 individual observations. For the hillslope soil test pits, the slope and aspect were measured with a Silva Ranger CL compass.

Laboratory Studies

The final phase of these investigations consisted of laboratory analyses conducted on soil samples from the study area in order to constrain the ages of deposits. Radiocarbon dating of organic materials included in strata provides one type of age estimate for those deposits. Magnetic susceptibility measurements yield a proxy measure of the degree of soil development in different profiles and, combined with other indicators of pedogenic alteration, strengthen inferences concerning the ages of deposits as well as histories of erosion and deposition. Finally, optically stimulated luminescence (OSL) dating provides an estimate of the amount of time that has passed since sediments were exposed to light. OSL analyses have the potential to yield the most direct evidence for the timing of erosion and deposition in the past.

Radiocarbon Dating

Radiocarbon (^{14}C) dating has been applied to archaeological problems for more than half a century. There is no need to review the technique itself here, to discuss technical advances during recent decades or to describe the various nuances of calibration. Adequate overviews are provided in most archaeology textbooks (e.g., Renfrew and Bahn 2000) and the journal *Radiocarbon* covers technical advances and the

many nuances of arriving at age estimates in great detail. This section describes sampling methods used in this study.

Initially, visible fragments of charcoal were collected while conducting field descriptions of profiles. This strategy yielded only one datable sample, from Fluvial Profile 5 in the 1992 survey area. This was from the densest concentration of redeposited charcoal encountered during the study. Because the majority of the research concerning landscape change was not conducted on archaeological sites, no hearths or other features containing dateable organic materials were encountered *in situ.* All of the remaining samples were recovered from strata that appeared to be stained by dispersed charcoal and in which small flecks of charcoal often were visible. Given the size of charcoal fragments and the proximity of many of the charcoal-rich deposits to the modern ground surface, these are not ideal conditions for the application of radiocarbon dating.

Aside from the piece of charcoal collected from Fluvial Profile 5, all additional samples were recovered by flotation, which facilitated retrieval of very small fragments of organic material. After appropriate strata were identified, 15 – 30 liters of sediments were excavated from each stratum and placed in 5 – 10 sealed plastic bags[40]. The bags were transported to the laboratory facilities at the Campo Arqueológico de Mértola where organic materials were recovered from each aliquot by flotation. The contents of each bag were emptied into a 25 liter bucket that was then filled with water. After a few minutes of mechanical agitation, the water and floating organic materials were decanted through a screen of mosquito netting. The materials were dried in the netting and sorted manually to separate charcoal from rootlets, insects, and other obviously recent organic materials.

Fragments of charcoal were examined under a binocular microscope to confirm that they were plant material, and weighed on an enclosed scale. Fragments weighing approximately 5 mg., the mass listed as optimal by the Arizona AMS Facility, were selected for assays. Four fragments from fluvial contexts were submitted for accelerator mass spectrometry (AMS) radiocarbon dating at that facility. Two were from the OSL profile adjacent to fluvial study unit 3, and one each were from fluvial profiles 5 and 7,

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[40] The quantity of sediment collected for flotation was determined judgmentally in the field, based on the degree of soil staining and quantity of charcoal visible. All sampled strata yielded datable fragments of charred organic material.

all in the 1992 survey area. Two fragments from hillslope deposits also were submitted, both from the OSL test pit at the base of the slope at Alcaria Longa.

Magnetic Susceptibility

Magnetic susceptibility is one of a suite of measurable magnetic properties of soils, sediments, and rocks that has been used to study a wide variety of phenomena in the earth sciences. Of these techniques, measurements of remanent magnetization are perhaps the most well known. These are familiar to many archaeologists because they are the basis of archaeomagnetic dating. Remanent magnetization refers to the irreversible magnetic “memory” of ferrimagnetic mineral grains that were aligned with earth’s magnetic field at the time heated sediments cooled and solidified. By measuring the direction of remanent magnetism in an oriented sample, it is possible to determine the direction of the geomagnetic field at that moment in the past.

The same magnetic memory occurs in rocks where, for example, it accounts for the ability of some naturally occurring magnetite ores (“lodestones”) to function as compasses by aligning with the current geomagnetic field. Studies of remanent magnetization in core samples from ocean floor crust played a prominent role in convincing the geological community of the viability of plate tectonic theory. Similar investigations demonstrated that the polarity of the earth’s magnetic field has reversed numerous times in the past, and researchers continue to work towards mapping movements of the magnetic poles and changes in the intensity of the geomagnetic field through time. A great deal of current geophysical research concerning magnetism in rocks focuses on the mechanisms of magnetization in mineral grains of various sizes and analyses of various types of remagnetization (see Dunlop 1995 for a useful overview).

Unlike remanent magnetization, magnetic susceptibility assays measure the response of an unoriented sample to a magnetic field produced in the laboratory. The measurements reflect the quantity and types of magnetic oxides and hydroxides contained within the sample. Early research into magnetic susceptibility of soils and sediments was conducted by Le Borgne during the 1950s and 1960s. He showed that surface layers of soil were magnetically enhanced by fires and pedogenic processes. The enhancement results in measurably higher levels of magnetic susceptibility, and in the case of many burned anthropogenic deposits the susceptibility may be orders of magnitude greater than

that of the unmodified adjacent or subjacent deposits. Le Borgne recognized the potential for applications to archaeological problems and his work, especially as it applies to archaeology, is summarized in Le Borgne 1965 (see also Dalan and Banerjee 1998 on the history of magnetic susceptibility research applied to archaeology).

Based on his pioneering work, Le Borgne proposed that burning was far more significant than pedogenic processes in increasing the magnetic susceptibility of sediments, thereby focusing early research on archaeological problems. Subsequent work on the magnetic properties of archaeological deposits led to the development of geophysical techniques for use in archaeological prospecting. For example, the recognition that fire alters the magnetic properties of sediments provided a theoretical foundation for the use of magnetometer surveys to locate archaeological features such as hearths or kilns that had been the sites of high-temperature fires in the past. As applications increased it became clear that susceptibility values on and near archaeological sites encompassed an exceptionally broad range of values, prompting Tite and Mullins (1971) to suggest that it was necessary to investigate more thoroughly the processes that control magnetic enhancement. Research undertaken during the 1970s illuminated some of the relationships between magnetic susceptibility and such variables as soil parent material, climate, and organic or anthropogenic inputs (Dalan and Banerjee 1998: 4).

In a seminal article published in *Science* in 1980, Thompson *et al.* demonstrated that studies of susceptibility and other magnetic properties of sediments could be applied to numerous environmental problems. Along with the publication in 1986 of *Environmental Magnetism* by Thompson and Oldfield, the article generally is credited with defining environmental magnetism as a distinct field within the earth sciences (e.g., Verosub and Roberts 1995: 2175). In both publications, the authors emphasized that magnetic parameters can be measured relatively rapidly and inexpensively, providing useful information about the "transformation and movement of magnetic minerals within and between the atmosphere, lithosphere, and hydrosphere… [for] subjects as diverse as meteorology, hydrology, sedimentology, geophysics and ecology" (Thompson *et al.* 1980: 481). They summarized early applications to studies of atmospheric particulate inputs, fire regimes, erosion and anthropogenic landscape change, sourcing fluvial

sediments, correlation of lacustrine deposits, and climate shifts. Curiously, although the authors clearly were aware of the archaeological applications of magnetic studies the definition of the field of environmental magnetism appears to have marked a turning point after which archaeological concerns were significantly less important in determining research agendas (Dalan and Banerjee 1998: 5).

Thompson's publications with his colleagues also created standard terminology and notation and outlined laboratory procedures that have become standard for measuring magnetic susceptibility and related parameters. Magnetic susceptibility (χ) is proportional to the abundance and grain size of ferromagnetic or ferrimagnetic minerals in a sample. It is measured by placing a sample in a weak alternating electrical field (<1 millitesla) with a high frequency on the order of 10 kilohertz and determining the ratio between the induced magnetization in the sample and the strength of the applied field. Additional measurements are used to investigate more completely the size and types of magnetic grains that produce the susceptibility signal. Saturation isothermal remanence magnetization (SIRM in Thompson *et al.* 1980, now frequently referred to more broadly as one component of isothermal remanence magnetism, or IRM; e.g., Verosub and Roberts 1995) uses a magnetometer to measure the magnetization of a sample exposed to a strong (1 tesla) d-c magnetic field. Remanent coercivity (B_{CR}) calculates the strength of the d-c field required to reduce the IRM to zero, completing a full hysteresis loop. The B_{CR} values and ratios of SIRM/ χ can be used to characterize the magnetic assemblage in a sample, aiding in differentiating between hematite and magnetite, and magnetic, paramagnetic, and superparamagnetic grains. These characterizations are particularly useful in studies where the degree of susceptibility in different samples is compared.

More recent research has expanded the suite of laboratory measurements used to characterize the magnetic assemblages in samples. Among other things, these measurements can be used to determine whether a sample includes single domain, pseudo-single domain, and/ or multi-domain magnetic grains, thereby contributing further to determining the mineralogy of the magnetic materials present. Environmental magnetism continues to contribute significantly to many types of research, including correlations between oceanic or lacustrine cores, variations in the intensity of the geomagnetic field in the past, studies of depositional and post-depositional processes,

provenance studies, paleoclimate reconstruction, pedogenesis and diagenesis, biomagnetism and others (see review in Verosub and Roberts 1995).

Research focused specifically on magnetic enhancement of soils and sediments has demonstrated that it is exceptionally complicated. Enhancement of sediments either through pedogenesis or by means of burning is affected by numerous geophysical, geochemical, and biological processes, and anthropogenic inputs add another layer of complexity. Many of the details concerning the processes of pedogenic enhancement are not fully understood, particularly the contributions of biogenic magnetic minerals (Dalan and Banerjee 1998: 5). Despite the unknowns, two points are important here: magnetic enhancement caused by pedogenic processes increases through time, and diagenetic processes can alter the magnetic enhancement of deposits after burial.

It is now recognized that pedogenic enhancement is widespread and that in many environments it can be as significant as fire-related magnetic enhancement. Pedogenic enhancement is caused by the conversion due to organic and inorganic processes of weakly magnetic oxides and hydroxides into more strongly magnetic forms, resulting in the formation *in situ* of fine-grained magnetite or maghemite (*ibid.*, with references; see also Thompson *et al.* 1980: 482). Cycles of oxidation and reduction that occur as soils are repeatedly wetted and dried appear to be significant in the pedogenic formation of the highly magnetic iron compounds. These and other iron compounds typically become adsorbed to clay particles that move downwards through the soil column as colloids. This process often is visible in the rubification of the B horizon, and it increases susceptibility well into the B horizon (Verosub and Roberts 1995: 2184). Magnetic susceptibility measurements in an undisturbed soil, then, tend to peak somewhat below the surface, usually within the uppermost 10 cm, and then fall off to much lower values (e.g., Thompson *et al.* 1980: 483). The enhanced susceptibility of soils has been used to aid in the identification and study of paleosols (see references in Verosub and Roberts 1995: 2184 – 2186) and it has been employed to investigate histories of erosion and deposition in many contexts (e.g., Brown 1992; Dalan and Banerjee 1996; see also Dalan and Banerjee 1998: 15 – 16, with references).

While pedogenic magnetic enhancement is persistent in many environments, the enhanced signal can be altered by diagenetic processes if a soil is buried and subjected to

long-term saturation with groundwater. The saturation creates oxygen reducing conditions in which fine-grained magnetites and other pedogenic magnetic minerals can be converted to pyrite or dissolved (Dalan and Banerjee 1998: 28, Verosub and Roberts 1995: 2187; see also Walker *et al.* 1978: 29). Presumably, dissolved minerals could be flushed from the soil column or reprecipitated at greater depths. Once these diagenetic changes occur, the magnetic enhancement is effectively removed or altered in unpredictable ways and magnetic susceptibility studies will be far less useful for the identification of buried soils or for reconstructing histories of erosion and deposition.

In fluvial contexts in the study area, sediments are saturated with groundwater below a certain depth for a significant portion of each year. Initial studies showed that these conditions are not conducive to the preservation of enhanced magnetic signals in buried soils; the magnetic susceptibility signals that may originally have been present generally are not measurable below the depth of seasonal saturation. Magnetic susceptibility studies in fluvial settings were therefore not particularly informative. The technique was, however, more useful in studying hillslope deposits. Soil samples for magnetic susceptibility studies were collected from test pits on hillslopes throughout the 1992 and 2004 – 05 survey areas. The patterns of change in susceptibility with depth are useful for inferring erosional histories. Also, following Brown (1992), susceptibility studies were focused in particular on sediments at the edge of floodplains and at the base of hillslopes. These loci are the most likely to yield useful information concerning hillslope erosion in the past. In addition, they frequently are located above the zone of groundwater saturation, such that the increased magnetic susceptibility of buried deposits is preserved.

For each soil test pit selected for magnetic susceptibility study, soil samples were collected and transported to the University of New Mexico Earth and Planetary Sciences Paleomagnetic and Rock Magnetic Lab. In the majority of cases, samples were collected at 5 cm depth intervals. In some particularly deep pits, the sampling interval was increased to 10 cm, and in one case the soil profile was sampled by soil horizon. In all cases, samples were collected using plastic trowels and transported in plastic bags or paper bags closed with rubber bands in order to avoid contamination that would be caused by the use of metal tools or staples.

In the lab, each sample was divided into three aliquots and the magnetic susceptibility of each aliquot was measured three times using an ASC Scientific MFK1-FA Kappabridge. The aliquots were weighed to the nearest 0.05 gram on a standard three-beam balance in order to calculate mass susceptibility and the results from each measurement of each aliquot were averaged to estimate the mass susceptibility for each sample. In rare cases where the susceptibility measured for one aliquot was an order of magnitude or more different from the other two aliquots, the outlier was removed before averaging[41]. The averaged susceptibility measurements were then graphed against depth using Microsoft Excel.

Optically Stimulated Luminescence

Optically Stimulated Luminescence (OSL) dating[42] is one of several chronometric methods that measure the time-dependent accumulation of physical changes to minerals induced by environmental radiation. These techniques estimate the timing of initial crystallization or the most recent exposure of minerals to specific energy sources. Fundamentally, they are based on the simple equation $t = ND/NDR$, which states that the time elapsed (t) since the target event is calculated by dividing the natural (or accumulated) dose measured in the sample (ND) by the natural dose rate (NDR). Related methods include fission track, thermoluminescence (TL), and electron spin resonance (ESR, also called electron paramagnetic resonance, EPR) dating.

Although initially developed and applied to archaeological problems less than a decade after the first radiocarbon dating, these techniques continue to be less well known and less frequently used by archaeologists. Many of the technical and conceptual difficulties that plagued early applications have been addressed in recent years, and the costs associated with analyses are beginning to decline. Archaeological applications likely will become more common in coming years. Wagner (1998) and Aitken (1990) provide extensive overviews of these techniques. Aitken (1998) discusses OSL in detail,

[41] In almost every case, repeated measurements on a given aliquot and the mass-corrected averages for multiple aliquots produced readings within a few percent of each other. Significant outliers were noted and removed in only 2 cases out of the 1062 aliquots.

[42] More precisely this is photon-stimulated luminescence dating as techniques that use both infrared radiation and light in wavelengths visible to humans are considered in this discussion. For the sake of simplicity, both are referred to as OSL except where the distinction is important for clarifying methods employed in this study.

Lian and Roberts (2006) provide a summary of recent developments in luminescence dating of sediments, and Roberts (1997) and Feathers (2003) provide overviews of applications in archaeology.

The four related techniques are distinguished from each other by different target events, the datable materials, and how the accumulated dose and natural dose rates are measured. Fission track dating measures the damage created in uranium bearing minerals and volcanic glass when U-238 undergoes spontaneous fission decay and releases high-energy particles. The high-energy particles create damage trails as they move away from the site of decay. These trails are counted in prepared samples using an optical microscope, yielding an estimate of the accumulated dose. The natural dose rate is calculated by determining the uranium content of the sample and from the known initial U-238: U-235 ratio. The technique measures either initial crystallization or the last time the material was heated above the temperature at which the damage tracks anneal, which varies in different materials. Fission track dating is the only one of these techniques that can be used on volcanic glass (obsidian).

Unlike fission track dating, TL, ESR, and OSL estimate accumulated dose by measuring the number of electrons that have been moved out of their original locations in a crystal lattice by ionizing radioactive energy. All crystals have natural defects, places where the actual lattice structure is different from the ideal structure that characterizes the mineral. Vacancies are non-occupied locations where an atom is missing. Substitutions or impurities occur where one element is substituted for another in the lattice or where there is an “extra” atom that occupies an interstitial space. The combination of a vacancy with an impurity or substitution is called a Schottky-Frenkel defect. Defects are most common at tilt boundaries and edge dislocations within crystals.

Defects are characterized by a charge deficit such that they can absorb free charges (electrons) as energy diffuses through the lattice[43]. Defects therefore allow electrons to move to higher-energy metastable states when excited, as described by solid state energy band theory. Essentially, ionizing radiation provides energy that moves an electron from its original location (or valence), creating a free electron plus heat. The free electron then either returns to a lower-energy position (recombines), releasing a

[43] Interestingly, crystal defects are also important in creating remanent magnetism (Dunlop 1995: 2161).

photon, or is held in a positively charged lattice defect called a trap. Occupied traps are called centers, and centers are quasi-stable unless another addition of energy once again frees the electron. Because it is radiation energy that allows electrons to move into centers, the total number of electrons held in traps is proportional to the accumulated dose. The upper limits of ages that can be determined by these methods are dictated by the total number of traps available and by the spontaneous movement of electrons from some traps back to their initial positions at ambient temperatures, called anomalous fading. Neither fading nor saturation of available traps should pose problems at the time scales investigated here.

The environmental dose rate for ESR, TL, and OSL can be calculated in one of two ways. Dosimeters or gamma ray spectrometers can be placed in the locations from which samples were taken. After an extended period of time (typically a year or more), the accumulated dose can be recorded and used to calculate an average natural dose rate. Alternatively, the sediments surrounding the sample can be collected. The natural radioactivity of those sediments and of the sample itself are estimated in the laboratory, typically by using an accelerator mass spectrometer (or, less commonly, neutron activation analysis) to measure the abundance of radioactive elements. Combined with knowledge of geographic location and the depth of burial, which allow for a calculation of the amount of radiation from cosmic rays that has affected the sample, these data are used to calculate a natural dose rate. Although it is more complicated, the second method generally is preferred because age estimates can be delivered more rapidly. Various factors require correction regardless of which technique is used. These include the different distances that different types of ionizing radiation (α, β, γ, and cosmic radiation) can travel through different materials, the history of burial, changes in moisture regime, disequilibria in decay sequences, and diagenetic changes.

Electron spin resonance measures the accumulated dose by applying microwaves and a magnetic field at right angles to each other. Unpaired electrons, those out of their original locations in the lattice, change the direction of their rotation in response to the energy inputs, absorbing some of the microwave energy. The measurable attenuation in the microwave energy is proportional to the number of occupied centers, which in turn is proportional to the time elapsed since initial crystallization. One advantage of ESR is

that the application of energy does not alter the locations of the trapped electrons, so multiple measurements can be taken. In archaeological applications, ESR is used most commonly to estimate the time elapsed since crystallization of hydroxyapatite in teeth and bones. Unfortunately, these materials are particularly susceptible to diagenetic changes that include absorbing environmentally available uranium and other radioactive materials, potentially altering natural dose rates by factors of up to 10^3 (e.g., Edward *et al.* 1984, Edward and Benfer 1993, Sandford 1993; Renfrew and Bahn 2000: 148 – 149 provide a basic overview). Mathematical models of diagenetic change provide a means of addressing this difficulty and arriving at corrected age estimates.

Thermoluminescence and OSL dating measure the accumulated dose by applying energy to a sample and using a photomultiplier to measure the light energy released when trapped electrons return to lower energy states. Luminescence had been observed and described as early as the 16th century, and Robert Boyle conducted experiments on it in the 17th century (Lian and Roberts 2006: 2451). Potential applications to archaeology and geology were enumerated in 1953 by Daniels, Boyd, and Saunders and archaeological applications to ceramics and fired bricks were first reported in 1958 (Grogler *et al.* 1968). Luminescence dating techniques were developed further during the 1960s and 1970s, primarily by Aitken and his colleagues at Oxford.

As the name implies, thermoluminescence stimulates luminescence by applying heat energy to a sample, typically by heating it rapidly to 500^{0} C. The energy input allows trapped electrons to escape the centers they had been occupying and return to their lower-energy valences, releasing photons. Because different traps have different energy thresholds (often referred to as “shallow” and “deep” traps), they are released at different times as heat energy builds up in the sample. Analysis of the light emitted per unit of time produces a glow curve that represents clearing of the different traps. A plateau in the glow curve is considered representative of the number of centers occupied due to exposure to environmental radiation since crystallization or the last heating of the sample. The total amount of energy released during that plateau therefore is proportional to the accumulated dose and is used to calculate an age estimate.

Thermoluminescence measurements clear all of the occupied traps in a sample. The differential energy thresholds of different traps both posed problems and created

opportunities in the development of the technique. In addition to the timing of energy release, the spectra released at different temperatures provide some information about which traps are cleared. Centers that release electrons below 280^0 C were determined to be particularly susceptible to anomalous fading, or the spontaneous emission of the electron and a photon due to the normal kinetic energy in the sample. To avoid this problem, samples typically are preheated to clear these unstable traps before measurements are taken.

While it has been used to date sediments, the most common applications of TL continue to be to dating archaeological ceramics and burned lithic materials. Variants of TL that involve different types of analysis of the glow curve produce estimates of the time elapsed since initial crystallization, since the last heating of a sample to above 300^0 C, or since a sample last was exposed to light. It is attractive for dating ceramics in that it provides a direct estimate of the time elapsed since firing; the target event and the dated event –manufacture and use of a vessel – are essentially the same.

Like heat, light (electromagnetic radiation in visible and near-visible spectra) can provide enough energy to clear shallow traps. The problems this created for dating ceramics or burned lithic artifacts were relatively minor, but it implied that TL potentially could be used to date the burial of sediments if stable shallow traps could be isolated. Experiments showed that the glow produced by quartz grains at 325^0 C was produced by the traps most sensitive to light. Measuring this glow could provide an estimate of the time elapsed since quartz-rich sediments last were exposed to light. Unfortunately, further experimentation showed that exposure to direct sunlight for more than 20 hours did not clear all of these traps. This problem of "partial bleaching" meant that TL produced anomalously old age estimates for many samples. Various techniques were developed by different researchers to address the problems of partial bleaching (reviewed in Lian and Roberts 2006: 2453 – 2456).

Building on this work, Huntley and colleagues began developing optically stimulated luminescence dating. First published in 1985, their work was premised on the idea that the best way to isolate the traps most sensitive to light was to stimulate luminescence with light. By applying light at one wavelength and measuring the luminescence created at another wavelength, it is possible to create a shinedown curve

analogous to a glow curve. Instead of clearing all of the traps and analyzing the glow curve in an attempt to determine which traps previously had been cleared by light energy, OSL targets only those traps sensitive to light.

Applications of OSL have become widespread in geological and geomorphic studies (e.g., Ellwein *et al.* 2011; Eriksson *et al.* 2000; Forman *et al.* 1993; Forman *et al.* 1995; Hanson *et al.* 2004; Lang 1994, 2003; Lian *et al.* 2002; McDonald and McFadden 1994; Stokes 1999; Stokes and Breed 1993; Stokes and Gaylord 1993; see also Lian and Roberts 2006, with references) to the extent that it can be considered "among the most significant chronological tools currently used in Quaternary research" (Lian and Roberts 2006: 2449). In addition to potentially being applicable at ages ranging from a few decades to as much as a million years, OSL targets quartz and feldspars, the two most common minerals on earth; it can be applied in many settings. For geomorphic research, the correspondence between target event and dated event provide obvious advantages. Archaeological applications also are becoming increasingly common (e.g., Bowler *et al.* 2003, Forrest *et al.*2003, Holliday *et al.* 2006, Lang and Wagner 1996; see also Feathers 2003 and Roberts 1997 with references).

Because different materials produce a variety of luminescence signals as multiple traps are cleared, luminescence dating is not yet as standardized as, for example, radiocarbon dating. Different techniques are applicable to different problems in different settings (e.g., Clarke *et al.* 1999; Lang 1994; Wallinga 2002). Broadly speaking, two different OSL techniques that target different minerals commonly are used. One uses visible light in the blue and green spectra to stimulate luminescence in quartz. The second, sometimes referred to as infra-red stimulated luminescence (IRSL), uses infra-red and near-infra-red light to stimulate luminescence in the fine-grained polymineral fraction of sediments, comprised predominantly of feldspars. The two problems that must be addressed in the majority of cases are partial bleaching and post-depositional mixing.

Proponents of IRSL claim that it significantly reduces problems with partial bleaching; one study reported complete bleaching after only 30 minutes of exposure to daylight on a foggy winter day in Germany (Lang and Wagner 1996). In addition, multiple aliquots can be dated and the results compared in order to determine whether

and to what extent partial bleaching may be a problem (e.g., Wagner 1998). Analyses of shinedown curves and normalization of differential sensitivities in multiple aliquots can also provide evidence of partial bleaching for either polymineral or quartz samples (Feathers 2003). IRSL with feldspars produces stronger luminescence signals and saturation is less problematic than in quartz, theoretically allowing for a greater datable time range. On the other hand, anomalous fading is a significantly greater problem in feldspars than in quartz, for reasons that remain obscure (Lian and Roberts 2006).

A recently developed technique builds on the logic of analyzing multiple aliquots and measures induced luminescence in single grains. Initially developed for feldspars (Lamothe *et al.* 1994), this technique has been adapted for grains of quartz (e.g., Murray and Roberts 1997; Olley *et al.* 2004), which typically are larger in most contexts due to their greater resistance to weathering. Comparing the results from dozens or hundreds of grains facilitates the identification of partial bleaching and statistical analyses can be used to correct for it and to generate a calibrated age estimate. Similarly, the distribution of luminescence signals produced by grains from an individual sample can be used to identify deposits significantly affected by post-depositional mixing (Feathers 2003). Also, due to their size, quartz grains can be etched chemically, removing several microns of material from the surface. This reduces some uncertainty in calculating dates because α radiation, although high-energy, does not penetrate beyond a few microns. Eliminating alpha radiation allows for more accurate age estimates because it increases the uniformity of the radiation field relative to the size of the sample.

However it is stimulated, the final step in generating an age estimate from the luminescence measured in samples (called intensity, *i*) involves determining what the luminescence represents in terms of an accumulated dose. As noted above, the intensity of a luminescence signal produced by a sample is proportional to the number of electrons moved into traps by radiation since the target event. To derive an age estimate, it is necessary to determine how much radiation is required to move an equivalent number of electrons into traps in that sample, called the dose equivalent. This dose equivalent is usually measured in Grays (1 Gy = 100 rads).

Two types of approaches have been used to determine dose equivalent. The additive approach measures the additional luminescence created by exposure to known

amounts of radiation in multiple aliquots of a sample. The data are used to construct a curve that is then projected back to the origin to estimate the accumulated dose in aliquots that were not exposed to additional radiation. Because the total number of traps in any sample is finite, this technique is susceptible to problems posed by saturation. In addition, the variable sensitivity of different aliquots to radiation introduces a source of error. Alternatively, the regenerative approach clears the traps in aliquots and then exposes them to increasing amounts of radiation until the initial signal is re-created. This technique is limited by the fact that the sensitivity of samples changes after excitation and eviction of electrons from traps. Also, for both techniques, laboratory exposure to radiation fills traps that are unstable over long periods of time. Samples are therefore preheated to clear these thermally unstable shallow traps. In many cases, the additive and regenerative techniques are used in concert to create a more accurate estimate of the dose equivalent, a process called the slide method.

Experiments by Murray and colleagues (e.g., Murray and Roberts 1998; Murray and Mejdahl 1999; Murray and Wintle 2000) showed that for quartz luminescence, a small dose of radiation applied after an OSL measurement could be used to create a correction factor for the regenerative method. This factor accounts for both the changes in sensitivity with exposure and for the variability in sensitivity between samples. Using these corrections, they pioneered the single aliquot regenerative method (SAR) that currently is considered to yield age estimates with the highest levels of accuracy and precision for quartz samples (Feathers 2003; Lian and Roberts 2006).

Samples

Because exposure to light clears the light-sensitive traps in a sample, OSL samples must be collected and transported to the laboratory in darkness. Different methods for accomplishing this include collecting samples at night, collecting samples under an opaque tarp, collecting blocks of sediment and removing samples from the center in darkness, and collecting samples by driving tubes into sediments. Samples were collected by the final two methods for the research reported here.

Initially, blocks of sediment were collected by excavating around a column measuring roughly 30 cm x 30 cm x a height sufficient to recover samples from the necessary depth. The blocks were then wrapped in several layers of opaque plastic,

marked for orientation, and transported to a closet that had been converted into a dark work space. In the dark work space, sediments were removed from the center of the block at appropriate depths and sealed in light-proof metal canisters. This method required significant extra excavation to extract the column and did not allow for particularly precise measurements of the depth of the sample. The samples labeled "Queimada 'upper'" and "OSA S1 STP5 'upper'" were collected using this method.

All subsequent samples were collected by driving tubes into a vertical face of sediments exposed by excavation. Initially, the profiles were cleaned with a shovel and trowel to expose a fresh face. After completing formal soil descriptions and identifying the strata of interest, tubes were pounded horizontally into the sediments. Clasts and the hardness of the sediments precluded using 8 cm diameter metal flue piping as was initially attempted. After some experimentation, 20 cm lengths of 5 cm diameter galvanized steel pipe were found to be adequate. A plug of rolled denim fabric was placed in the end of the pipe to minimize exposure to light in case the sediments crumbled during collection. An 8 kg sledgehammer then was used to force the steel pipe into the sediments at measured depths.

In order to collect an adequate quantity of sediment, four lengths of pipe were used at the same depth in each stratum. The pipes were then removed by excavation of the sediments around them and sealed with duct tape. Because the cost of shipping the samples to the laboratory in the steel pipes was prohibitive, the samples were taken to the dark work space where the sediments were removed using a chisel, knife, and hammer. A few cm from each end of each pipe were discarded because of the possibility of light contamination, and the remaining sediments were placed in opaque PVC piping, sealed with aluminum foil and duct tape, and shipped to the laboratory for analyses. This technique required slightly less excavation, but the repackaging of sediments was exceptionally labor intensive. It was preferred primarily because it afforded more precise measurement of the depth of sample collection.

In addition to the OSL samples themselves, smaller samples of superjacent and subjacent strata were collected and sealed in plastic bags, to be used to determine background radiation and dose rate. Other samples were sealed in film canisters, to be used for calculating moisture content; the suite of samples is referred to here as a sample

set. Three OSL sample sets were taken from fluvial profile 3, adjacent to the site of Cerro da Loiça. Additional OSL sample sets were taken from exposures of sediments at the base of slopes below the sites of Alcaria Longa (4 sets) and Queimada (3 sets) and at 1992 survey area slope 1 (2 sets). Samples were taken from multiple strata in each profile in order to determine the timing of deposition of different units as well as to test for internal consistency in the OSL dates. Pertinent stratigraphic information is presented in Appendix 1.

All samples were packed along with information on provenience, soil-stratigraphic descriptions, and stratigraphic sketches, and shipped to Dr. Paul Hanson at the University of Nebraska's Geochronology Laboratory at Lincoln. Dose rate values were calculated from inductively coupled plasma mass spectrometry (ICP-MS) analysis of K, U, and Th from bulk sediment samples. These analyses were performed at ALS Chemex Inc. The cosmogenic dose rate contribution was estimated using equations from Prescott and Hutton (1994) that are based on latitude, elevation, and sample depth. Equivalent dose values were determined on Risø models DA 15 and DA 20 TL/OSL readers using the single aliquot regenerative (SAR) method (Murray and Wintle 2000) and 90 to 150 μm quartz grains. Quartz sand was isolated using sodium polytungstate treatments to remove heavy minerals and hydrofluoric acid treatments to remove feldspars and etch quartz grains. Preheat and cutheat temperatures of 220^{0} C were chosen based on preheat plateau experiments. For multiple-grain results, final ages were based on a minimum of 20 aliquots per sample, and ages were based on the final mean De values. Single-grain age estimates were based on a minimum of 100 accepted grains, and the final ages were based on the modal values for each sample.

Summary

Various methods from the earth sciences were employed in this research with the goals of illuminating the history of landscape change in the two surveyed areas and of generating data pertinent to determining whether those changes reasonably can be attributed to human activities. After gaining an initial familiarity with the landscape, the author identified loci for detailed study of deposits exposed by the recent formation of incised channels across the study area. Additional locations were chosen judgmentally for catenary studies undertaken to augment the data produced by fluvial stratigraphic

studies. Temporally diagnostic artifacts and the relative degrees of pedogenic alteration of different deposits provided initial information concerning the history of landscape change in the surveyed areas. Subsequently, laboratory research helped to constrain the timing of the inferred changes. Radiocarbon dating of included organic materials constrains the ages of some strata. Magnetic susceptibility studies provide additional information concerning the degree of pedogenic alteration of different deposits, as well as local histories of erosion and deposition. Finally, OSL dating provides direct estimates of the timing of deposition and burial of individual strata.

Specifically, the author completed 73 formal in-field soil-stratigraphic profile descriptions over the course of four seasons of fieldwork in the study area. Of these, 15 profiles were recorded where recent arroyo formation has exposed stratified deposits. The remaining 58 descriptions were of soils and strata exposed in test pits excavated along 11 hillslopes in the surveyed areas. Seven charcoal samples recovered from four different profiles were submitted for AMS radiocarbon dating. In addition, 13 OSL age estimates were calculated using sediment samples from five of the profiles. Of these, seven were multiple aliquot age estimates and six were single grain estimates; age estimates for three of the samples were calculated using both techniques. Magnetic susceptibility was measured for 1062 aliquots derived from 354 sediment samples taken from 39 of the profiles. Expectations and guidelines for interpreting the resulting data are presented in the next chapter.

Chapter 7:

Expectations and Interpretive Guidelines

Each of the methods described in the preceding chapter produced data relevant to discerning the history of landscape change in the study area. There are three related components of reconstructing that history: chronology, or when the landscape changed; process, or how the landscape changed; and inferences regarding the causes of landscape change. Previous studies provide frameworks for interpreting these data; within these frameworks, the data generated during this study provide insight into the ages of different deposits, what those deposits represent in terms of changes in the landscape, and the likely causes of landscape change in the past.

Chronology – Field Observations

As in any historical science, establishing chronological control in archaeological and geoarchaeological research provides the foundation on which subsequent arguments concerning process and causation are built (e.g., Ramenofsky 1998). In the current research, two types of data collected in the field were useful for determining the ages of deposits. Pedological studies allowed the identification of buried soils that represent protracted periods during which geomorphic surfaces were stable in the past. In addition, different degrees of pedogenic alteration in different deposits constrain their ages. Chronological controls also were provided by the presence and stratigraphic locations of temporally diagnostic artifacts. Laboratory techniques used to further constrain the ages of different deposits are considered separately below.

Pedological Studies

Soils form slowly on stable geomorphic surfaces as sediments at and near the surface weather and are altered by additions, removals, transformations, and translocations (Simonson 1978; see also Birkeland 1999 and Buol *et al.* 1997). Therefore recognizable soil horizons, either at the surface or buried, represent extended periods of landscape stability. In addition, soil development follows a more-or-less predictable trajectory such that the degree of pedogenic alteration can be used to determine the general age of a surface, the timing of the initial deposition of sediments in which soils

formed, or the approximate length of time a stratum was exposed at the surface (e.g. Birkeland 1999; Gile and Grossman 1979; Harden 1982; Harden and Taylor 1983; Huckleberry 2001; McFadden *et al.* 1983)[44]. As noted above, the rates and trajectories of soil formation vary with parent material, climate, organic inputs, and other conditions so it is necessary to control for these variables. Degrees of soil development cannot be assumed to reflect the same chronological information in widely separated areas or where any of the soil forming factors has been dramatically different, as often is the case in different topographic settings.

Several characteristics observable in the field can be used to determine the degree of pedogenic alteration of a deposit. In arid climates, pedogenic calcium carbonate ($CaCO_3$) accumulates through time and calcic (Bk or K) horizons, sometimes called "caliche," develop below the surface in recognizable stages (e.g., Gile *et al.* 1966, Machette 1985). Other chemical salts such as gypsum ($CaSO_4\,2H_2O$) and halite (NaCl) accumulate in analogous ways in hyperarid environments, forming subsurface By horizons (e.g., Birkeland and Gerson 1991). In the study area, however, precipitation is sufficient to flush carbonates and chemical salts through the soil column and into the groundwater; no calcic soils were present. Other characteristics that reflect degree of pedogenesis include changes in color, the development of ped structure, accumulation of pedogenic clay, and the alteration of original depositional structures or boundaries. The combined changes in initially homogeneous deposits create recognizable soil horizons with characteristic properties.

Pedogenesis changes the color of deposits over time in various ways depending on vertical position in the soil column, parent material, the nature of inputs and transformations, the abundance of water, and other variables. In general, deposits at the surface become darker in color through time as organic carbon from plants and soil biota accumulates, creating an A horizon. Where plants are absent or are removed by erosion or human activities, this process can be reversed, especially in warm climates.

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[44] This is something of a simplification. Soil formation actually represents a balance between two sets of processes, termed pathways. Progressive or proanisotropic pathways, which usually are considered "normal" soil formation, promote horizonation and chemical stability; regressive or proisotropic pathways, such as extreme bioturbation, promote homogenization or instability (Hole 1961, Johnson and Watson-Stegner 1987). In the majority of cases, and everywhere in the study area except in plow zones, progressive pathways have been dominant over regressive such that generalizations concerning the greater ages of deposits in which more well-developed soils are present should be accurate.

Interestingly, the oxidation of carbon in the soil because of erosion may be a significant source of the greenhouse gas carbon dioxide (Montgomery 2007: 212 – 213).

Color changes below the A horizon depend on the specific processes of transformation and translocation at work in a given environment. Subsurface horizons can be whitened by eluviation, creating an E horizon, or by deposition of carbonates or salts, creating Bk, By, or other horizons (see e.g., Buol *et al.* 1997, Birkeland 1999, or Soil Survey Staff 1975, 1993 for extensive discussions of these and other processes). In the study area, the dominant process appears to be the translocation of clay particles as colloids from at and near the surface and illuviation in argillic B horizons. Probable sources of the clay include weathering of surface materials and aeolian inputs. Iron compounds adsorbed to the clay particles increase the redness of the B horizon as the clay is redeposited, a process termed rubification.

Below the B horizon (the zone of deposition of materials transported out of superjacent horizons), typically there is either a layer of sediments that has not been altered extensively by weathering related to soil-forming processes or bedrock. This is the soil parent material and it is termed the C horizon (or frequently R if rock). Changes in color in the A and B horizons usually are determined by comparison to the C horizon unless there is reason to believe that the soils are forming in materials deposited from other locations, for example materials redeposited from areas upstream in a fluvial system. The original color of the parent material obviously impacts the changes in color that occur as materials are added or removed by pedogenic processes. For example, red schist bedrock is widespread in the northern portion of the 2004 – 05 survey area; degree of soil development must be inferred from other characteristics than rubification of the B horizon.

The amount of water entering the solum is the single most important driver of pedogenic processes in the vast majority of situations. Water increases the rates of both chemical and mechanical weathering and is the primary means of translocation of materials downward through the soil column. Therefore, pedogenesis tends to proceed more rapidly in wet climates and geomorphic positions that receive significant run-on, such as floodplains and the lower portions of slopes. Long-term exposure to groundwater also alters the chemical composition of sediments by removing less stable compounds.

For example, long-term saturation generally creates an oxygen-reduced environment and ferrous iron ions may be dissolved, remain in solution, and be leached out of the soil (Walker *et al.* 1978: 29). In addition, seasonal or permanent saturation by groundwater significantly impacts soil color. Saturated soils often develop gray or greenish "gleyed" colors. Soils that repeatedly are saturated and dried usually develop red or black mottling, lamellae enriched in clays and oxidized iron compounds, and other features. These collectively are termed redoximorphic, denoting their origins in repeated vacillations between conditions that favor oxidation and reduction.

In addition to changes in color, sediments develop ped structure as soil formation occurs. Peds are natural soil aggregates, and their structure is classified according to type, size and grade. Ped type describes shape, and is divided into granular, angular blocky, subangular blocky, prismatic, columnar, and platy. Size is divided into five classes from very fine to very coarse. Grade refers to the distinctness and degree of structural development of the peds, and is divided into five classes from single grain to strong. Additional information concerning these and the definitions below is presented as the "Key to Soil Descriptions" in Appendix 1.

In general, ped type changes through time from granular to subangular or angular blocky, primarily reflecting the accumulation of pedogenic clays on ped surfaces as soil development progresses. Prismatic, columnar, and platy types develop in particular circumstances that are rare in the study area. For example, prismatic structure is common in sodic soils and vesicular A horizons, columnar structure often reflects an abundance of clays that shrink and swell significantly with changes in moisture, and platy structure may reflect strong leaching or mechanical forces such as trampling. In general, larger peds also indicate more advanced pedogenesis, although mechanical disturbance alters ped size and, to a lesser extent, type. Grade tends to increase with time.

Many changes in soil color and structure are caused or strongly affected by the movement of pedogenic clays through the soil column. As soil development progresses, the accumulation of these clays in the B horizon becomes perceptible in the field in other ways as well. Initially, clay films are deposited along the pathways of downward movement of water. These films form as coatings on and bridges between grains, in pores in the soil, and eventually on the faces of peds as they develop. In addition to their

locations, clay films are characterized in the field according to their distinctness and amount. Amount is divided into four classes, from very few to many, and distinctness is divided into three categories: faint, distinct and prominent. Each of these classifications follows a general trajectory from weak to strong soil development.

In addition to the clay films, the total accumulation of clay in the B horizon eventually can alter the texture class of that horizon. When using clay accumulations to compare the degree of soil development in multiple deposits, it is important to consider differences in inputs of clay into the solum. This is particularly true of fluvial settings where, for example, flooding can repeatedly emplace clay-rich sediments at the surface. Subsequent downward movement of water through the soil may redeposit these clays rapidly (Birkeland and Gerson 1991: 277; see also Walker *et al.* 1978). This significantly accelerates the formation of clay films and the rapidity with which textural differences between horizons become apparent.

The final characteristics of deposits that can be measured in the field, and which reflect degree of soil formation, are the alteration of initial depositional structures and the development of boundaries between soil horizons. Fluvial deposits often initially are laid down in thin beds or laminae. These thin strata have different grain sizes, reflecting changes in the competence of the stream (i.e., its ability to move sediments and clasts). Deposits on and at the base of hillslopes may have analogous stratification caused by multiple episodes of downhill movement of unconsolidated sediments, although the beds tend to be thicker. After deposition, if the strata remain near the surface, the laminae and bedding are obscured or destroyed by various natural mixing processes including faunalturbation, root growth, etc. Initial depositional structures tend to be destroyed rapidly in areas with high biotic activity such as floodplains where, unless the deposits are buried rapidly below the zone of significant bioturbation, they are likely to be obscured within decades.

Conversely, the visible differences between soil horizons tend to increase through time as pedogenesis progresses. In addition to the differences of color and changes in texture noted above, the boundaries between soil horizons progressively become more distinct and tend to become smoother, parallel to the ground surface. The distinctness of boundaries is classified into four categories, from diffuse to abrupt, and the topography is

described as one of four classes ranging from broken to smooth. In general, however, even the most well-developed soil horizon boundaries are less abrupt than erosional/ depositional boundaries and the two can be distinguished visually and by characterizing differences in grain size and texture across the boundary.

Several factors complicate the development of soil horizons and the erasure of initial depositional structures. The trajectory of horizonation can be altered significantly if there are textural differences between strata when they initially are deposited. In well-developed soils, textural differences between horizons that develop as clays and other materials are translocated within the soil column affect further pedogenesis in analogous ways. When the differences in texture are large enough, they impact pedogenesis by altering the downward movement of water through the soil profile. Where fine-grained deposits overlie coarser deposits, the water's bonds at the molecular level ("surface tension") combined with the higher water holding capacity of finer-grained sediments may inhibit the downward movement of water into the lower deposit. Similarly, and more commonly, the lower infiltration rates characteristic of fine-grained deposits beneath coarser sediments slow or stop the downward movement of water, creating an aquitard or an aquiclude. These cause water preferentially to flow downhill along the boundary between the two units. These processes promote deposition of clays and other weathering products, accelerating the development of characteristics that may appear pedogenic[45] (Walker *et al.* 1978: 19-21). In these situations, pedogenic processes may actually serve to enhance original depositional structures, maintaining the boundaries between depositional units.

A related problem is that of polygenetic soils. As erosion and deposition move sediments across a landscape, they can alter the soil horizons present at any given location. For example, erosion episodically removes the uppermost sediments on many hillslopes, so one or a series of B horizons may be present at the surface or beneath an A horizon that is developing in an exhumed B horizon. Downslope, the A horizon may be thickened and could be buried by B horizon materials eroded from higher on the slope, locally creating inverted soil stratigraphy. In exposures of floodplain deposits, many

[45] Because they involve the downhill or downstream movement of subsurface water, these technically are classified as diagenetic changes, or changes affecting buried deposits and not directly related to soil formation in the superjacent strata. The distinction is not critical for the purposes of this study.

strata are likely to be present with varying degrees of pedogenic alteration and varying degrees of preservation. Boundary characteristics and stratigraphic relationships are particularly important for differentiating *in situ* soil development from layers emplaced or altered by erosion and deposition. In all cases, if the surface is stable for a sufficient period of time continued soil development eventually will overprint the old horizons, a process called soil welding.

The Profile Development Index (PDI) provides a semi-quantitative way to compare the degree of soil development in different deposits based on changes in parent material that have been demonstrated to be time-dependent (Harden 1982; Harden and Taylor 1983). In cases where the other soil forming factors are comparable, PDI values should primarily reflect the temporal component of pedogenesis. Unfortunately, the PDI was developed for comparing soils that had not been affected significantly by geologically-recent erosion or deposition. Virtually all of the deposits examined in this study were altered by at least one episode of erosion and/ or deposition, and polygenetic soils are ubiquitous in floodplain environments and at lower positions on hillslopes. Not only is it difficult to calculate a PDI value for such deposits, the results generally are useless in that the calculated values are not comparable between locations unless they have exactly the same history of erosion and deposition.

For the purposes of this study, then, the depositional history and general ages of deposits at each profile are inferred from boundary morphology and the texture, color, clastic content, and other characteristics of each stratum on a case-by-case basis. Comparisons to hillslope deposits aid in the interpretation of fluvial stratigraphy. Pedogenic characteristics in each stratum are used to classify the degree of soil formation into general categories of none, weak, medium, and strong (c.f. Holliday 2004: 27). These are best viewed as ordinal level data. Deposits that have not been impacted by pedogenesis retain original depositional structures and show no evidence of color alteration or ped development and clay films are absent. Weak soil development is characterized by erasure of some or the majority of original depositional structures, slight color alteration, weak or nonexistent ped development, and weak to nonexistent clay films. In the study area, it reflects a period of soil formation on the order of decades to a century. Moderate development is reflected in erasure of original depositional structures,

visible color alteration, and moderate ped development and clay film morphology. The deposits in which moderately developed soils are present have been stable at the surface for centuries to a millennium. Strongly altered deposits are characterized by clear color alterations easily measurable with the Munsell chart, and strong expression of ped structure and clay film morphology. These deposits have been in place for millennia.

Artifacts

Unless they are intrusive, temporally diagnostic artifacts in or below a stratum provide a *terminus post quem* date for that deposit; logically the stratum could not have been emplaced before the artifacts were produced. Although the claimed accuracy of age estimates may be overly optimistic, the inclusion of temporally diagnostic ceramic assemblages has been used for decadal-scale dating of deposits at several locations in the American Southwest (Force 2004; Force and Howell 1997; Force *et al.* 2002). Artifacts are used frequently in geoarchaeological studies to provide more general age estimates. This section reviews the issues involved in using artifacts as chronological indicators.

In general, the overall abundance of artifacts in a deposit provides a reliable initial indication of whether the artifacts are intrusive. If numerous artifacts of different types and sizes are present throughout a definable stratigraphic unit, deposition (or redeposition) likely was synchronous with deposition of the stratum. If only one or a few artifacts are encountered, or if they are visibly size-sorted, it is more likely that their positions have been altered by bioturbation or other post-depositional mixing processes. The likelihood of post-depositional mixing can be evaluated in the field in other ways as well, for example by observing krotovina (filled insect and animal burrows), other evidence of burrowing, soil cracking, and the morphology of boundaries between strata.

The position of artifacts within a stratum also can provide useful information regarding the relationship between the artifacts and the matrix in which they are encountered. Artifacts deposited on a surface are likely to be mixed downward by numerous processes including trampling, plowing, and bioturbation. The depth of redeposition due to trampling varies significantly with soil texture. In loose, sandy soils artifacts can be moved downward as much as 16 cm, while in loamy sand the trample zone can be 3 – 8 cm in depth, and finer-textured deposits are significantly less

susceptible to artifact redeposition due to trampling unless saturated with water (Gifford-Gonzalez *et al.* 1985, Schiffer 1987).

If the position of artifacts was significantly affected by trampling, their abundance should decrease with depth below the upper boundary of a stratum in most cases. For sand, artifact abundance should be distributed quasi-normally around a mode at a depth of a few cm below the former surface. In all cases, where the stratum is sufficiently thick the lower portion should lack artifacts. These vertical distributions of artifacts would provide an indication that initial deposition of the matrix antedated deposition of the artifacts. Argilloturbation and many other natural processes generally mimic these patterns, with the depth of redeposition constrained by the depth of soil cracking, root penetration, etc. [46]

Plowing mixes near-surface deposits, creating a plow zone in which artifacts are displaced from their original locations of deposition. Despite the image conjured by the phrase "turning the soil", most plows and cultivators – including the agricultural disks and rippers commonly used in the study area – do not actually invert the plowed deposits. Instead, they break up and churn deposits to a given depth. While this can lead to significant horizontal displacement of artifacts, it takes numerous cultivation events to completely redeposit artifacts vertically throughout the plow zone. In areas that have been plowed relatively few times, artifacts may be encountered relatively near the depth of original deposition.

As plowing continues, the plow zone develops several diagnostic characteristics. These include clay drapes or pendants at the base of the zone, related to the rapid downward translocation of clays following plowing and the different rates of infiltration in plowed vs. unplowed deposits. Similarly, gravelly lag deposits often form at the surface, reflecting the increased soil erosion associated with cultivation. Where such characteristics are evident, it is reasonable to infer that long-term cultivation probably has significantly redeposited artifacts horizontally and vertically throughout the plow zone. In such cases, the presence or absence of artifacts in subjacent deposits can provide some clues concerning the original vertical location of artifacts in the plow zone.

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[46] Cryoturbation, on the other hand, tends to move artifacts in the 4 – 8 cm size range upward through the soil column (Benedict and Olson 1978: 43 – 44; Johnson *et al.* 1977). This process is rare outside of very high altitude or latitude sites.

The processes of and patterns produced by redeposition due to bioturbation are more complicated. The degree of biotic impacts on clast position and soil formation in some areas prompted Johnson *et al.* (1987) to popularize the term "biomantle" for the upper stratum of soils strongly affected by bioturbation. Like plow zones, biomantles lack internal stratification and soil horizonation, and often there are unusual characteristics such as stone lines at the lower boundary. Where a biomantle can be recognized, it is highly likely that the majority of artifacts within it have been moved some distance vertically or horizontally from their original positions. In most cases, however, the degree of bioturbation is less and the cultural deposits are likely to retain a moderate or high degree of stratigraphic integrity. Evaluating the degree of disturbance requires an understanding of the various bioturbation processes that may have occurred.

It has long been recognized that earthworms can bury archaeological materials by ingesting underlying sediments and depositing castings at the surface; none other than Charles Darwin published the first book on the subject in 1881 (see also Darwin 1837). More recent research has clarified that earthworms tend to move objects larger than the diameter of their burrows (< 1 cm for most species) downwards, while objects smaller than their burrows may be moved upwards or displaced horizontally (Stein 1983; see also Balek 2002). Over time, the process can create concentrations of buried larger artifacts near the lower limits of earthworm activity. These might be mistaken for original depositional surfaces, especially as earthworm burrows often are small enough to escape detection when color and texture differences between strata are minimal. The depth of mixing and the degree of horizontal or vertical displacement of artifacts depend largely on the number and species of earthworms present and, in particular, on whether they are surface- or subsurface-casting (Canti 2003).

Other burrowing insects and animals can alter the position of artifacts in analogous ways. Of these, the most thoroughly studied are pocket gophers (*Thomomys bottae;* e.g., Bocek 1986, 1992; Erlandson 1984; Johnson 1989, 1990, 2002). As with earthworms, gophers tend to displace downwards objects larger than the diameter of their burrows (approximately 6 – 7 cm) by digging underneath them, while smaller objects may be moved upwards or displaced horizontally. Gophers can thereby concentrate larger artifacts in stone lines or stone zones that they create beneath the surface, near the

lower limits of their burrowing activity. In some cases, the degree of mixing caused by gophers can be substantial, with estimates ranging from 5% of artifacts displaced/ hundred years (Erlandson 1984) to 100% displacement in as little as 88 years (Bocek 1992).

Bioturbation is not the only process that can create buried stone lines. The bedload in stream channels often consists of coarse clasts and it may be buried and later exhumed completely or in cross-section. Erosion also can create lag deposits that subsequently can be buried. Observations of clasts (including artifacts) contained in stone lines or stone zones provide some indication of their genesis: the clasts in stone lines created by fluvial processes are likely to be imbricated and at least somewhat rounded. While the degree of rounding is likely to be less, clasts in lag deposits also are likely to be preferentially oriented with the long axis parallel to the surface. Clasts in stone lines created by bioturbation will be randomly oriented and the degree of rounding will be similar to that of clasts throughout the superjacent deposit. In addition, lag deposits and stone lines that are fluvial in origin are likely to be located at stratigraphic discontinuities, while the matrix above and below those created by bioturbation is likely to be similar.

In addition to faunalturbation, floralturbation can be significant in some environments. Root growth can displace artifacts laterally and when roots decompose artifacts may fall downward through the resulting pores. A more significant process is root throw. When large trees fall, the root mass carries upward large quantities of soil, along with artifacts and other clasts. As the root mass disintegrates the sediments are eroded away by wind or water, leaving a lag deposit of clasts and artifacts at the surface; root throw therefore tends to displace artifacts upwards through the soil column (Johnson 1990, 2002). Obviously this process is most significant in densely-forested areas, especially those with shallow soils and/ or loose substrates where trees are particularly vulnerable to toppling by wind.

Because these are ubiquitous processes that can have significant impacts on three-dimensional artifact location, the potential for redeposition by bioturbation should be evaluated for all archaeological deposits. That it is necessary to do so when artifacts are used to infer the timing of deposition of sediments seems obvious. Careful observations

of soil attributes and the positioning of clasts are necessary to determine the degree to which artifacts may have been displaced. The presence of visible krotovina in soil profiles provides an initial indication of faunalturbation. Both Stein (1983) and Johnson (1989), however, suggest that extreme bioturbation creates situations in which krotovina will be largely invisible because there is no discernable difference in color or texture between the matrix and the materials that fill in burrows. In such cases the presence of numerous earthworms or other burrowing animals should provide clues that bioturbation might be significant. In addition, both authors suggest that soil horizons will be largely or completely obscured within the zone of bioturbation (i.e., the biomantle) in these instances (see also Canti 2003). Where the degree of mixing is somewhat less but still significant, it often creates irregular or broken soil horizon boundaries (e.g., Frolking and Lepper 2001).

Soil texture also provides some preliminary indications that bioturbation may be significant. Vertical displacement of artifacts by faunalturbation generally is greatest in sandy soils (e.g., Peacock and Fant 2002). Surface-casting earthworms create surficial deposits rich in organic materials that tend to have a crumb or granular structure and a loam or sandy loam texture (Canti 2003, Darwin 1881, Stein 1983). They also are most abundant and active in relatively moist climates with moderate average temperatures, they prefer loamy to sandy soils, and like other fossorial biota they are attracted to organic materials including those present in archaeological sites (Stein 1983). Size-sorting of artifacts and the presence of a stone line that includes artifacts near the upper boundary of the soil B horizon also imply that faunalturbation may have redeposited the artifacts.

Where bioturbation is significant, it can limit the usefulness of artifacts for chronological or behavioral inferences (e.g., Frolking and Lepper 2001). Repeated patterns in the stratigraphic position of artifacts obviously are preferable to the position of one or a very few artifacts when they are used to build chronological inferences. Where relevant materials are present in large numbers, statistical analyses can help to determine the extent of disturbance (e.g., Grave and Kealhofer 1999 for phytoliths, Worman *et al.* 2009 for lithic artifacts). Similarly, those analyses can reveal general patterns of change through time in deposits that retain some degree of stratigraphic integrity (e.g., Lundquist

2005 for lithic debitage). As noted by Grave and Kealhofer (1999), archaeologists must begin to adopt a more nuanced approach to bioturbation than the current dichotomous attitude that views all deposits as either undisturbed or disturbed to the extent that they lack significant chronological or culturally relevant information.

In the study area, the effects of bioturbation on the locations of most artifacts appear to be relatively minor and generally are localized and easily identifiable. Earthworms are not abundant, due in large part to the texture of soils and seasonal aridity and temperature extremes. Ants and other soil-dwelling insects are, however, common and they almost certainly have impacted the horizontal position of the smallest artifacts as well as fragmentary organic remains. Neither gophers nor mole-rats were observed at any time in the study area, and no mounds of the type produced by these burrowing species were noted. While rabbits and hares are common, their warrens are clearly identifiable from surface indications and in profile in arroyo banks or soil test pits and they were readily avoided during fieldwork. The density of trees suggests that root throw is not a major source of disturbance, at least currently. In-field observations did not indicate that subsurface concentrations of artifacts were created by post-depositional processes. Therefore, included artifacts generally were useful for dating deposits, although single, isolated artifacts and small fragments of organic material were not useful evidence by themselves.

Even where post-depositional mixing is minor or nonexistent, two additional factors must be considered when using artifacts to constrain the ages of strata, and fluvial deposits in particular. First, there may be a significant time lag between the production and initial deposition of artifacts on or near a site and the movement of those artifacts into the fluvial system. For example, ongoing erosion currently is exhuming cultural materials from sites that are centuries old and transporting them into and through fluvial systems across the study area. Presumably, cultural materials were abundant on and near those same sites while they were occupied. Therefore, if there were multiple episodes of hillslope erosion and floodplain deposition, several strata with cultural materials may be present in floodplain deposits. Stratigraphic relationships provide a simple means of determining which deposit was emplaced closer to the date of production of the included artifacts.

The second factor to consider is that many types of artifacts are only broadly temporally diagnostic. For example, in the study area ceramic roof tiles are a ubiquitous artifact class. They first were made and used during the Roman period and they have been common in all subsequent periods up to the present. While the forms of the tiles have changed, facilitating the differentiation of types produced during different time periods (Boone 2002; see also Boone and Worman 2007), small fragments frequently do not retain the characteristics of overall shape and surface treatment that allow for such differentiation. In this study, geographic proximity of sites is used to infer the likely age of artifacts that are only broadly diagnostic. Specifically, if a stratum in a fluvial profile contains abundant fragmentary artifacts, it is assumed that they were produced and used on nearby sites. If surface finds indicate that the nearby sites all were occupied during the same time period, it is assumed that the fragmentary artifacts in the fluvial stratum were produced during that period. Similarly, if one upstream site is significantly nearer to the fluvial profile than others, it is assumed that the fragmentary artifacts were produced and used on that site. Following these guidelines, stratigraphic and geographic data were used to evaluate the chronological significance of artifacts included in fluvial deposits.

Chronology – Laboratory Studies

In-field observations of artifact locations and the degree of pedogenic alteration of deposits were used to identify loci and particular strata for additional study using laboratory techniques. For those loci, the laboratory methods described in the previous chapter provide additional chronological information that both tests and supplements data produced by field observations. By estimating the age of an object included in a stratum, radiocarbon dating yields chronological information that is analogous to that provided by artifacts. There are, however, additional complexities related to the types of samples and to the method itself. The degree of pedogenic alteration of sediments can be used, with some caveats, for relative dating of deposits. Magnetic susceptibility studies augment field observations, offering additional evidence for pedogenesis that can be used to identify buried soils and to infer histories of erosion and deposition. Finally, OSL measurements generate relatively straightforward estimates of the ages of deposits,

provided that they have not been subjected to exceptionally high levels of post-depositional mixing.

Radiocarbon Dating

Radiocarbon assays use the known rate of radioactive decay to estimate the time elapsed since an organism stopped incorporating ^{14}C into its tissues. In this case, the dated event – the death of a plant or animal – and the target event – the timing of deposition – could be significantly different (Dean 1978; see also Ramenofsky 1998, with references). Ideally, as with artifacts, radiocarbon samples provide a *terminus post quem* date for strata because the plant materials must have been burned and incorporated into the sediments before they were deposited. However, again as with artifacts, bioturbation or other types of redeposition can create questionable associations between samples and the surrounding sediments. In addition, intrusive younger organic materials such as roots can burn in place or be subject to diagenetic alteration and become practically indistinguishable from charcoal created by human activities. Alternatively, it also is possible that the dated charcoal derives from wood that had been dead for decades or centuries before it was burned, yielding an age estimate older than the target event (human activity). These problems are especially acute for small fragments of charcoal outside of cultural features because of the challenges of identification and because the likelihood of redeposition can be difficult to determine.

To begin to address these potential problems, the stratigraphic positions of samples were evaluated in the field. It is reasonable to assume that buried concentrations of cultural materials including charcoal were deposited either while upstream/ uphill archaeological sites were inhabited or during a subsequent period of erosion that exhumed cultural materials at the sites and moved them downhill and/ or into the fluvial system. Because sites currently are being exhumed by erosion, and because recently-redeposited sediments below even the largest sites contain relatively low densities of artifacts and charcoal, older (i.e., more deeply buried) strata with higher densities of cultural materials probably were deposited during occupation of sites uphill/ upstream. This is especially likely given that refuse disposal practices at small, rural sites likely consisted of tossing materials downhill, away from the main structures.

Because it usually floats, concentrated deposits of charcoal are unlikely to have been transported great distances because transport generally would disperse the charcoal. Where preserved, they must also have been buried rapidly because charcoal is fragile and, at least in fluvial systems, highly mobile. For the deepest, densest concentrations of charcoal and other cultural materials exposed in a profile downstream from a site, then, the timing of deposition is likely to approximate closely the occupation of that site. Any landscape changes reflected by profiles must be inferred separately from additional data; the dated charcoal only provides a temporal reference point.

Ideally, the problem of old wood can be addressed by selecting samples that appear to be fragments of twigs and other small growth wherever possible. These portions of plants are unlikely to have been dead for any appreciable period of time before burning and the radiocarbon age estimates from these fragments therefore are likely to be nearer the target event, deposition. The size of the fragments encountered in this research generally precluded identification of the part or species of plant represented. Another approach is to date multiple samples in order to constrain more closely the timing of the target event. Although funding generally was inadequate to submit multiple samples from individual strata for dating, multiple samples were collected whenever possible. In part because of the many potential problems with estimating the timing of deposition using fragmentary plant materials that potentially are intrusive or redeposited, samples were taken from profiles where artifacts, soils, and in some cases OSL dates provide additional means of chronological control. Radiocarbon age estimates are used here as one among several techniques that help to constrain the timing of fluvial deposition and, ultimately, the landscape changes inferred from fluvial stratigraphic studies.

Magnetic Susceptibility

As discussed at length in the previous chapter, the magnetic susceptibility of surface deposits increases as they are altered by pedogenesis or exposed to fire. Diagenetic processes can, however, reverse or alter the increase in susceptibility, particularly if sediments are exposed to groundwater for extended periods of time; magnetic susceptibility studies were carried out primarily on hillslope deposits for this

research. Patterned changes in susceptibility with depth are used to illuminate histories of erosion and deposition at different locations in upland environments.

Where it is due to soil formation, the increase in susceptibility in an undisturbed soil typically reaches peak values somewhat below the surface and extends into the B horizon (Thompson *et al.* 1980: 483; Verosub and Roberts 1995: 2184). Where susceptibility readings are highest at the surface and decrease monotonically with depth, it is likely that recent erosion has removed some quantity of sediments from the surface. On the other hand, where susceptibility readings remain relatively high throughout the uppermost 10 – 20 centimeters of a soil, or peak below the surface within that zone and then decline with depth, it is reasonable to infer either landscape stability or the recent addition of pedogenically altered materials from higher on the slope. Finally, a peak in magnetic susceptibility below the surface suggests a buried soil and recent deposition.

Because susceptibility increases as pedogenesis progresses, the degree of magnetic susceptibility of surface and near-surface deposits should be useful as a relative dating method. As with other comparisons of degrees of soil formation, however, it is necessary to control for variables that affect pedogenic alteration; where it is used to infer the relative ages of different soils, it is important to demonstrate that increases in magnetic susceptibility are caused by similar changes to similar materials. The factors identified in Jenny’s (1941) “ClORPT” equation must be comparable. In particular, the parent materials must be similar in terms of the abundance of magnetic minerals and they must include a similar suite of minerals that can be transformed into more strongly magnetic forms by pedogenic processes.

For the purposes of this study, similarities in bedrock as shown on geologic maps were used as an indication that parent materials and soil forming processes were comparable between the 1992 survey area and the southern half of the 2004 – 05 survey area. Differences in magnetic susceptibility then provide one indication of the degree of pedogenic alteration, and therefore the age, of different deposits. Ideally, it would have been possible to investigate more thoroughly the magnetic mineralogy of samples of soils from both of the surveyed areas using additional laboratory techniques. Measurements of isothermal remanence magnetism and remanant coercivity, for example, could have been used to characterize the magnetic mineralogy of samples from both study areas to provide

the basis for using magnetic susceptibility data for relative dating. Time and funding were, however, insufficient to complete these tests. Magnetic susceptibility, then, is used only as one among several characteristics considered when evaluating the relative ages of different deposits. With very few exceptions, the susceptibility data correspond well with other observations, suggesting that the overall comparisons are valid.

Optically Stimulated Luminescence Dating

One of the most important advantages of OSL dating for this type of research is that the target event – deposition of a stratum – and the dated event – the last time sediments in or beneath that stratum were exposed to light – are essentially the same. Interpreting the chronological information should be straightforward, in the absence of major post-depositional mixing, partial bleaching, or sample contamination. For this research, the degree of post-depositional mixing and the possibility of contamination were evaluated by dating multiple aliquots and single grains from each sample and analyzing the coherence of the resulting age estimates. In addition, samples were taken from multiple strata at each profile where OSL dating was employed. Based on the principle of superposition, comparisons of the age estimates from different strata provide a second test of the reliability of the technique. Finally, OSL samples were collected from study loci in which artifacts and/ or radiocarbon assays provided additional chronological information. Paired multi-aliquot and single-grain analyses of sediments from specific strata show that partial bleaching is a problem in the study area. This causes multi-aliquot measurements to overestimate the age of a stratum, often significantly; single-grain ages provide more accurate chronological information and are preferred for the final reconstructions of landscape change.

Fluvial Systems

Determining the ages of deposits is only one facet of reconstructing a history of landscape change. An understanding of geomorphic processes provides a starting point for interpreting what those deposits represent in terms of how the landscape changed. Examinations of sediments in fluvial and hillslope contexts generate different but complementary information about the geographic extent and severity of erosion in the past, and data from each context inform interpretation in the other. A process-oriented

approach to historical reconstruction also provides the foundations on which inferences regarding the causes of landscape change in the past can be built.

As the name suggests, fluvial geomorphology concerns the forms of, processes related to, and change through time in stream systems and associated landforms. For the present research, the pertinent body of knowledge covers erosion, transport, and deposition of sediments in streams and floodplain environments. These processes are relevant to interpreting fluvial strata and specifically the landscape changes that can be inferred from studying them. Initially, it would seem that a simple relationship should exist such that hillslope erosion would lead to floodplain deposition. While this often is true, fluvial systems are complicated in that their behavior is determined by numerous variables. Among these, the behavior of the system at any given point in time is determined, in part, by antecedent states; fluvial systems are therefore complex systems in the strict sense.

Complex Response

Both experimental and field studies have documented the complex nature of stream systems. Classic studies by Gilbert (1917) showed that increased sedimentation due to hydraulic mining in the western United States caused pulses of alluvium to move downstream through river systems. At any given place below a mine, alluviation caused by the increased sediment inputs was followed eventually by erosion and deflation of the river channel after the mining inputs ceased. Although remnants were present in some locations, deposits indicative of increased sedimentation (analogous to those that indicate major hillslope erosion) might only be present near the site of erosion for a limited period of time and could be encountered later at various points downstream. A given stratigraphic profile along the river might appear to reflect erosion, alluviation, or relative stability depending on its distance in time and space from the increased sediment input.

In an influential series of publications reporting on laboratory and field studies, Schumm and his students expanded on this work (e.g., Patton and Schumm 1981; Schumm 1977; Schumm and Parker 1973; see also Ritter *et al.* 1995 with references). The body of research demonstrates that changes in extrinsic conditions such as base level, discharge, or sediment load propagate through the fluvial system in a manner analogous to that noted by Gilbert, although response to a change in base level obviously moves in

the opposite direction. In addition, the studies showed that a single change in extrinsic conditions could cause multiple episodes of response through time, a behavior termed complex response. Complex response can make inferring the cause(s) of erosion or deposition particularly difficult, as multiple episodes of erosion or deposition might be caused by a single change in conditions.

Schumm's research also documented changes in the state of stream systems (i.e. from depositional to erosional or vice-versa) without any apparent change at all in external conditions. He therefore suggested that stream systems are controlled by intrinsic thresholds, a concept that has been applied broadly in geomorphology to many landforms and systems (e.g., Bull 1991; Ritter *et al.* 1995; Selby 1993). Imperceptible changes in a system, such as a very gradual decrease in the forces resisting erosion (due to weathering, for example), can eventually force the system beyond a threshold, leading to rapid and dramatic geomorphic change like slope failure or channel formation.

Schumm's work highlights some of the difficulties inherent in interpreting fluvial stratigraphy. For example, a stratum indicative of floodplain deposition might be present in a stratigraphic profile because of recent or ongoing erosion on the adjacent hillslope. Alternatively, it might be present because of past erosion on the adjacent hillslope or on a distant hillslope somewhere upstream, or because the stream cut into and redeposited hillslope or floodplain sediments as it incised its bed (perhaps more than once) because of a lowering of base level at some time in the past, or for other reasons. Floodplain erosion itself might be caused by changes in external conditions, by the crossing of an intrinsic geomorphic threshold, or it might be a second response to a change that occurred in the past. Clearly researchers must consider multiple possibilities and examine multiple locations when interpreting fluvial stratigraphy in order to determine which interpretation is the most likely.

General Models

Despite the interpretive difficulties presented by the complex behavior of fluvial systems, general models of geomorphic and fluvial processes (e.g., Bull 1991, 1997; Ritter *et al.* 1995) provide a starting point for determining what fluvial strata represent in terms of landscape change. These models build on and synthesize decades of research aimed at determining the ways in which extrinsic conditions affect erosion and

alluviation in stream systems, much of it focused on the ephemeral stream systems of the American Southwest (e.g., Bahre 1991; Bryan 1925, 1940, 1942; Cooke and Reeves 1976; Hack 1942; Hall 1980; Hereford 1984; Leopold 1976). At the simplest level, erosion occurs when the forces favoring movement of sediments (e.g. gravity, water, wind) exceed those holding sediments in place (e.g. vegetation, gravity, compaction). The balance can be altered by numerous factors including tectonic movement, climate changes, and human activity; the effects of the majority of these external changes are mediated through changes in plant communities (Thornes 1987, 1990; Thornes and Gilman 1983).

Regardless of the initial cause(s) of erosion on a hillslope, mobilized sediments generally move downhill and eventually enter the fluvial system (but see e.g., Parsons *et al.* 2004 and Wilcox *et al.* 2003 concerning sediment storage). The subsequent behavior of the fluvial system is determined by the balance between the amount of sediment entering the system and stream competence, or the ability of the stream to move sediments downstream and, ultimately, into the ocean or a closed basin. When sediment inputs exceed the ability of the fluvial system to move those sediments, floodplain alluviation occurs. Sediment flux generally is proportional to erosion on adjacent or upstream hillslopes, but can also be impacted by upstream erosion of the floodplain, aeolian inputs, or other factors. All other things being equal, if hillslope erosion increases, layers of sediments are likely to be deposited on floodplains.

When stream competence exceeds sediment supply, on the other hand, sediments will be removed by the fluvial system. Stream competence is proportional to discharge, the volume of water carried in the system per unit time[47]. This variable may be affected by changes in effective precipitation, by changes in drainage basin size (i.e., stream capture), or by anything that alters the production of runoff from hillslopes (i.e., changes

[47] This is a simplification. Stream competence is determined by numerous related factors including water velocity, channel slope, discharge, and channel morphology. Several equations, developed from both theoretical calculations and empirical observations, illustrate the relationships between these variables. Three that are commonly used for measuring and/ or calculating competence are critical bed velocity, critical shear stress, and stream power (see discussion in Ritter *et al.* 1995: 197 – 200). For the purposes of this study, I assume that channel slope at any given location is roughly constant through time, that the morphology of channels in floodplain sediments is essentially unconstrained, and that flow velocity is proportional to slope, channel morphology, and discharge. Therefore, competence is proportional to discharge.

in infiltration rates or increases in the area of exposed bedrock). Removal of sediments by the fluvial system generally occurs through the formation of channels on the floodplain. Initially, especially in arid or semiarid environments, these may be discontinuously incised channels that migrate upstream, removing sediments at the upstream head cuts and depositing channel fans downstream (Bull 1997; Patton and Schumm 1981).

If stream competence exceeds sediment inputs during a significant period of time, the fluvial system will become continuously incised throughout a given reach (Bull 1997; Selby 1993: 238). Due to the increased force exerted by the weight of a greater depth of water and the increased velocity of that water, runoff concentrated in channels is orders of magnitude more effective than sheetflow in entraining and transporting sediments (e.g., Parsons *et al.* 2004; Wilcox *et al.* 2003). Therefore, continuously incised systems more efficiently capture runoff and mobilized sediments in an area and flush those directly into a trunk stream, lake, or ocean. Over time, the incised stream is likely to widen the initial channel as it continues to remove sediments stored on the floodplain, eventually creating a smaller floodplain inset below a terrace that is the remnant of the older floodplain (e.g., Graf *et al.* 1987; Leopold 1976).

To some degree, the differences between these general models and complex response models are differences of scale. The general models build on smaller scale observations and principles – erosion occurs when the forces favoring movement of sediments exceed the forces holding them in place – and lead to general conclusions – when stream competence consistently exceeds sediment inputs, the fluvial system will remove sediments stored on the floodplain. Complex response models, on the other hand, tend to describe system behavior at the meso-scale.

The classic example of complex response, multiple episodes of channel incision in response to a single lowering of base level, can be conceived of as a meso-scale response of the fluvial system. After the initial change in conditions, the behavior of the system at any specific point in time or space may be difficult to predict. Episodes of channel incision, however, fit within the more general description of system behavior as long-term removal of sediments when an external change, in this case steepened slope angle due to lowered base level, increases stream competence. Similarly, discontinuously

incised stream systems may be quasi-stable around a threshold value between alluviation and erosion. Their behavior is complex and to some degree unpredictable (e.g., Bull 1997; Patton and Schumm 1981). However, major changes in external conditions would force the entire fluvial system to be dominated by either erosion or deposition at longer time scales. Therefore, while complex response highlights the difficulties inherent in interpreting fluvial stratigraphy, it does not imply that the difficulties are insurmountable. Careful observations and comparisons of data from numerous locations should provide a basis for teasing apart the history and causes of landscape change.

Fluvial Stratigraphy

The stratigraphic studies reported here focus on three related questions concerning landscape change: how did the landscape change through time? What caused those changes? And (as discussed above) when did those changes occur? Field studies of fluvial stratigraphy bear on all three questions. Characteristics of floodplain deposits reflect aspects of the fluvial system at the time of deposition. Changes in the drainage basin above the location of a profile can be inferred from the changes in the fluvial system, providing clues to the extent and nature of landscape change. An understanding of geomorphic processes also provides an initial means of determining why those changes occurred.

Several physical attributes of floodplain deposits are determined by the nature of the fluvial system. Most notably, grain size is determined by stream competence. Simply put, larger and faster-flowing streams are capable of moving larger clasts, while smaller, slower streams entrain and redeposit smaller particles. Although this relationship is straightforward, it does not always allow for easy interpretation of fluvial profiles without additional information.

Strata with abundant gravel- and cobble-sized clasts imply the presence of a stream in which enough water flowed with enough force to remove smaller particles and to move the bedload clasts. Not all rocky strata were deposited by streams, however. In addition to the bioturbation processes considered above, mass movements such as landslides also can create deposits dominated by large clasts, and some erosional processes generate rocky lag deposits by removing smaller particles. Due to the nature of deposition, however, landslide deposits frequently are poorly-sorted, with clasts and

sediments of various sizes. In addition, the clasts tend to be angular, are not aligned in any particular direction, and are present throughout the stratum. Depending on the nature of the erosion, lag deposits may have more uniform clast sizes, but in general the clasts will be angular and in many cases they are unaligned. For example, erosion caused by plowing has created lag deposits dominated by angular gravels and small cobbles across the surface of much of the study area.

Stream bedload deposits, by contrast, generally consist of clasts that are at least somewhat rounded and imbricated (preferentially aligned with the long axis perpendicular to the flow of water and the intermediate axis subparallel to flow and tilted upstream). In addition, the lower boundary of such deposits usually is abrupt and erosional. By altering the downward movement of water through the solum, the textural difference between the bedload deposit and subjacent deposits often maintains an abrupt boundary for long periods of time regardless of subsequent pedogenic alteration. When there are multiple periods of channel incision, new channels often will follow the course of previous ones (e.g., Force *et al.* 2002). Where they are preserved, stream bedload deposits often appear in the banks of modern channels as laterally continuous stone lines with an abrupt lower boundary comprised of rounded and imbricated clasts.

Finer-grained deposits may indicate floodplain deposition due to hillslope erosion. Alternatively, they can be emplaced by flooding that mobilizes and redeposits materials from higher on the floodplain. When sediment-laden floodwater overtops an incised channel, flow velocities decrease dramatically outside the channel and fine particles settle on the inundated portion of the floodplain. Discharge during a flood usually rises, peaks, then diminishes. Strata laid down by overbank flooding therefore often fine upwards, with coarser sediments deposited at the base during the higher flows and finer deposits settling out as flow velocity decreases. Aside from this tendency, floodplain deposits emplaced by overbank flooding tend to be well sorted and fine-grained, usually dominated by silt- and clay-sized particles. Clasts, if present, are likely to have been rounded by long-term movement through the fluvial system. Depending on proximity to the channel and individual flood hydrographs, original depositional structures may include horizontal laminae and bedding.

Strata deposited on floodplains due to erosion on adjacent hillslopes generally resemble the hillslope deposits. In contrast to materials redeposited from higher portions of the floodplain, the sediments are less likely to be well sorted and are more likely to include coarser grain sizes such as sand and small gravels. They are unlikely to fine upwards as noticeably as overbank deposits, generally fining and thinning away from the foot of the slope instead. Included clasts are likely to be angular. Horizontal laminae and bedding may be present if the deposits are reworked by the fluvial system during or after deposition. These differences in grain size, sorting, and clast rounding provide some guidelines for distinguishing between strata deposited by overbank flooding and those emplaced due to erosion on adjacent hillslopes. Finally, where channel bedload deposits are present cross-cutting relationships and stratigraphic position can rule out overbank deposition in some cases. Differentiating the deposits often remains difficult in practice, especially when the strata are altered by post-depositional pedogenesis. Comparisons to soils and sediments present on adjacent hillslopes often provide crucial additional information.

Following these general guidelines, characteristics of floodplain deposits can be used to infer the origins of and the processes that initially emplaced individual strata. A general history of hillslope erosion, channel formation, and floodplain deposition at specific points on the landscape can be reconstructed from careful inspection of fluvial profiles. In order to infer what the changes in the fluvial system reflect in terms of changes in the drainage basins above each profile, it is necessary to apply the general models of fluvial processes outlined above. Similarly, process-oriented geomorphic principles can be used to infer why changes occurred, i.e., the mechanisms most likely responsible for landscape change.

Landscape Change

The erosive power of water moving across a landscape is determined by the interrelated variables of slope angle, discharge, flow velocity, and the presence and morphology of channels. At the landscape scale, slope angle is determined by the elevation difference between hill summits and local base level and by the actual pathways water takes between the two. In the study area, local base level is determined by the large river and ribeira systems that flow in bedrock channels. The presence of Roman-

era river fortifications at Mértola, as well as ancient mills and fish weirs along larger streams throughout the study area, shows that there has been little change in local base level during at least the past two millennia. Similarly, the presence of recognizable iron-age hilltop archaeological sites shows that there has not been any radical lowering of hilltops during the same period of time. In addition, the pathways of minor channels are largely determined by hills that consist of bedrock outcrops with thin veneers of soil. These pathways could not have changed appreciably in the past few millennia. Therefore, at the landscape scale, slope angle has been essentially constant in the study area throughout the period of interest. At smaller scales, slope angle is altered by the formation of stream channels on floodplains (e.g., Bull 1997), but channel formation itself must be a response to changes in other conditions affecting the fluvial system.

If slope angle is essentially constant during the period of interest, flow velocity is proportional to discharge and is affected by channel presence and morphology. There are several important differences between sheetflow and runoff carried in channels. When rills and larger channels form, they concentrate runoff. The greater depth of the water increases its weight and therefore the erosive force exerted on the substrate. One mathematical description of this relationship is the DuBoys equation for boundary shear stress, $\tau_c = \gamma RS$, which states that the boundary shear stress (the amount of force exerted on the stream bed) is equal to the specific weight of water multiplied by the hydraulic radius (closely approximated by average stream depth), multiplied by the slope (Ritter *et al.* 1995: 199).

In addition to concentrating runoff, erosion in channels generally reduces surface roughness by removing vegetation. Channels also form roughly perpendicular to the face of a slope, creating a more directly downhill path for runoff that otherwise would move around small obstacles. The combination of increased depth, lowered surface roughness, and more direct flow path creates higher flow velocities in channels. The sixth power law states that the volume or weight of the largest particle moved in a stream varies as the sixth power of flow velocity (*ibid.*). The size of clasts transported by channels is therefore much larger than clasts moved by sheetflow. Channels are orders of magnitude more effective than sheetflow in capturing and removing both water and sediment from an area. Once formed, channels tend to increase in length and depth unless an abundance

of loose sediments overwhelms the ability of the canalized water to transport those sediments or coarse lag deposits limit further incision.

Channel shape also affects stream competence. Cross-sectional geometry is significant because it affects water depth. Sinuosity, a measure of the ratio of the length of the channel to the straight-line length of the valley, can impact flow velocities by altering the average slope of the stream bed. Aside from the large river and ribeiras, stream channels in the study area are incised into fine-grained floodplain sediments. These sediments are readily transported by the stream systems, and they hold a vertical face. Channel morphology therefore essentially is unconstrained. It is unlikely to have been radically different when channels formed in the past and, for the purposes of this study, can be treated as a constant.

Evidence for the presence of channels in the past, then, suggests that water and sediments were transported rapidly to trunk streams following precipitation events. If those channels formed roughly contemporaneously throughout the study area, they very likely did not appear because the stream systems all crossed internal thresholds simultaneously; they formed in response to a change in external conditions. As slope angle and base level are essentially constant, and because no dramatic changes in channel location or morphology are likely to have affected flow velocities, channel formation must have been due to a change in discharge. Discharge, in turn, is determined by precipitation and the storage of water in hillslope sediments.

Field observations are not directly applicable to illuminating changes in rainfall in the past. Paleoclimatic information bearing on the subject is limited. As discussed in Chapter 5, the data suggest that there were no major changes in precipitation during the Islamic period but that smaller changes might have occurred during the 11^{th} and 12^{th} centuries. If precipitation in the study area has seen no major fluctuations at the scale of human lifetimes during the Common Era, changes in stream discharge must have been determined primarily by the storage of water on hillslopes. Storage is a function of slope angle, vegetation cover and substrate. As noted above, slope angle has not changed appreciably during the time period of interest. Vegetation increases infiltration rates and water storage in several ways. It provides a partial shield against the force of raindrops hitting the soil, reducing raindrop erosion and the formation of crusts that inhibit

infiltration and increase runoff. Many types of vegetation also produce a layer of organic mulch, and the mulch as well as plant stems, roots etc. increase surface roughness, slowing runoff and increasing infiltration (e.g., Abrahams *et al.* 1988; Thornes 1987; Wilcox *et al.* 2003). Finally, through evapotranspiration vegetation prevents some meteoric water from ever entering the fluvial system, further diminishing erosive potential.

In addition to vegetation, physical characteristics of the substrate affect rates of infiltration. This is particularly true of surface texture, with coarser materials having higher infiltration rates and lower rates of evaporation that removes moisture directly from the soil column (e.g., Kemper *et al.* 1994; Poesen 1986; Poesen *et al.* 1990; Worman 2004; see also Abrahams *et al.* 1988). In turn, the amount of infiltrated water that can be stored in the soil column, called the water holding capacity, is strongly affected by sediment texture; finer sediments generally hold more water. Finally, where bedrock is impermeable, thicker layers of soil and sediment obviously have the potential to store more moisture than thinner soils.

Following from these principles, in the study area and for the time period of interest, any changes in the total amount of water entering the fluvial system most likely were determined by changes in vegetation cover and the thickness and physical characteristics of soils on the hillslopes. In addition to strata that were themselves emplaced because of hillslope erosion, stream bedload deposits exposed in fluvial profiles also can be taken as evidence of reduced vegetation cover on hillslopes in the drainage basin. In addition, they likely reflect geographically extensive changes in the substrate, specifically soil erosion. Removal of soil reduces the total amount of water that can be stored on hillslopes. Erosion of A horizons exposes clay-enriched B horizons that typically have lower infiltration rates, thereby increasing both the volume of runoff and the rapidity with which water enters the fluvial system following precipitation. Similarly, severe erosion can expose bedrock with consequences that are analogous but more extreme.

Clearly changes in vegetation and soil erosion are parameters that are likely to be influenced by human activities such as animal herding, agriculture, or intentional burning. In theory, then, and in the absence of indications of major changes in

precipitation in the past, people very likely caused Common Era landscape changes in the study area that are reflected in the fluvial profiles. Demonstrating this, however, requires a consideration of when the inferred landscape changes occurred and an understanding of the local history of settlement and land use so that temporal and causal connections between human activities and landscape change can be established.

Hillslopes

Fluvial stratigraphic studies generate insight into the location and areal extent of past erosion, and a process-based approach coupled with contrasts between the two surveyed areas provides both a theoretical grounding and empirical evidence concerning anthropogenic causes of landscape change. Using the techniques described above, investigations in fluvial contexts also provide evidence concerning the timing of landscape change in the study area. Inferred histories of landscape change based solely on fluvial data are, however, arguably incomplete. Studies of hillslope deposits address several lacunae. By investigating directly the loci where a significant proportion of human activities occur, they can yield additional insights into human-landscape interactions. Not only is the information they produce important for interpreting fluvial stratigraphy correctly, hillslope studies can document the severity of past erosion and provide additional data relevant to constraining the timing of landscape change in the past.

A Landscape Geomorphology Approach

Although combining the terms landscape and geomorphology may seem redundant, a significant number of researchers persist in attempting to reconstruct histories of landscape change solely from investigations of fluvial stratigraphy and morphology. One of the most significant problems encountered by geomorphologists who attempt to infer histories of landscape change from fluvial stratigraphic studies is that of complex response, discussed at length above. Comparing the stratigraphic record at multiple locations within a fluvial system provides much information that is useful for determining what the strata at each location represent. Nonetheless, determining with certainty the cause(s) of the recorded landscape changes may be impossible without additional information. Because complex response does not affect hillslope processes,

interpretation of hillslope deposits is more straightforward;[48] sediments deposited at the base of a slope must have originated on that slope or *in situ* through a combination of weathering and aeolian inputs, and pedogenic studies facilitate differentiating between the two possibilities.

Studying soils and deposits on hillslopes also facilitates an understanding of the behavior of fluvial systems within a landscape context. As discussed above, the behavior of the fluvial system at narrow and broad scales is determined by the balance between inputs of sediment and water. The amount of each entering the fluvial system is, in turn, determined largely by hillslope conditions and processes[49]. In addition, hillslope studies reveal the histories of erosion and deposition on the hillslopes themselves, providing direct evidence of landscape change. By combining investigations of fluvial stratigraphy with detailed studies of hillslope deposits, other researchers have been able to build satisfying reconstructions of histories of landscape change while simultaneously constructing strong arguments regarding the causes of the inferred changes (McFadden and McAuliffe 1997; Pederson *et al.* 2001; Tillery *et al.* 2003).

Related work has identified the importance of slope aspect in long-term hillslope evolution in some environments (Burnett *et al.* 2008). The study area is located at a latitude and in an environment in which differences in solar radiation on slopes of different aspect are expected to influence soil moisture and temperature and, therefore, plant communities and slope form (Kirkby *et al.* 1990). Studies of hillslope deposits reported here as well as informal observations concerning the symmetry of landforms suggest, however, that the impacts of aspect on erosion are minimal in the study area. The lack of more significant influence of aspect may be due to human impacts on plant communities (i.e., typical farming and grazing practices are the same on slopes of all aspect) and the rarity of steep, deep canyons in the study area.

A landscape approach addresses many of the interpretive problems posed by complex response by isolating some of the variables affecting stream systems. In

[48] There are, however, broadly analogous internal thresholds that can affect long-term hillslope evolution. For example, the development of strong argillic or calcic soil horizons over the course of millennia can dramatically reduce infiltration rates, eventually triggering massive erosion of superjacent sediments. There is no indication that this occurred in the study area at any time during the Holocene.

[49] Bear in mind the caveats presented above: there have not been significant changes in local base level or total landscape relief, drainage patterns have not changed appreciably, precipitation is assumed to be roughly constant, etc.

addition, it generates information concerning significant hillslope processes such as sediment storage (Parsons *et al.* 2004; Wilcox *et al.* 2003). The movement and storage of sediments within drainage basins impact the behavior of stream systems. It also strongly affects the opportunities the landscape offers for various types of production; erosion of hillslope soils reduces the amount and quality of land available for grazing or agriculture, but may also create a situation in which increased runoff can be directed towards productive plots located at the base of hillslopes (e.g., Yair 1994; see also Thornes and Gilman 1983, and Wainwright 1994). Examining hillslope soils and deposits therefore facilitates more satisfying historical reconstructions of landscape change and at the same time can provide information crucial to understanding human-landscape interactions.

Catenary Studies

Studies of soils and sediments in upland contexts typically consider the variability of those deposits at different locations on a slope. First applied to the study of soils by Milne in 1935 (Birkeland 1999: 235), the term catena in this context specifically refers to the variability of soils along (up and down) a hillslope as well as the relationships between soils at different locations:

> A soil catena is the variation of soils as a function of position along a slope. Soil morphology commonly differs from one position to the next as a function of the influences of either different local soil moisture regimes on pedogenesis, or geomorphic processes such as erosion of debris and soils upslope and deposition of the latter materials downslope. (Birkeland and Gerson 1991: 267)

In other words, soils typically vary because moisture inputs are different in different geomorphic positions. For example, increased evaporation towards the summit of a hill combined with the downslope movement of water at and beneath the surface strongly influences pedogenesis in the different settings. In addition, the downhill movement of sediments alters soil morphology at different positions along a slope.

In order to characterize the variability in deposits along a slope, researchers usually excavate soil test pits in the five geomorphic sections of the slope: the summit, shoulder, backslope, foot of the slope, and toe of the slope (Birkeland 1999: 231). Examination of the soils reveals the range of variation due to differential pedogenesis at different positions. The entire journal *Catena* is dedicated to exploring issues related to the many nuances of soil development on hillslopes in different environments.

Despite many intricacies, several broad generalizations apply in the majority of contexts and are relevant to the present study. Even in the absence of severe erosion, soils at the backslope and shoulder positions are likely to be relatively weakly developed. Runoff and subsurface flow remove water from these positions following precipitation and these loci are the most susceptible to slow, long-term sediment loss due to processes of erosion such as creep and sheetwash. The summit position tends to be relatively dry for similar reasons, but the shallower slope angle typically creates a more stable geomorphic surface. Because it is less susceptible to erosion, soils at the summit are likely to be thicker and more strongly developed than those at the shoulder and backslope positions. The foot and toe slope positions receive both runoff and mobilized sediments from uphill portions of the slope. Soils at these positions, then, generally will be thicker and more strongly developed than those at all higher positions.

These generalizations can be used to identify evidence for erosion in that catenary pedostratigraphic studies can document deviations from the expected patterns. This is especially true where the past erosion was substantial and rapid. For example, the presence of truncated soils higher on the slope and deeper, stratified, polygenetic soils at the base provides straightforward evidence of erosion. Although the question of what caused that erosion must be considered separately, the timing of the erosion can be inferred where the stratified deposits at the base of the slope can be dated.

Combined with pedological information, repeated patterns in the stratigraphic position of artifacts that have not been redeposited by post-depositional disturbance provide one type of information concerning landscape stability and the timing of change in the past. If hillslopes in the study area have been stable throughout the later Holocene, relatively well-developed soils should be present in all geomorphic positions. Soils at the foot and toe of slopes should be particularly strongly developed. Soils at higher positions should be moderately to strongly developed, depending on the time available for pedogenesis, slope angle, and other factors. Deposits that incorporate Islamic period artifacts should be preserved near the surface at higher points as well as lower, buried only by the sediments that have accumulated due to aeolian inputs and bioturbation processes that bring fine sediments to the surface. Because these artifacts would have remained in the zone of active mixing of deposits, some likely would be visible at the

surface wherever buried deposits were present. These expected relationships are summarized in figure 7.1.

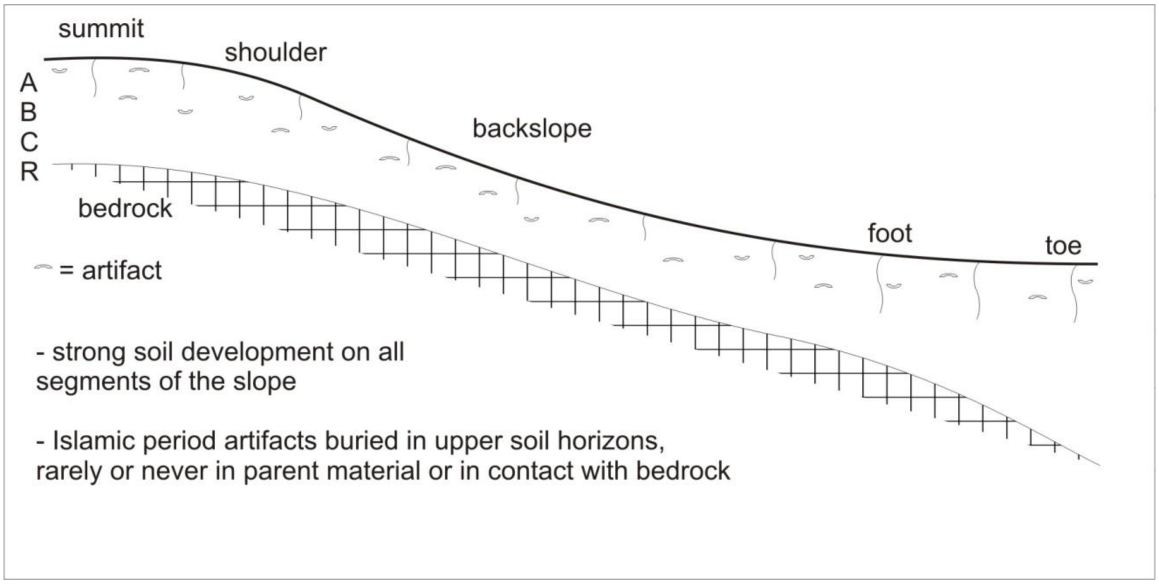

Figure 7.1: Schematic representation of expected soil development and stratigraphic position of artifacts where slopes have been stable through the later Holocene (>2000 yrs.)

Severe, rapid erosion, on the other hand, would alter these catenary relationships and the position of artifacts in predictable ways. If widespread, severe erosion occurred in the study area during the Islamic period, pre-Islamic and Islamic era deposits should be absent from the upper segments of hill slopes (summit, shoulder, and backslope) or present only as thin, localized strata and lag deposits. Soil development should be weak in those locations, reflecting deposition and pedogenesis during the centuries since the Christian *reconquista*. Artifacts dating to the Islamic period likely would be present as lag deposits at the base of the solum and, because of bioturbation and other mixing processes, throughout the thin slope soils. The lower portions of slopes (foot and toe) should preserve evidence of deposition during the Islamic period. Older soils should be buried by hillslope sediments that incorporate Islamic period artifacts. The surface deposits should exhibit only weak to moderate pedogenesis. These expected relationships are presented in figure 7.2.

If, on the other hand, slopes in the study area became unstable only recently, Christian Medieval and modern materials should be mixed with Islamic period artifacts in deposits that accumulated recently at the base of slopes. These would exhibit only inherited pedogenic characteristics, and they would cap strongly developed soils. Higher

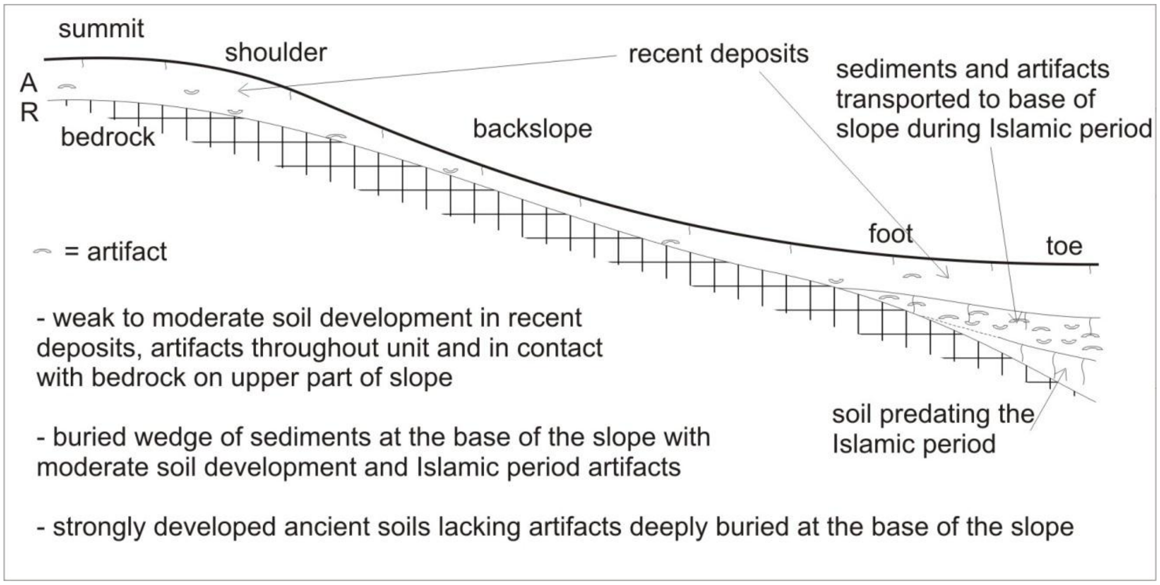

Figure 7.2: Schematic representation of expected soil development and stratigraphic position of artifacts where significant erosion occurred during the Islamic period.

on the slope, the soils should show evidence for recent erosion; B or C horizons should be exposed at the surface. Except where affected by mixing processes, artifacts should be rare or absent at any appreciable depth in the hillslope soils. Figure 7.3 shows schematically the expected distributions of soils and artifacts for this case.

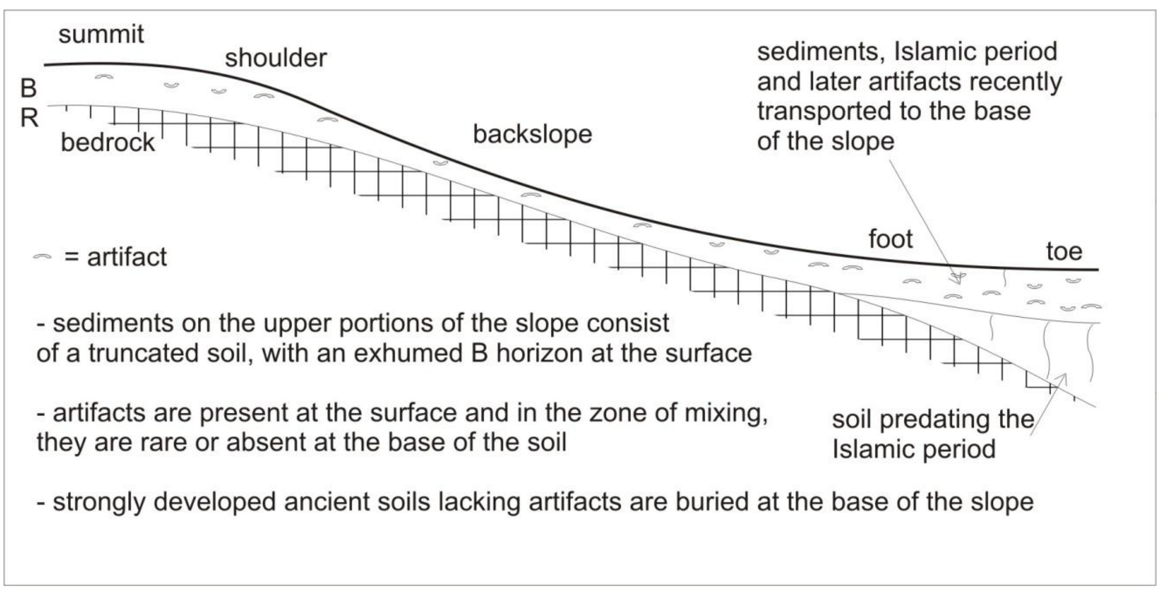

Figure 7.3: Schematic representation of expected soil development and stratigraphic position of artifacts where there has been severe recent erosion.

Summary

The combined data from fluvial stratigraphic studies and from catenary investigations can provide a strong foundation for reconstructing how the landscape changed in the past. An understanding of geomorphic processes allows for some insight into the probable causes of that landscape change. Soil characteristics, artifacts, radiocarbon dating, OSL dating, and magnetic susceptibility measurements illuminate the timing of those changes. Correlations between landscape change and changes in human activities inferred from archaeological and historical data provide one line of evidence relevant to determining whether the landscape changes were anthropogenic. Additional evidence is provided by a comparison of the trajectories of landscape change in the two surveyed areas. Finally, paleoclimate reconstructions suggest that landscape change was not driven by major climate shifts. In concert, the information facilitates an historical reconstruction of how and when the landscape in the study area changed as well as providing the foundations for strong inferences about why it changed.

Chapter 8:

Results and Interpretations, Fluvial Contexts

All of the data produced during this investigation are presented in the appendices. Full pedostratigraphic descriptions and detailed interpretations of each profile are given in Appendix 1, along with graphs illustrating changes in magnetic susceptibility with depth. Radiocarbon and OSL age estimates also are included in Appendix 1 for each locus from which samples were analyzed. The magnetic susceptibility data used to generate the summary graphs are presented separately in Appendix 2, and the complete OSL data are presented in Appendix 3. This chapter summarizes pertinent in-field observations and laboratory results for each study unit exposed by recent arroyo formation, along with a soil test pit excavated near the base of the hillslope at Alcaria Longa during the first season of fieldwork. Initial interpretations are offered concerning the ages of deposits and what they reveal about the history of landscape change in each of the surveyed areas.

Eight formal pedostratigraphic descriptions were completed at locations in the 1992 survey area where recent channel formation has exposed stratified deposits. These are designated Fluvial Study Units 1 – 7 and the Cerro da Loiça OSL Soil Test Pit. Six analogous locations were chosen for formal descriptions in the southern portion of the 2004 – 05 survey area, identified as Fluvial Study Units 04-01 – 04-06. One additional fluvial profile was described subsequently in the same area. Located at the base of a slope on which soil test pits were excavated in order to study hillslope deposits, it is identified in Appendix 1 as 2004 – 05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 5. The locations of the fluvial profiles in the 1992 survey area are shown in figure 8.1, and figure 8.2 shows the locations of the fluvial study units in the 2004 – 05 survey area. The fluvial study units in the 1992 survey area are considered first in this section, followed by the fluvial study units in the 2004 – 2005 survey area. An initial comparison of the data for the two surveyed areas is presented, highlighting contrasts that indicate different histories of landscape change in each area.

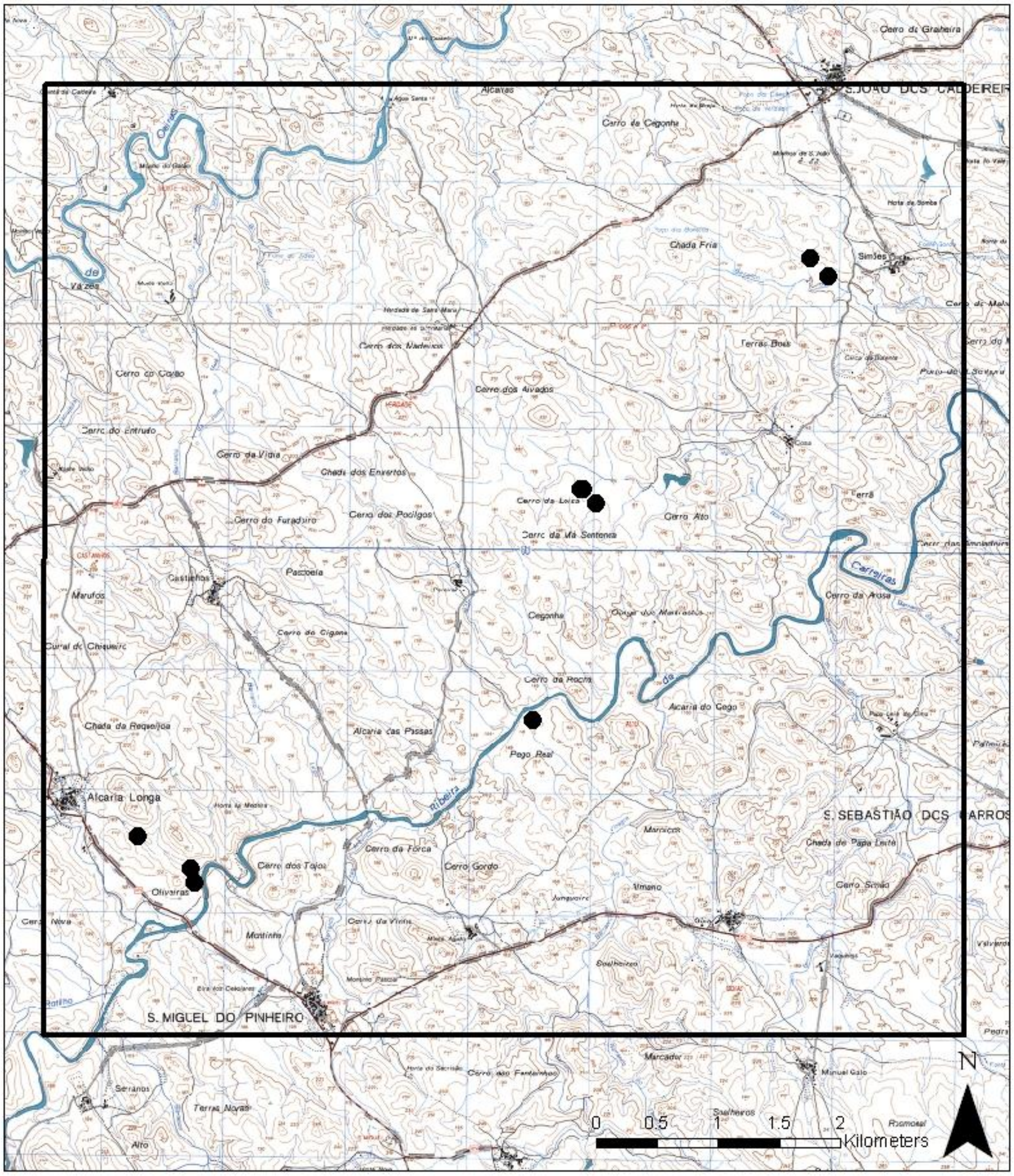

Figure 8.1: Map showing the locations of fluvial study units in the 1992 survey area.

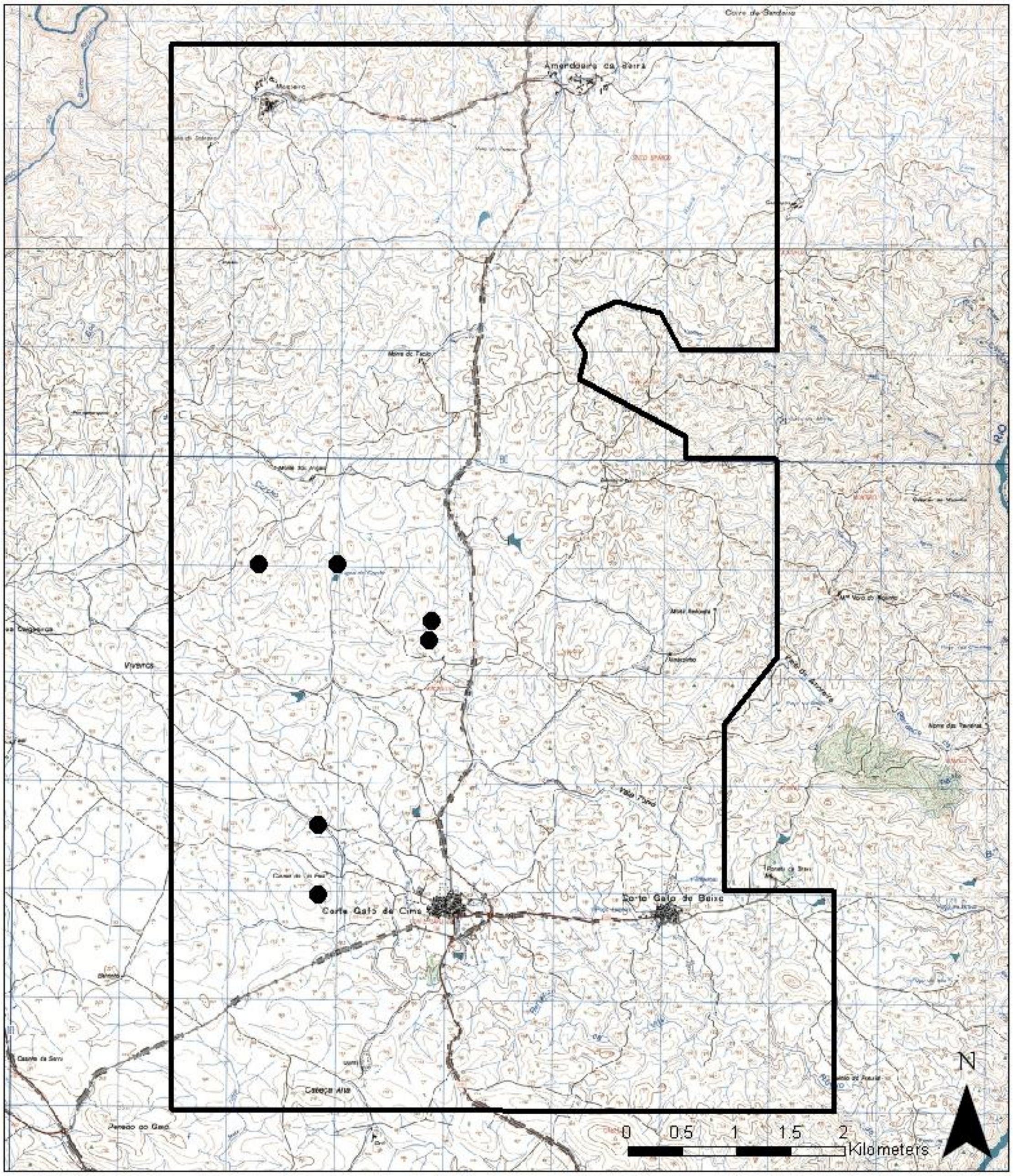

Figure 8.2: Map showing the locations of fluvial study units in the 2004 - 05 survey area.

1992 Survey Area

The fluvial study units in the 1992 survey area expose a variety of strata. Some were deposited or reworked by small-scale fluvial systems, others by higher-order streams, and some are *in situ* hillslope deposits exposed by lateral movement of small, incised ephemeral stream systems. Figure 8.3 provides measured profile drawings of each study unit where arroyo formation has exposed sediments emplaced fluvial processes (i.e., study units 2, 6, and 8 are excluded). Taken together, the profiles record an episode of widespread erosion in the past, followed by a protracted period of relative landscape stability and then by renewed hillslope erosion and floodplain deposition. Wherever artifacts were present, their stratigraphic position indicates an association between the past erosion and the occupation of nearby sites during the Islamic or Roman periods. Radiocarbon assays for samples from the best contexts corroborate this association, as do OSL age estimates. The subsequent interval of relative stability corresponds temporally to a period of economic stagnation and depopulation following the Christian *reconquista*. The recent and ongoing episode of erosion appears to be correlated with widespread changes in land use during the 20th century. The evidence strongly suggests that humans have caused major soil erosion and landscape degradation in the study area during the later Holocene.

Study Unit 1

Study units 1 and 2 are located in the small wash below the transitional/ Islamic period site of Queimada. Queimada consists of a large, dense scatter of rooftile fragments and other ceramic materials associated with the remains of a small masonry structure that was partially excavated in the 1990's and again during the summer of 2004. The outlines of three rooms were visible, arranged in a linear fashion from the summit of the hill downwards along a ridge above the wash. Figure 8.4 shows the foundations of the walls of the lowest of the three rooms. The site appears to have been a small rural farmstead. Calibrated mean probability radiocarbon dates from the site suggest initial use in the 7th century (647 CE; Geochron lab number GX-21332) and occupation until, or later reoccupation during, the late 9th to early 10th Centuries (873 and 903 CE; Arizona lab numbers AA62720 and 62719. Dates are reported fully in Boone and Worman 2007).

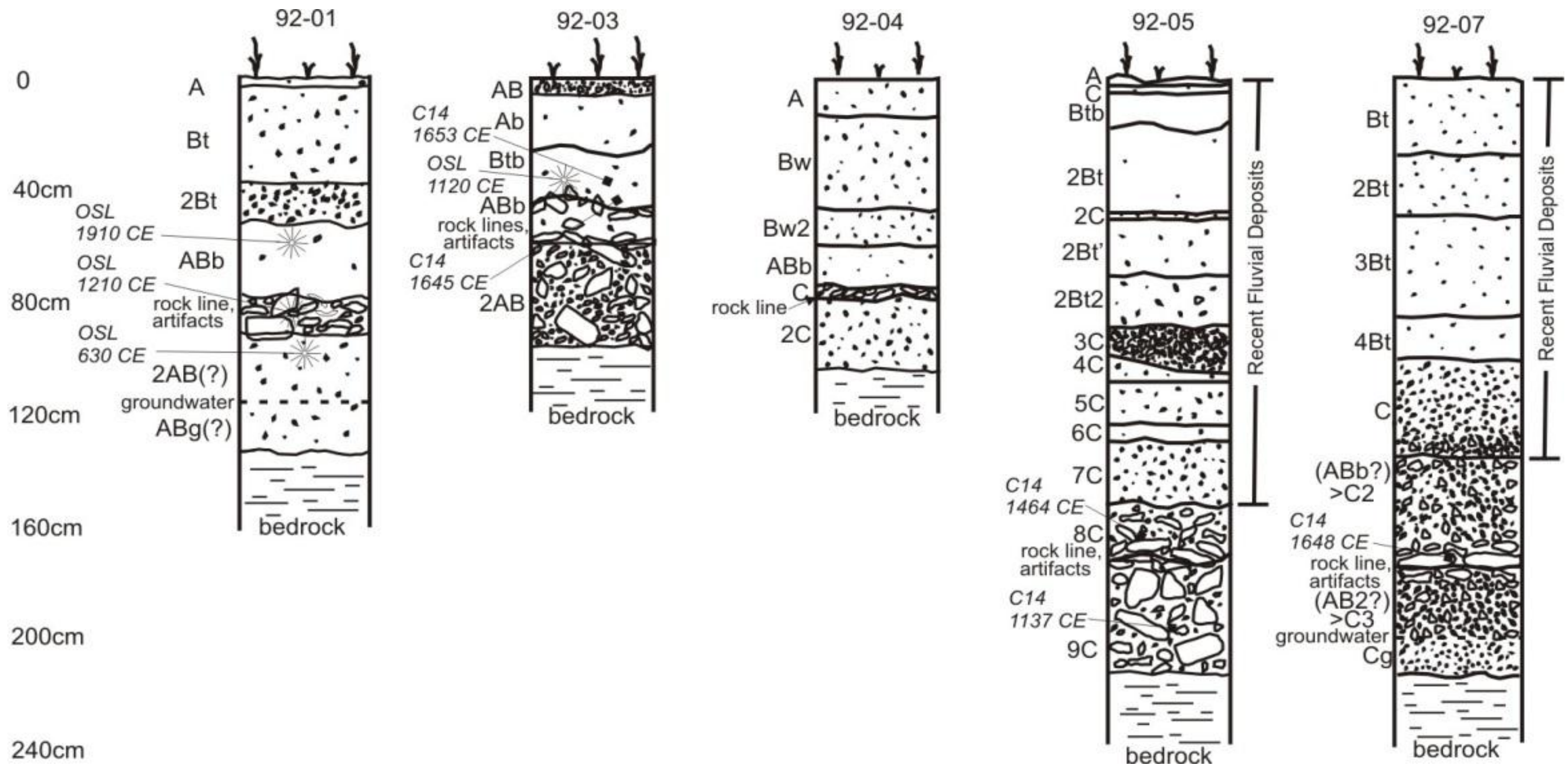

Figure 8.3: Measured profile drawings of fluvial study units in the 1992 survey area, showing soil-stratigraphic units, depth of stone lines, and locations of clasts, artifacts, and samples taken for age estimates. OSL ages for 92-01 are by correlation to adjacent soil test pits. All OSL ages are from single-grain assays. Note that "stippling" shows size and location of clasts; see sediment descriptions in text and Appendix 1 for sediment textures.

Study unit 1 exposes a series of strata emplaced or reworked by the small seasonal stream below the site. The basal deposits are difficult to interpret because they were saturated and partially submerged by groundwater during fieldwork. Angular clasts and the lack of artifacts suggest that there was an initial period of rapid colluvial deposition antedating occupation by agricultural populations, i.e. during the Pleistocene or associated with the Pleistocene – Holocene transition. A single-grain OSL assay from sediments in the same stratigraphic position in the OSL test pit, located a few meters away, suggests that slow deposition at the base of the hillslope continued through the Roman era; the stream likely removed those younger deposits at the location of the fluvial profile.

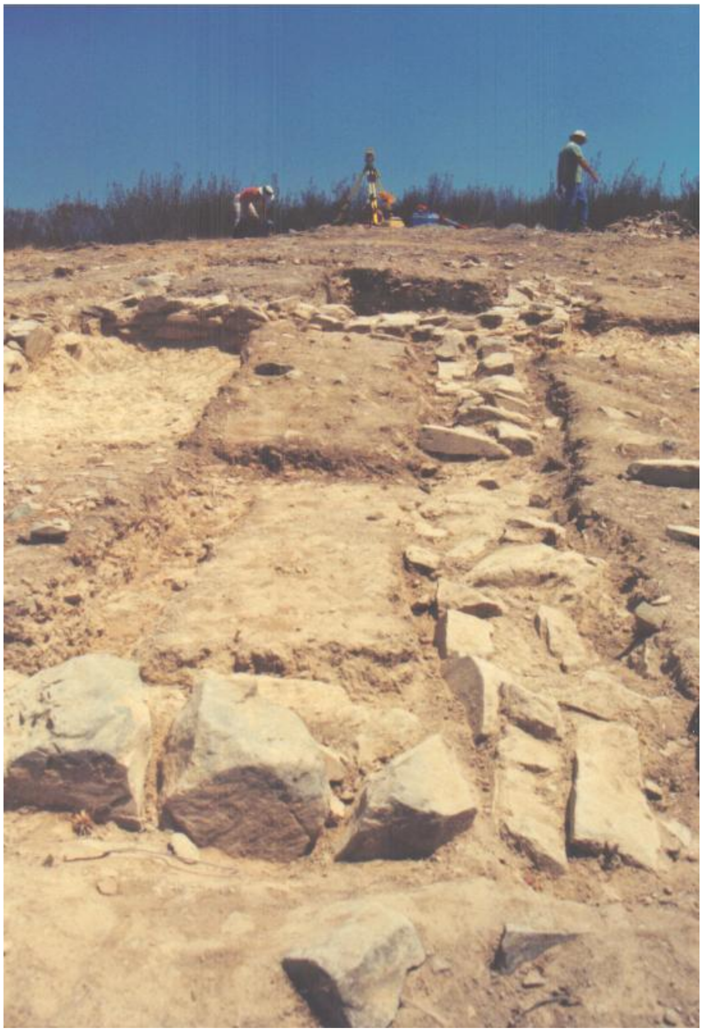

Figure 8.4: Photograph of excavations at Queimada showing wall foundations.

The superjacent, rocky stratum is the bedload of an incised stream channel, probably similar to that which is present today. The inclusion of artifacts suggests arroyo formation, most likely associated with significant hillslope erosion, during or after occupation of the nearby site. The stone line appears to be laterally continuous with a lag deposit encountered in the OSL pit and soil test pit 5, both located toward the base of the slope a few meters away. A single-grain OSL assay on a sample taken from the lower portion of lag deposit at test pit 5 returned an age estimate of 790 +/- 70 BP (1210 CE), suggesting erosion and channel formation during the later Islamic period.

The structure, clastic content, and texture of the overlying unit suggest that it is a buried soil, representing a protracted period of landscape stability. The clear lower boundary is due to a dramatic change in clastic content and texture and most likely is not indicative of recent deposition. Clay films, however, are not quite as strongly expressed as would be expected in a well-developed soil, perhaps due to eluviation in the past when the sediments were at/ near the surface. The interpretation of this unit as reflecting landscape stability and moist conditions on an unincised floodplain is not entirely unproblematic and partially relies on comparisons to nearby hillslope soils and dated strata from test pits excavated at the base of the hill. A single-grain OSL age estimate from this unit at the OSL test pit suggests that it remained at or near the surface until approximately 90 years ago. In any case, pedogenic characteristics are weakly expressed in all of the overlying strata and they clearly reflect recent, rapid deposition, probably associated with changes in land use during the 20th century.

Study Unit 2

Study unit 2 is situated where a meander of the same seasonal stream has cut through and exposed hillslope deposits downstream from Queimada. It is at the base of the backslope portion of a hillslope and at the edge of a small floodplain; the channel has removed the foot and toe slope deposits. Straightforward soil horizonation and the single peak in magnetic susceptibility in the rubified, cambic Bw horizon imply that pedogenesis has outpaced deposition and suggest no significant recent erosion or addition of sediments in this location. The clear lower boundary of the Bw horizon that would appear to contradict this interpretation is most likely attributable to plowing before channel incision made mechanical cultivation impractical in this location.

No artifacts or organic materials were encountered that can be used to estimate the timing of deposition. The color and ped structure characterizing the Bw and Bt horizons suggest moderate soil development, comparable to that observed in other soils in the study area where included artifacts suggest that the sediments were deposited after approximately 1,000 years ago. As in study unit 1, the clay film morphology is somewhat weaker than would be expected given the inferred age of the deposits. In this case, it likely is due to the position of the study unit in a location that would have received little run-on and few or no fluvial inputs.

Given the geomorphic position of the exposure, the majority of the data are consistent with widespread hillslope erosion approximately during the Islamic era; sediments removed from higher on the slope likely were deposited during that cycle of erosion and had been preserved intact until the recently-formed arroyo cut through them. Recent hillslope erosion does not seem to have affected these deposits significantly, although the abrupt lower boundary of the A horizon implies recent mobility and redeposition of the uppermost few cm of sediments. It is at least plausible that this slope was cultivated only a few times during the 20th century before the formation of the current channel made access difficult or impossible.

Study Unit 3 and Cerro da Loiça OSL Soil Test Pit

Study units 3 and 4 are in a small incised wash near the Roman era site of Cerro da Loiça and the Cerro da Loiça OSL Soil Test Pit is located adjacent to study unit 3. Although the site has not been excavated, surface finds including terra sigillata ceramics, tegulae (Roman-style ceramic roof tiles), and a single coin indicate that it was occupied during the later Roman period (ca. 1st to 5th Centuries CE). The horizontal extent of the scatter of artifacts and building stone, and the location of the site on the valley floor suggest that it was a modest rural farmstead. A photograph of some of the artifacts present at the surface is reproduced in figure 8.5.

The strata in study unit 3 and the OSL test pit broadly mirror those in study unit 1; a photograph of the exposure prior to cleaning and recording is shown in figure 8.6. The basal stratum appears to have been rapidly deposited, probably in an episode of landscape change related to major climate shifts prior to significant occupation of the area by agrarian populations. The superjacent unit consists of the bedload and fill in an old stream channel and it includes artifacts that almost certainly originated on the nearby site, providing a maximum age for this deposit in the Roman period. The angularity of the clasts in the bedload deposit suggests that the channel persisted for a relatively short period of time. The lack of rounding also reflects short transport distances, which is expected given that the stream drains a small basin (.175 km^2). The unusually deep soils in this area, relative to the rest of the study area, may have facilitated rapid stabilization of the landscape and filling of the channel following arroyo formation.

Figure 8.5: Photograph of surface artifacts at Cerro da Loiça, showing terra sigillata sherds and fragments of tegulae and coarse wares. 1 € coin (slightly larger than US quarter) for scale.

The ped structure and clay film morphology in the overlying Btb horizon (analogous to the upper portion of the 2ABb horizon in the OSL Soil Test Pit) imply a protracted period of landscape stability and soil formation. As the clastic content of the bedload deposit made it impossible to recover OSL samples and impractical to recover organic materials by flotation, the upper and lower portions of the Btb horizon (again, equivalent to the 2ABb horizon above the stone line) were sampled to provide a minimum age for the subjacent deposit and to test for gradual filling of the channel following the shift to aggradation. Accepted uncritically, the radiocarbon results suggest that the channel filled relatively rapidly during the mid-17th century. The estimated age (median date) of the carbon sample recovered by flotation of sediments taken from the lower portion of the unit at a depth of 40 – 45 cm is 1645 CE (2 sigma calibrated range 1515 – 1951 CE with four intercepts, Arizona lab number AA 76890). The estimated age of the fragment recovered by flotation of sediments taken from the upper portion at a

depth of 30 – 35 cm is 1653 CE (2 sigma calibrated range 1517 – 1951 CE with five intercepts, Arizona lab number AA 76889). The similarities in the age estimates imply that the fragments likely reflect a single episode of burning in the past, burning that perhaps triggered erosion that mobilized hillslope sediments that then filled the channel.

Figure 8.6: Cerro da Loiça OSL exposure prior to excavation and recording. Note the large rooftile fragment to the right of the shovel. Smaller artifacts also were present in the streambed facies of large, sub-horizontally oriented clasts. Folding rule in 20 cm segments.

OSL ages, on the other hand, suggest that the fine sediments filling the channel are significantly older than the included organic materials. Multi-aliquot analyses suggested channel filling during the later Roman era, but a single-grain reanalysis of sediments from the 2ABb horizon above the channel bedload deposits in the OSL Soil Test Pit showed that the multi-aliquot ages are anomalously old due to partial bleaching. The single-grain age estimate of 880 +/- 70 years BP (1120 CE) indicates channel filling during the late Islamic period. There is no reason to suspect any significant error in the

single grain age estimate. Given the shallow depths from which the samples were taken and the high potential for bioturbation in the loamy floodplain deposits, it is reasonable to conclude that the radiocarbon-dated samples are intrusive (figure 8.3 illustrates the stratigraphic relationships between the samples).

The angularity of the clasts in the bedload, as noted above, suggests that the incised channel persisted for a relatively short period of time, perhaps on the order of years or decades. This, in turn, implies that initial channel formation as well as filling may have occurred during the later Islamic period, and the OSL age estimate corresponds remarkably well with the radiocarbon assay from the most reliable context encountered during this study, sample SU5 FS#47, collected from Fluvial Study Unit 5. The radiocarbon age estimate, discussed in greater detail below, is for a sample from a context that reflects channel formation and rapid initial filling. The inferred timing of channel incision adjacent to Cerro da Loiça is particularly significant because it suggests that channel formation was related to widespread landscape change during the later Islamic period, and not to localized erosion around sites while they were occupied (i.e., during the Roman era, in this case). Even if the channel formed and began to fill earlier, the OSL date reflects channel filling caused by significant hillslope erosion in the drainage basin during the later Islamic period.

Overall, the deposits above the stone line are a cumulic soil profile. They reflect an extended period of sediment deposition at low points on the landscape following an initial episode of severe erosion, channel formation, and initial filling. The channel appears to have remained buried, reflecting a relatively stable landscape, until there was renewed hillslope erosion/ floodplain deposition associated with increasing human pressure on the landscape in the 20th century. The abundant evidence of bioturbation and mixing due to plowing in the Ab horizon suggests that finer horizonation and original depositional structures may have been obliterated, obscuring some of the evidence for recent deposition. The clear lower boundaries of the AB and ABp horizons at the surface, however, demonstrate that they were deposited recently, and pedogenic characteristics suggest that they consist primarily of soils eroded from adjacent hillslopes. The increased clastic content suggests deflation prior to the modern episode of arroyo formation.

Study Unit 4

Although there are no artifacts to provide temporal control and radiocarbon and OSL samples were not collected here, the deposits exposed in study unit 4 correlate well with those in study unit 3 and the Cerro da Loiça OSL pit. Differences in texture and clastic content between the facies exposed in each cut reflect their positions within the fluvial system. The only exception to a straightforward correlation is that the preservation of original depositional structures in the lowest stratum in study unit 4 shows that it is fluvial in origin, as opposed to the basal unit higher in the drainage basin that probably was emplaced by mixed colluvial and alluvial processes. With the current data, it is not possible to determine whether the lowest stratum in study unit 4 reflects the presence of a stream in the distant past or when the arroyo formed that contains Roman period materials in the upstream profile. The lack of artifacts lends only weak support to the former hypothesis as artifacts are rare in this location, farther from the site. In either case, there is clear evidence for erosion and arroyo formation during or after the Roman period in the form of a stone line analogous to that which contains artifacts in profile 3. The superjacent horizon again shows some evidence for protracted landscape stability and pedogenesis. The uppermost 60cm of sediments show little evidence of soil formation and were apparently deposited recently, prior to the formation of the current arroyo.

Study Unit 5

Study unit 5 is located where a small tributary stream channel cuts through floodplain deposits and joins the much larger Ribeira do Carreiras. Upstream along the tributary is a small, unnamed archaeological site; artifacts at the surface show that the site dates to the Islamic period. The predominance of imbricated, angular and subangular clasts in the basal stratum implies that it was deposited by the tributary stream that drains the basin in which the site is located. Figure 8.7 is a photograph of the profile taken during recording.

Artifacts diagnostic of the califal period were recovered from the basal stratum, as was charcoal that produced a later Islamic period radiocarbon date (2 sigma calibrated AMS date: 1035 – 1219 CE with one intercept and median probability at 1137 CE; sample SU5 FS#47, Geochron lab number GX-30696). The abundance of charcoal and

artifacts in this deposit, the burial together of charcoal and numerous ceramic artifacts of different types, and the depth of burial below the modern ground surface, make this the best context encountered during this study in which to apply radiocarbon dating. Because it is fragile and highly mobile in fluvial systems, the amount of charcoal in the deposit and its association with heavier, more durable ceramics suggests that the cultural materials did not travel far in the stream and that they were emplaced and buried rapidly; deposition and burial very likely occurred shortly after the organic materials were burned and dumped as refuse. In addition, the relative lack of tree wood in cultural contexts dating to the later Islamic period (see summary of macrobotanical study by Boone and Carrión, chapter 3) suggests that old wood is unlikely to be a problem in this case. The target event, deposition, therefore is likely to be very close to the dated event, death of the burned plant material.

Figure 8.7: Photograph of fluvial study unit 5. White tags label pedostratigraphic units, locations of artifacts and charcoal near the base, and inset channel to the right.

The amount of cultural material and the lack of artifacts in superjacent strata that originated in the same drainage basin also suggest that the basal stratum was deposited while the site was occupied, probably because of intentional dumping of refuse into the stream. Alternatively, major erosion in the drainage basin of the tributary stream may have moved dense midden deposits from the recently-abandoned site into the fluvial system. The sediments were then redeposited in an incised channel at the edge of the floodplain of the ribeira and subsequently buried by continued deposition. While it is

possible that erosion at a later date exhumed cultural sediments and transported them into the stream, it seems unlikely that erosion throughout a drainage basin or even along a channel could create the observed concentration of artifacts and charcoal in the basal stratum after midden deposits had been exposed at the surface for any significant period of time.

The texture, ped structure, gradual lower boundary, and greater clast rounding in the next higher stratum suggest an extended period of relative landscape stability. The tributary evidently debouched onto the floodplain of the ribeira at a fairly constant elevation, and there most likely was episodic deposition and/ or reworking by large flood events on the trunk stream. Sediments from the lower portion of this stratum were processed by flotation in order to recover organic materials suitable for radiocarbon dating. The median-probability date of 1464 CE derived from the sample that was submitted for dating suggests that the channel was filling with fine sediments by that time. This may indicate that renewed human pressure on the landscape caused erosion by approximately that date. Alternatively it is possible that, several centuries after major erosion during the Islamic period, new soils were forming on hillslopes and slow, non-anthropogenic erosional processes once again were delivering fine sediments to the fluvial system. The fact that the stratum is capped by floodplain deposits shows aggradation along the major trunk stream after the 15^{th} century.

The higher strata in the profile reflect rapid floodplain deposition due to overbank flooding of the ribeira. The single exception is a lenticular gravelly stratum that is probably a filled channel cut into floodplain deposits by the small tributary. None of these strata exhibits even moderate pedogenesis; they were all deposited rapidly and then buried before being altered by pedogenic processes. It is likely that the sediments were deposited at least in part because of widespread soil erosion in the surrounding area, and the lack of soil development suggests that much of the deposition occurred as recently as the 20^{th} century.

In sum, the basal stratum in study unit 5 records an episode of erosion and channel formation in the past. Artifacts and radiocarbon dating suggest that this occurred during the later Islamic period. The cycle of erosion was followed by a protracted period of relative stability that lasted until further filling of the tributary channel during the 15^{th}

century. After the filling of the tributary channel, deposition caused aggradation along the ribeira, very possibly reflecting landscape and soil recovery following major erosion during the Islamic period. Subsequently, the rate of aggradation increased dramatically due to recent changes in land use that initiated another cycle of widespread hillslope erosion, floodplain deposition, and arroyo formation that exposed the profile.

Study Unit 6

Study units 6, 7, and 8 are near the site of Alcaria Longa. Alcaria Longa is a large hilltop village that was occupied approximately from 950 – 1150 CE. It is comprised of roughly 35 house compounds and covers an area of 1.6 hectares (Boone 1994, 2002; see also Boone and Worman 2007). Study unit 6 is located at a small spring in the wash northeast of the site. The unit was chosen in the hope that it would yield preserved pollen from a waterlogged context; none of the samples yielded sufficient microbotanical remains for analysis. Because spring deposits tend to be complex and only a small exposure was revealed by recent cleaning of the spring, the stratigraphy is not particularly informative regarding landscape evolution. The presence of a weakly developed B horizon at the surface is consistent with recent erosion, and the fact that the spring had been mechanically cleared of sediments also suggests that recent erosion may have buried it. Gravelly strata imply at least one and possibly two periods of increased spring flow in the past. These might be correlated with increased rainfall and/ or the presence of thicker, stable hillslope sediments, facilitating greater storage of groundwater.

Study Unit 7

Study unit 7 is located lower on the same wash as study unit 6, near the confluence of the tributary arroyo with the much larger Ribeira do Carreiras. The stratigraphy is similar to that at study unit 5 with the exception that the lack of artifacts in the basal deposit suggests that it was emplaced before occupation of the site. The two overlying strata (C3 and C2) contain numerous artifacts and therefore date to some time during or after the Islamic period; these are analogous to the basal deposits in study unit 5. Clast content suggests that they are bedload deposits from an old stream channel. Also, as in unit 5, the paucity of artifacts in superjacent strata derived from the same

drainage basin suggests that the hillslope erosion and arroyo formation occurred during or shortly after the major occupation of the site in the later Islamic period.

Clast and soil characteristics indicate rapid deposition and burial of the lower of the two strata (C3) without prolonged exposure at the surface or in the fluvial system. This implies an episode of channel formation associated with rapid hillslope erosion and floodplain aggradation that very likely occurred during occupation of the site. The rounding and imbrication of clasts in the stone line at the upper boundary of the unit, and the concentration of ceramic artifacts without significant quantities of charcoal, suggest that an incised channel persisted in the area at a stable elevation for some period of time after initial channel formation and filling, flushing fine sediments and lighter materials like charcoal into the trunk stream. The incised channel very likely persisted because erosion had removed soils from adjacent hillslopes, causing an increase in runoff and discharge.

A charcoal fragment recovered by flotation of sediments taken from within or immediately above the stone line at a depth of 170 – 185 cm yielded a mean probability age estimate of 1648 CE (2 sigma calibrated range 1517 – 1951 with five intercepts). The size of the fragment (6.5 mg), its proximity to the current and recent surfaces, the loamy texture of the sediments, and the evidence for bioturbation in superjacent strata suggest that it could be intrusive. If it is not, the age estimate implies that an incised channel persisted in this location until the 17^{th} century. The persistence of the channel for almost two centuries longer than the analogous channel in Study Unit 5 may be attributable to the small spring upstream. Alternatively, it could reflect more severe hillslope erosion adjacent to the larger site (Alcaria Longa) during the Islamic period. More severe erosion would have increased the period of time necessary for sediments to accumulate on nearby hillslopes. Not only would hillslope sediments reduce runoff, they had to be in place before they could be transported into the fluvial system and fill the channel. The current data do not allow for any of these possibilities to be ruled out. Hillslope studies carried out adjacent to Alcaria Longa (reported below), however, showed that soils were almost completely stripped from hillslopes in this location, providing some support for the last scenario. Regardless of whether it is intrusive, the remarkably close correspondence of the radiocarbon date with those from samples taken

from the Cerro da Loiça OSL profile is suggestive of widespread burning during the 17th century, perhaps associated with recolonization of rural areas.

The clastic content and ped structure of the two strata above the lower stone line (C2 and C) imply that filling of the arroyo after the occupation of the site was followed by periods of relative landscape stability. Artifacts in the lower of the two probably are redeposited from higher in the fluvial system. A second, weak stone line is present between these strata, and the degree of clast rounding suggests increased inputs from the ribeira. The bed of the tributary stream apparently was stable at that elevation for a prolonged period of time, flushing fine sediments into the trunk stream. Again, the presence of the channel may be related to the spring upstream. The rarity of artifacts in the upper C horizon suggests that the sediments were deposited by the ribeira or that they initially were deposited on adjacent hillslopes after the site was abandoned and subsequently moved into the fluvial system.

The ped structure in most of the superjacent strata (the Bt horizons) initially seems to imply a moderate degree of soil formation. However, given the similarities in texture and the clear to abrupt boundaries between the lower ones and the weak clay film morphologies in the uppermost, these are probably recent deposits with some inherited pedogenic characteristics that have been altered relatively rapidly due to high inputs of water and fine sediment to the soil. The dramatic decrease in clasts and the increased rounding of those clasts that are present suggest that sediments were, for the most part, deposited by overbank flooding of the ribeira. The uppermost meter of deposits probably is related to widespread hillslope erosion during the 20th century.

Study Unit 8

Study unit 8 is located at the base of the slope below Alcaria Longa and is not in a fluvial context. It is included here because it initially was described during the same field season (2003) as the seven fluvial study units in the 1992 survey area and because it provides a useful point of comparison. The pedostratigraphy is almost identical to that described later in Alcaria Longa soil test pit 5 and the Alcaria Longa OSL test pit, both located nearby. The similarities reflect favorably on the field descriptions of soils in terms of replication of results.

At the base of the exposure, rounded clasts in contact with the bedrock suggest that the area was stripped of sediments in the past. The stratigraphic position of artifacts well above this unit places the timing of this event before significant human occupation of the area; like the basal units described in study unit 3, the erosion was probably related to major climate changes in the past, perhaps at the Pleistocene – Holocene transition. The structure, texture, and clay film morphology of the lowest stratum show that it has been near the surface and altered by pedogenic processes for multiple millennia, as it is among the most strongly developed soils examined in the study area.

Above the lowest unit, the structure and clay film morphology of the Bt stratum reflect moderate soil development. Changes in clast content imply different depositional processes than the basal stratum. The diffuse lower boundary shows that deposition occurred at least several centuries in the past. The inclusion of artifacts suggests the movement of sediments to the base of the hillslopes at some time during or after the Islamic period. Alternatively, the artifacts may have been introduced by plowing or other post-depositional processes; almost all are tiny flecks of rooftile or burned clay, and the few pieces large enough to be identified with certainty as rooftile fragments are present within the uppermost 13 cm of the stratum. The pattern is consistent with redeposition due to repeated plowing or heavy trampling on a wet surface. The data from study unit 8 do not allow either post-depositional disturbance or deposition during the Islamic period to be ruled out, although OSL data from the adjacent test pit (described below) support introduction of artifacts by post-depositional processes. Most likely, the Bt unit was at the surface during the Islamic period, and soil characteristics are consistent with disturbance and erosion in this location at that time.

Although recent plowing has obscured many pedogenic characteristics in the surface deposit, the soil attributes are consistent with recent, renewed accumulation of soils transported off of the hillslopes. Two peaks in magnetic susceptibility, at 5 – 10 and at 15 – 20 cm below the modern ground surface, corroborate the impression of ongoing deposition at the base of the hillslope. In sum, study unit 8 reflects erosion and deposition prior to dense human occupation of the area, followed by several millennia of landscape stability. Renewed hillslope erosion and post-depositional disturbance

occurred during the Islamic period, and were followed by several centuries of landscape stability before recent changes in land use practices again destabilized hillslopes.

Discussion

A prominent stone line reflects the persistence of an incised channel for some period of time in the past at each of the study units in the 1992 survey area where sediments were emplaced by the fluvial system (i.e., all units except for 2, 6, and 8). Temporally diagnostic artifacts and a radiocarbon assay from profile 5, as well as artifacts in profiles 1, 5, and 7, show a correlation between the past cycle of channel formation and the Islamic period occupation of the area. Artifacts in profile 3 and the Cerro da Loiça OSL profile and stratigraphic correlations between profiles 3 and 4 demonstrate that channel formation occurred in that basin during or after the Roman period. OSL assays indicate significant hillslope erosion and channel formation and filling there and at profile 1 during the later Islamic period.

In each case there is additional evidence that the past channel formation was followed by a period of landscape stability prior to renewed hillslope erosion and channel formation. The relative stasis is associated with depopulation after the Islamic period, which allowed sediments to accumulate and soils to form once again on hillslopes. The landscape appears to have remained relatively stable prior to dramatic increases in anthropogenic pressure that occurred during the 20th century. A second radiocarbon assay from profile 5 shows that the channel in that location maintained a quasi-stable elevation until the 15th century. Although possibly from a sample introduced by bioturbation, a radiocarbon date from profile 7 suggests channel filling there during the 17th century. That assay and two others from profile 3 imply widespread burning in the area during the 17th century, possibly associated with renewed population growth in rural areas or episodes of drought (Drake *et al.* n.d.).

Temporally diagnostic artifacts, radiocarbon dates, and OSL age estimates therefore help to constrain the timing of landscape change in the past. The data suggest that incised channels, represented by the stone lines, formed roughly contemporaneously across the surveyed area. In fact, the radiocarbon date that reflects channel formation at study unit 5 and the OSL dates from strata reflecting erosion and channel formation and filling adjacent to the sites of Queimada and Cerro da Loiça all overlap in the 12th century

at the 1-sigma confidence level. Within the limitations imposed by current technologies, erosion and channel formation occurred simultaneously at the dated loci across the 1992 survey area. The temporal correlation implies that they formed in response to similar conditions. In order to test these inferences further, the depth to each stone line was compared to the size of the drainage basin above the profile. Similarly, the depth of the modern channel also was compared to the size of the drainage basin. The results are presented in figures 8.8 and 8.9.

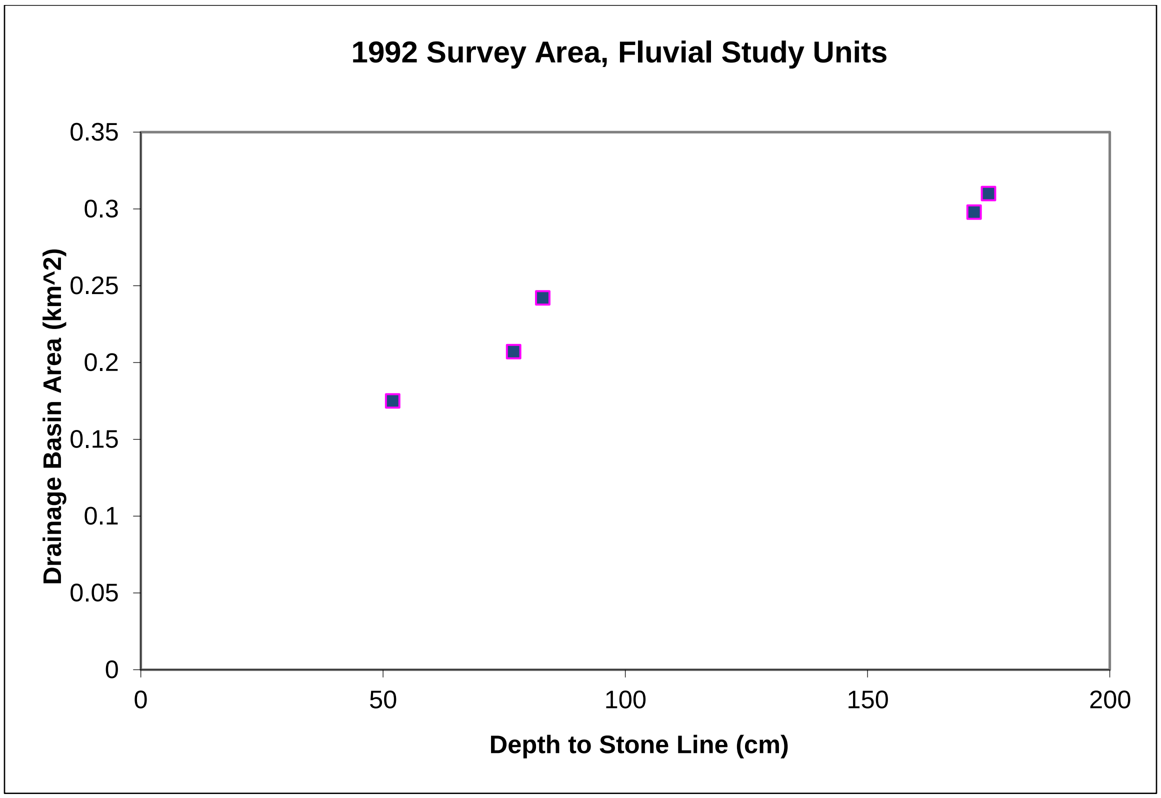

Figure 8.8: Drainage basin area vs. depth to stone line, 1992 survey area.

All other things being equal, larger drainage basins will produce more sediment and runoff than smaller basins. The increased discharge in the fluvial system in larger drainage basins creates the potential to cause deeper channel incision. Similarly, the higher sediment flux creates the potential to build thicker floodplain deposits. If each drainage basin and fluvial system experienced similar changes in factors affecting erosion and deposition, and if those changes occurred at about the same time, there should be regular relationships between the depths to the stone lines and modern channels and

drainage basin area. On the other hand, if any of the profiles shows a markedly different pattern it is likely that processes acting in that drainage basin were different in nature, timing, or duration from processes in the other basins.

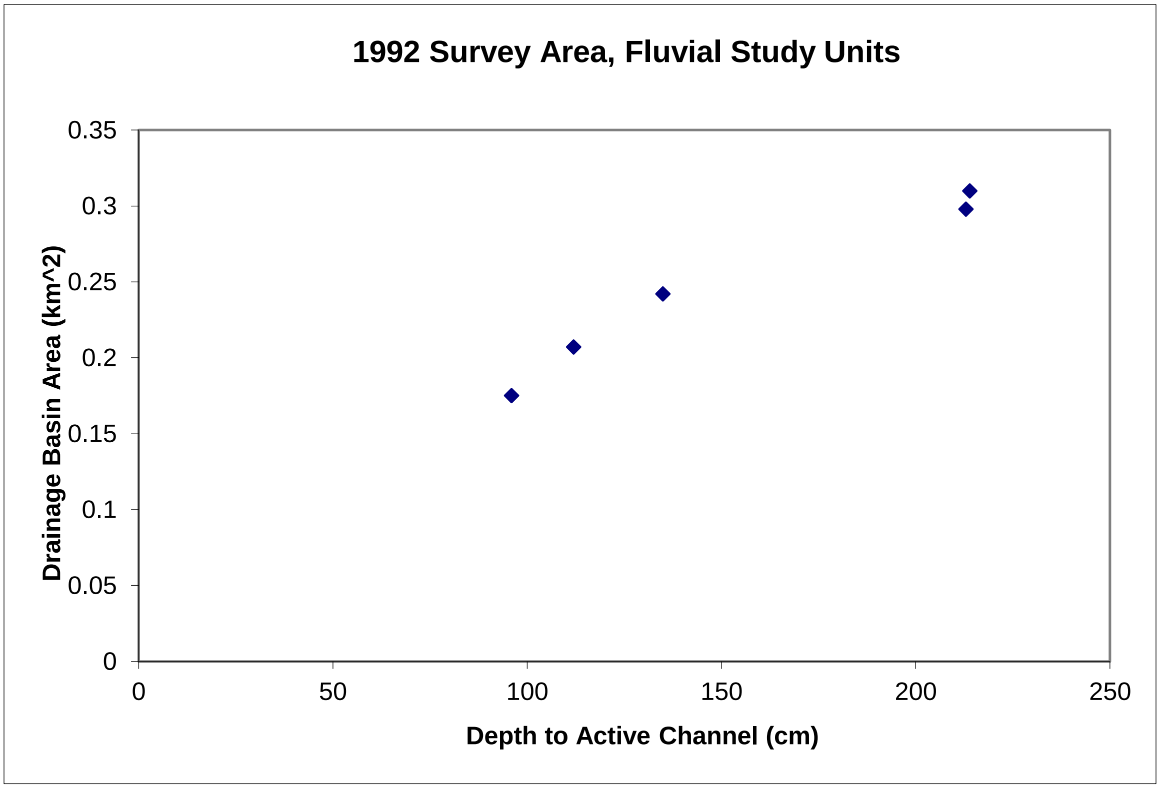

Figure 8.9: Drainage basin area vs. depth to active channel, 1992 survey area.

The temporal inference, that the depths to the old channels (i.e. the stone lines) are related to the timing of channel formation and subsequent floodplain deposition, relies on the untested assumptions that loose surface sediments accumulate at similar rates and land use has been similar in the different drainage basins. Land use practices currently are similar and, given the similarities in bedrock, soil types, and aeolian inputs, these assumptions seem warranted. The amount of sediment available to be moved to the base of slopes and redeposited by fluvial systems prior to the recent formation of incised channels – and therefore the thickness of those floodplain deposits – therefore should be proportional to the size of the drainage basin and the time elapsed since the last cycle of channel formation.

As figures 8.8 and 8.9 show, there are roughly linear relationships between drainage basin size and depth to stone lines as well as basin size and depth to the active channel. In addition, the patterns are remarkably similar in both graphs. While this is no more than a preliminary test, it suggests that each of these basins and fluvial systems has responded in similar ways to changes in factors affecting erosion and deposition both in the past and in the present. It also implies that the current cycle of arroyo formation may be a reasonable analog for the past episode of channel incision; the channels probably were continuously incised from somewhere above each study unit through to the local trunk stream, as they are today. Coupled with the age estimates for various strata and inclusion of artifacts in all but one of the stone lines, this provides support for the inference that erosion and arroyo formation in the past were caused by human activities just as they have been during the 20th century. Perhaps most importantly, the inferences are consistent with the constraints on the timing of landscape change inferred from other data.

In sum, the fluvial study units in the 1992 survey area all support the same reconstruction of landscape evolution in the study area as follows: Before occupation by agrarian populations, there was a widespread episode of hillslope erosion and deposition at lower points on the landscape. In study unit 3 and at other locations observed in the field, the abundance, angularity, and orientation of clasts suggest that mass movements ("landslides") were one significant process of landscape change at that time. Observations at study units 5, 8, and possibly 4 suggest that erosion removed all loose surface sediments in many locations. This finding corresponds well with Chester and James' (1991, 1999) conclusion that there was a major episode of hillslope erosion and valley floor alluviation in the Algarve region prior to 7400 BP (see also Thornes and Gilman 1983 for a discussion of similar findings in southeastern Spain). It seems reasonable to infer, as they do, that this episode of landscape change was caused by major climate shifts related to the Pleistocene – Holocene transition.

Subsequently, during the early to mid-Holocene, hillslopes appear to have been stable for several millennia, allowing sediments to accumulate and soils to form. These soils are not well represented in the current sample, in part because the basal units in several of the exposures were saturated by or immersed in groundwater during fieldwork.

In other contexts where the basal units were visible, later erosion seems to have removed or reworked these mature soils, or the deepest sediments were too deeply buried in the past to have been affected significantly by near-surface pedogenic processes. One example of these older soils was, however, present at the base of study unit 8 and other examples were encountered in the hillslope soil test pits discussed below. The data seem to corroborate Chester and James' inference of relative landscape stability and soil development from approximately 7400 to 3000 BP.

The data further suggest that there was an episode of renewed erosion associated with increased population densities during the Islamic period. Sediments were transported to the base of hillslopes and into the fluvial system throughout the surveyed area. Streams incised their channels, some of them reaching bedrock, and their bedloads are represented by the stone lines visible in the fluvial study units. As there is no evidence for major climate shifts at the time (i.e., similar in severity to the Pleistocene – Holocene transition), the formation of channels likely was caused primarily by human activities that triggered widespread soil erosion and increased runoff from hillslopes. Another phase of landscape stability and pedogenesis ensued, temporally correlated with a significant reduction in population density during the Christian medieval period. Radiocarbon dates suggest that the channels began to fill during this period of relative stability, as sediments accumulated and soils formed on adjacent hillslopes. Finally, changes in land use practices during the 20th century initiated another episode of widespread hillslope erosion, causing floodplain aggradation and eventually culminating in the recent incision of stream systems throughout the study area. Again, these results mirror those of Chester and James and other geomorphologists working in the region who attribute major landscape changes after 3000 BP to human activities.

2004-05 Survey Area

The seven fluvial study units described in the 2004 – 2005 survey area expose strata deposited and reworked by fluvial processes in first-order and larger stream systems, as well as *in situ* hillslope deposits. Figure 8.10 provides measured profile drawings of the six exposures initially recorded as fluvial study units. The last exposure was recorded during hillslope studies. It is discussed here and shown in a photograph; the measured profile drawing is incorporated into the figure describing that hillslope in

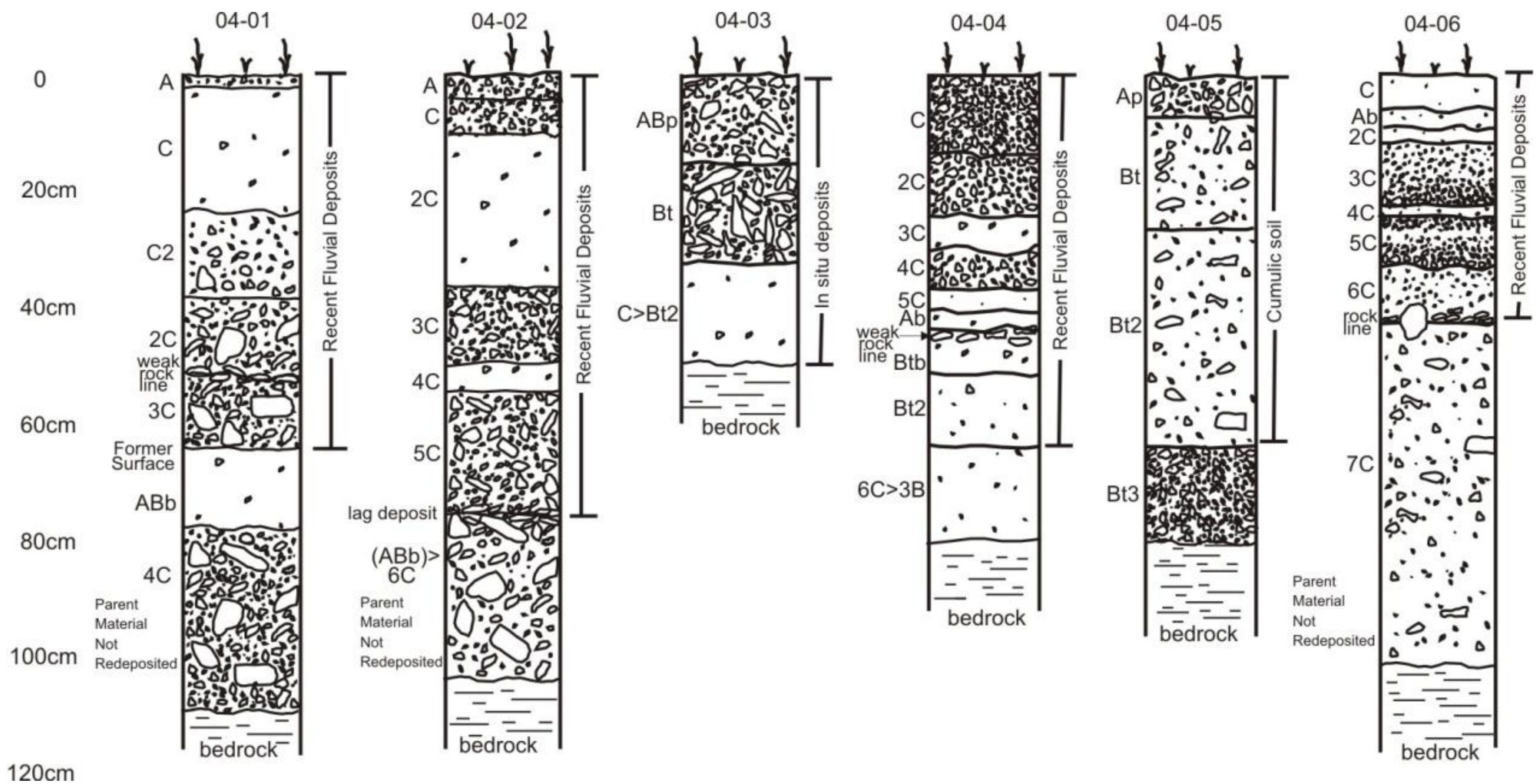

Figure 8.10: Measured profile drawings of fluvial study units in the 2004-05 survey area, showing soil-stratigraphic units, depth of stone lines, and locations of clasts. Note that "stippling" shows size and location of clasts; see sediment descriptions in text and Appendix 1 for sediment textures.

chapter 9, below. The profiles show evidence for hillslope erosion, floodplain deposition, and channel formation. Soil characteristics and stratigraphic relationships in addition to a single temporally diagnostic artifact suggest that all of the landscape changes occurred recently, within approximately the past century. Several profiles included stone lines, evidence of arroyo formation antedating the current incised channels. The sequence of cutting, filling, and renewed cutting most likely is due to complex response in the fluvial systems; the fluvial systems responded to changes in sediment load and hydrology caused by widespread alteration of land use practices during the 20^{th} century. The profiles did not produce any clear evidence for a significant period of erosion during the Holocene prior to the recent increase in anthropogenic impacts.

Study Unit 04-01

Study unit 04-01 is located in the upper reaches of the Barranco do Corcho, approximately 250 meters upstream from a major confluence that roughly doubles the drainage area of the system. The site of Monte do Corcho, occupied at least episodically since the Roman period, is located less than one kilometer to the north (downstream). Despite the proximity of this large site, inhabited for a long period of time, no artifacts were present in the fluvial strata that would help to constrain the timing of deposition.

The two basal units in the profile represent a past period of landscape stability long enough to allow significant soil formation. At the base is a minimally modified C horizon that appears to be made up primarily of decomposing bedrock; color, texture, structure and clay film morphology suggest that this unit was probably deeply buried in the past. The superjacent ABb unit was at or near the surface in the past, and the color, texture, and clay film morphology imply a moderate degree of pedogenesis. This unit pinches out in other parts of the exposure. It was completely removed by erosion in some places and the clear lower boundary in other locations suggests that at least some of the preserved areas were redeposited before burial. While the expression of pedogenic characteristics is higher in this stratum than in any of the superjacent strata, this is not an exceptionally strongly developed soil. The most likely explanation is that the stratum includes sediments that were relatively deeply buried, minimizing pedogenesis, and/ or that it includes sediments redeposited from hillslopes. In either case, the expression of

pedogenic characteristics would have been further reduced by mixing when it was reworked and redeposited.

The superjacent strata in the exposure exhibit weak pedogenic alteration, often with either clay film morphology or structure more strongly expressed than the other characteristic. The meaning of this combination in terms of relative ages and degree of pedogenesis is somewhat ambiguous, but it suggests that some of the pedogenic characteristics very likely are inherited and that soil formation has been accelerated by the abundance of water and fine sediments in fluvial system. These strata probably are made up primarily of redeposited hillslope soils. This impression is corroborated by the presence of two weak stone lines that show that incised channels were present in the past. In both cases, soil characteristics and the variability in clast size and rounding imply that the channels were present for short periods of time, on the order of years to a few decades at most.

While the chronological information that can be inferred from the stratigraphy at unit 04-01 is somewhat ambiguous, it is consistent with a long period of landscape stability in the past followed by more recent erosion. Because of the erosion and possible redeposition of the oldest preserved soil (the ABb horizon), it is not clear whether past landscape stability persisted for centuries or millennia. The makeup of the basal stratum implies that it, at least, has not been disturbed for a period of time on the order of millennia.

The initial period of stability was followed by locally severe erosion of the floodplain and rapid deposition of sediments that originated on the surrounding hillslopes. The deposition was interrupted by episodic, short-lived channel formation. These were probably discontinuous channels that were present before the formation of the current through-flowing channel. The overall pattern is consistent with a major disruption that increased sediment flux and discharge during approximately the past century. The ensuing episodes of deposition and channel formation appear to reflect complex response, with multiple bodies of sediment transported through the fluvial system. The behavior of the system has since changed again with the formation of the current channel, which is continuously entrenched throughout this reach and all lower points.

Study Unit 04-02

Study unit 04-02 is located in an arroyo that cuts through the floodplain of a small tributary to the Barranco do Corcho, approximately 725 meters west of study unit 04-01. The stratigraphy broadly mirrors that at study unit 04-01 in that it appears to reflect an extended period of landscape stability in the past followed by recent impacts to the system resulting in multiple episodes of deposition and channel formation as described by complex response models. There were no artifacts present and no organic materials suitable for radiocarbon dating were recovered that could help to constrain the timing of landscape change.

Based on observations of nearby locations where the arroyo cuts through undisturbed sediments, the basal deposit appears to be decomposing bedrock that is the parent material for the soils forming in this drainage basin. Strong expression of pedogenic characteristics, including clay film morphology, color, texture, and structure, indicates that this stratum was near enough to the surface to be affected by pedogenic processes for a period of time on the order of centuries to millennia. While it is not possible to determine the age of the deposit with greater accuracy with the current information, comparisons to deposits in the 1992 survey area (e.g., fluvial study unit 3) suggest that it initially may have been emplaced by colluvial and fluvial processes during a period of landscape change caused by major climate changes at the Pleistocene – Holocene boundary. The basal stratum is capped by imbricated clasts that clearly are derived from that deposit; this lag deposit indicates that a channel previously cut into, eroded and reworked some of the parent material.

The superjacent strata in the exposure exhibit weakly developed pedogenic characteristics. The sediments were deposited recently by fluvial processes, as demonstrated by the preservation of original depositional structures (e.g., laminae, bedding). They might be flood couplets, as coarser sediments alternate with fine and most strata fine upwards. Although several show relatively strongly expressed structure, weak clay film morphology is consistent with minimal pedogenesis; structure is more strongly expressed in sediments with higher clay content, as often is the case. The relatively strong expression of structure in what otherwise appear to be recently emplaced units is likely due to the abundance of moisture and fine sediments in the floodplain

environment. The degree of rounding of clasts suggests minimal exposure to running water; taken with the other observations, this implies that the upper 75 centimeters of sediments were deposited relatively recently.

Study unit 04-02 reflects an extended period of landscape stability in the past followed by more recent landscape change. The upper horizons of a well developed ancient soil apparently were stripped by erosion and channel formation, leaving the basal unit in place. The superjacent A – 5C strata represent alternating periods of deposition and channel formation as sediments moved through the fluvial system as described by complex response models. Weak expression of pedogenic characteristics in these strata suggests that they are all relatively recent, implying that the changes resulting in disequilibrium in the system also were recent. Finally, the fluvial system became entrenched throughout this reach, suggesting a second change in state to one dominated by rapid removal of water and sediments and minimal deposition.

Study Unit 04-03

Study unit 04-03 is situated in the upper reaches of a small tributary to the Barranco do Corcho, south and east of study unit 04-02. The exposure is a few 10's of meters downstream from the headcut that marks the uppermost extent of a continuously incised channel that connects to the Barranco. The channel appears to cut through a monogenetic soil as it exposes a simple profile with A/ B/ C horizons. There is no evidence for significant sedimentation in the recent past, although erosion clearly is occurring now.

The expression of time-dependent pedogenic characteristics (i.e., structure and clay film morphology) in the basal stratum of study unit 04-03 is as strong as any encountered in the study area, suggesting a period of soil formation on the order of millennia. The stratum is made up of decomposing bedrock with evidence for significant illuviation of pedogenic clays. Prominent mottling reflects frequent, prolonged saturation with groundwater. Although the presence of pedogenic clays shows that the basal stratum has not been deeply buried (>> 1 m), the relative lack of clasts suggests that the overlying strata formed during extended periods of weathering and erosion that removed finer sediments.

Clay film morphology in the superjacent Bt horizon similarly suggests a protracted period of pedogenesis. Structure is not as strongly developed, but this is at least in part due to the high clastic content of this horizon. The uppermost 15 cm are a plowed horizon (ABp) that is similarly enriched in gravels. The gravel content of these strata and the magnetic susceptibility data both suggest that erosion has removed as much as 10s of cm of fine sediments in this area. Plowing has mixed the remnant A horizon with the B horizon, resulting in enhanced magnetic susceptibility at and near the surface. It is not possible to determine with the current data when the ongoing erosion started, but the gradual, smooth lower boundary of the Bt horizon suggests that that horizon does not reflect a previous and separate episode of rapid erosion. The pedostratigraphy at study unit 04-03 is consistent with an extended period of soil formation accompanied by gradual removal of fine sediments from this upland location, followed by a period of more rapid erosion associated with recent plowing of the hillslopes.

Study Unit 04-04

Study unit 04-04 is located northeast of study unit 04-03, approximately 180 meters downstream along the same arroyo. The profile reflects a prolonged period of landscape stability and pedogenesis in the past, followed by recent hillslope erosion and arroyo formation. This study unit provides a link between the profiles observed lower in the fluvial system and the relatively undisturbed upland soils recorded upstream, showing sedimentation and channel formation in response to recent changes in land use in the study area.

At the base of the exposure at study unit 04-04, the 6C>3B horizon is decomposing bedrock with evidence for a relatively high degree of pedogenic alteration. The clay film morphology and structure are not as strongly expressed as in the basal horizon in study unit 04-03, suggesting that the 6C>3B horizon was more deeply buried in the past than the analogous horizon upstream. The three superjacent horizons are a weakly developed, truncated soil that formed in deposits that filled an older channel. Soil structure is relatively strongly expressed, while clay film morphology suggests minimal pedogenesis. The combination probably reflects relatively high water inputs and some of the pedogenic characteristics may be inherited. The overall degree of soil development suggests that this initial channel probably formed some time within the past century and

that infilling was followed by at least a few decades of local landscape stability. The filling and period of relative stability suggest that the channel probably was discontinuous.

The uppermost 42 cm of deposits at study unit 04-04 are a series of strata that evince almost no measurable pedogenesis. The soil characteristics suggest that each was deposited rapidly and subsequently covered before significant soil formation occurred. It is plausible that each represents a separate episode of hillslope plowing and cultivation and attendant soil erosion; farmers in the area typically cultivate cereal crops on individual plots of land roughly every 7 – 10 years.

Study unit 04-04, then, reflects an extended period of landscape stability in the past, probably encompassing several millennia. At some point within roughly the past century, erosion removed an unknown quantity of sediments as a channel formed and partially filled. A period of relative stability ensued that lasted as much as a few decades. Subsequently, the nearby hillslopes were destabilized again and sediments originating there were deposited at lower points on the landscape. Finally, the extant, continuously incised channel formed. The strata appear to record the effects of recent agrarian land use practices and provide some insight into the stratigraphic complexity observed downstream, where changes in sedimentation and hydrology induced by human activities in multiple small drainage basins are recorded.

Study Unit 04-05

Study unit 04-05 is located roughly 2.5 km south of study units 04-01 – 04-04 in a narrow valley with a poorly defined floodplain on a small tributary to the Barranco da Vila. The channel becomes discontinuous a few 10's of meters upstream, but it is continuous from above the study unit through to the Barranco. The deposits record a long period of slow sedimentation and pedogenesis, followed by more recent, rapid deposition at low points on the landscape.

Ped structure and clay film morphology in the deepest stratum at study unit 04-05 suggest a prolonged period of landscape stability and soil formation in the past. The degree of clast rounding suggests that some of the clasts were exposed to moving water, implying fluvial inputs or reworking. Other observations, including the roughness of the surface of the bedrock, the color of the sediments, and clast orientations, suggest *in situ*

weathering; this appears to be a cumulic soil horizon. Similar characteristics in the superjacent deposit show that it also is cumulic, with slow deposition of sediments from hillslopes combining with *in situ* weathering and aeolian deposition to create a relatively thick and well developed soil horizon over the course of centuries to millennia.

The structure and gradual lower boundary of the superjacent Bt horizon indicate that it is genetically related to the deeper horizons and that it has been in place for a significant period of time, on the order of many decades to centuries. As with the horizons beneath, it appears to be cumulic. The weak expression of clay films implies recent inputs and some degree of mixing; these sediments may have been plowed in the recent past. The clear lower boundary, clay film morphology, and structure of the Ap horizon indicate rapid, recent deposition and reworking. These deposits almost certainly were emplaced due to hillslope erosion following recent plowing. In sum, the cumulic soils at study unit 04-05 reflect a very long period of relative landscape stability, with slow deposition at low points on the landscape combining with *in situ* weathering to produce thick soil horizons. Subsequently, sedimentation rates increased dramatically, most likely because of human activity during the 20th century.

Study Unit 04-06

Study unit 04-06 is sited approximately 640 meters north of 04-05 in a broad, well defined floodplain in the upper reaches of the Barranco da Vila. The complicated stratigraphy appears to reflect relatively recent channel formation followed by significant deposition. The basal stratum is made up of decomposing bedrock, as indicated by the color, texture, and clast content. The moderately expressed structure and the weak clay film morphology suggest that these sediments were deeply buried in the past, below the zone of active pedogenesis. The thickness of the stratum indicates a protracted period of landscape stability and bedrock weathering before the initial formation of an incised channel in this location. The superjacent 6C deposit incorporates an imbricated stone line and appears to be predominantly composed of reworked parent material. It reflects initial erosion and channel formation in this location and the structure, color, texture, and clay film morphology suggest a period of relative stability for the channel at this elevation. The clear lower boundary and the lack of differentiation within the subjacent deposit, however, show that the channel did not persist for a period of time long enough to cause

pedogenic alteration of near-surface deposits; the channel was not present for more than a few decades at most.

The overlying deposits exhibit very little evidence of pedogenesis, implying that they were buried rapidly after recent deposition. Original depositional structures are preserved in the four units above 6C (2C – 5C), a characteristic common in weakly developed floodplain soils. The color, structure, clay film morphology, and boundaries of each unit corroborate the impression of rapid deposition followed by burial after a period of years to a few decades at most. The superjacent Ab horizon also exhibits weak pedogenic characteristics, and it incorporates large quantities of well preserved organic material (i.e., leaves, twigs), suggesting recent burial. The C horizon at the surface shows no evidence of pedogenic alteration and the texture suggests that it is a recent deposit emplaced by overbank flooding. In sum, the profile records initial channel formation in the area several decades to as much as a century ago, followed by a brief period of stability and then rapid deposition of sediments on the floodplain and within the channel prior to the formation of the current, through-flowing incised channel. The data are consistent with the recent changes in the fluvial system having been caused by human activities, specifically plowing and cultivation of the surrounding hillslopes.

Hillslope Soils: Slope 1, Soil Test Pit 5

This test pit, initially described during studies of hillslope deposits, exposes fluvial stratigraphy. It is located along the Barranco da Vila, slightly more than ½ km downstream from study unit 04-06. A photograph of the exposure is reproduced in figure 8.11. The ped structure, texture, and color of the basal stratum indicate a protracted period of pedogenesis, on the order of millennia. It clearly grades downward into decomposing bedrock.

The overlying deposit reflects channel formation and filling, as indicated by the presence of a stone line at its base. It appears to be composed predominantly of reworked parent material from the deepest stratum. In this unit, at a depth of 75 cm below the modern ground surface, there was a single sherd of a type produced through the mid-20th century. It was somewhat rounded due to transport in the stream system. Although single artifacts are not conclusive chronological markers, the sherd implies channel filling during the 20th century, temporally associated with the advent of extensive, mechanized

Figure 8.11: Photograph of slope 1 soil test pit 5, which exposed fluvial deposits in the 2004 - 05 survey area. Note sherd *in situ* at point of trowel.

agriculture in the area. Given the lack of pedogenic alteration of the subjacent deposit, the channel did not persist for an appreciable period of time, also implying that the channel initially formed during the 20th century. Characteristics of the overlying strata show that they all were deposited rapidly and buried before significant soil formation occurred. In sum, the strata reflect a long period of landscape stability followed by channel formation during the 20th century. Subsequently, the channel filled and sediments were deposited on the floodplain prior to the formation of the deeper, through-flowing modern channel.

Discussion

Taken together, the stratigraphic profiles recorded at the fluvial study units in the 2004-2005 survey area reflect landscape change caused by, and the response of the fluvial systems to, recent changes in agrarian land use practices. The most straightforward evidence for landscape change is derived from the first-order streams that cut through hillslope soils. The soil exposed at study unit 04-03 reflects a long period of relative landscape stability during which the production of fine sediment through bedrock weathering and other inputs (i.e., aeolian) exceeded the rate of erosion. This was followed by a recent, dramatic increase in erosion rates. Study units 04-04 and 04-05 are in similar geomorphic positions, but slightly lower in the fluvial system, several 10s of meters downstream from the headcuts that mark the upper limits of continuously incised stream systems. In both cases, they show evidence for recent erosion and channel formation as well as recent deposition as sediments were removed from adjacent slopes.

The remaining study units are located still lower in the stream systems and present more complicated stratigraphy. In each case, the data are consistent with recent

deposition and erosion. The basal units reflect extended periods of landscape stability in the past, followed by the initial formation of discontinuous channels. The superjacent strata appear to record the movement of several bodies of sediment through the fluvial system as described by complex response models and by descriptive models of the behavior of discontinuous ephemeral stream systems (e.g., Bull 1997, Schumm 1977). The resulting stratigraphy is complicated and the pedostratigraphic data can be ambiguous regarding the timing of landscape change. Pedogenic characteristics in some deposits are inherited; many of these strata are redeposited, well-developed hillslope soils. In addition, soil characteristics such as ped structure can form rapidly in floodplain environments due to seasonal inputs of water and fine sediments. On the whole, the lack of well developed horizonation in the deposits and the clear boundaries between units suggest that they were emplaced recently and that rapid burial has inhibited pedogenesis.

Finally, in a second major change in the character of the fluvial systems in the surveyed area, each of the streams has incised throughout the reaches observed and head cuts have migrated upstream significantly, with channels forming through hillslope deposits. The current conditions therefore favor rapid removal of water and sediments from the area, with minimal deposition on floodplains during rare overbank flooding events. While the evidence for earlier channels is suggestive of complex response, the modern channels reflect a longer-term, larger-scale shift of the system to a state dominated by sediment removal. This appears to be a response to decreased infiltration rates and increased runoff caused by the removal of soil from hillslopes. The ambiguities encountered in these profiles in the banks of higher order streams, located below larger drainage basins, are inherent in studies of strata deposited by large stream systems and highlight the importance of an integrated approach to geomorphic studies that incorporates data from both fluvial and upland contexts.

No artifacts that would help constrain the timing of landscape changes were encountered while recording the initial fluvial study units in the 2004-05 survey area, and no organic materials suitable for radiocarbon dating were observed or collected. Soil characteristics and stratigraphic relationships, however, suggest that the landscape changes occurred during approximately the last century. Fortunately, an additional fluvial unit was described during subsequent investigations of hillslope deposits. A

temporally diagnostic sherd in channel fill near the base of that profile was of a type commonly in use as late as the mid-20th century, suggesting that significant landscape changes in the 2004-05 survey area occurred in response to changes in land use patterns that have taken place since the early 20th century.

Four of the fluvial profiles in the 2004-05 survey area included stone lines or lag deposits indicative of previous channel formation. On average, the clasts in the stone lines in the 2004-05 survey area were more angular than those in the 1992 survey area, implying that the channels persisted for less time. The angularity of the clasts also is consistent with the interpretation of the channels in the 1992 survey area as older and representing through-flowing channels as opposed to the recent, discontinuous channels inferred for the 2004-05 survey area. In addition, all of the fluvial study units in the 1992 survey area that exposed floodplain deposits included clear stone lines. Of the five units in the 2004-05 survey area that exposed floodplain deposits, four contained stone lines and these were generally less obvious than those in the 1992 survey area. Again, this is consistent with the suggestion that continuous, through-flowing channels did not form and persist for any length of time in the 2004-05 survey area in the past.

As in the 1992 survey area, the depth to the stone lines and total channel depth were compared to the size of the drainage basins. The results are presented in figures 8.12 and 8.13. The data presented in figure 8.13 suggest that there is a roughly linear or geometric relationship between drainage basin size and depth of the active channel. As noted above, this is an expected pattern given that drainage basin size is proportional to the quantity of runoff and sediment that may be transported in the fluvial system. The data summarized in figure 8.12, however, show no discernible linear relationship between drainage basin size and depth of stone lines. Although this is a preliminary test, it suggests that the stone lines do not represent the past existence of through-flowing, incised drainage networks in the 2004-05 study area. Instead, it is consistent with the stone lines having formed in discontinuous ephemeral stream systems in which the amount of water carried in a channel and the erosive potential of discharge would be related to the length of the incised channel as well as drainage basin size. In discontinuous systems, the length of the channel has no necessary relationship to total drainage basin size (Bull 1997). In sum, although it is not conclusive, the evidence

suggests that significant erosion and channel incision have only recently affected the 2004-05 survey area.

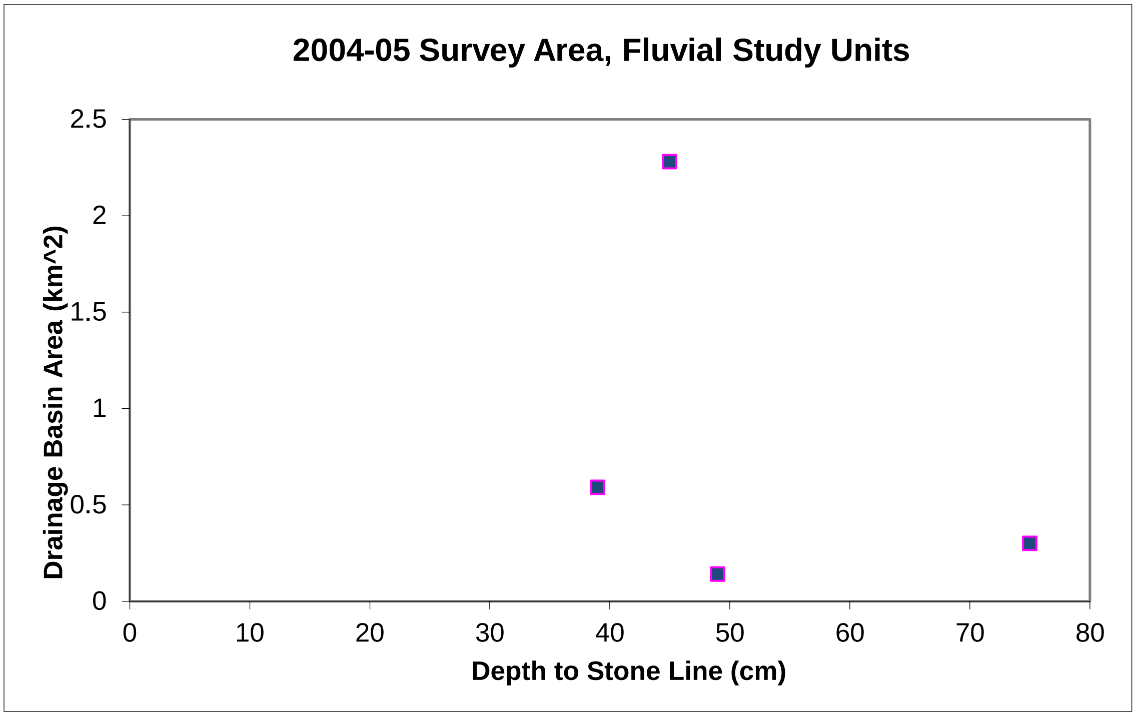

Figure 8.12: Drainage basin area vs. depth to stone line, 2004-05 survey area.

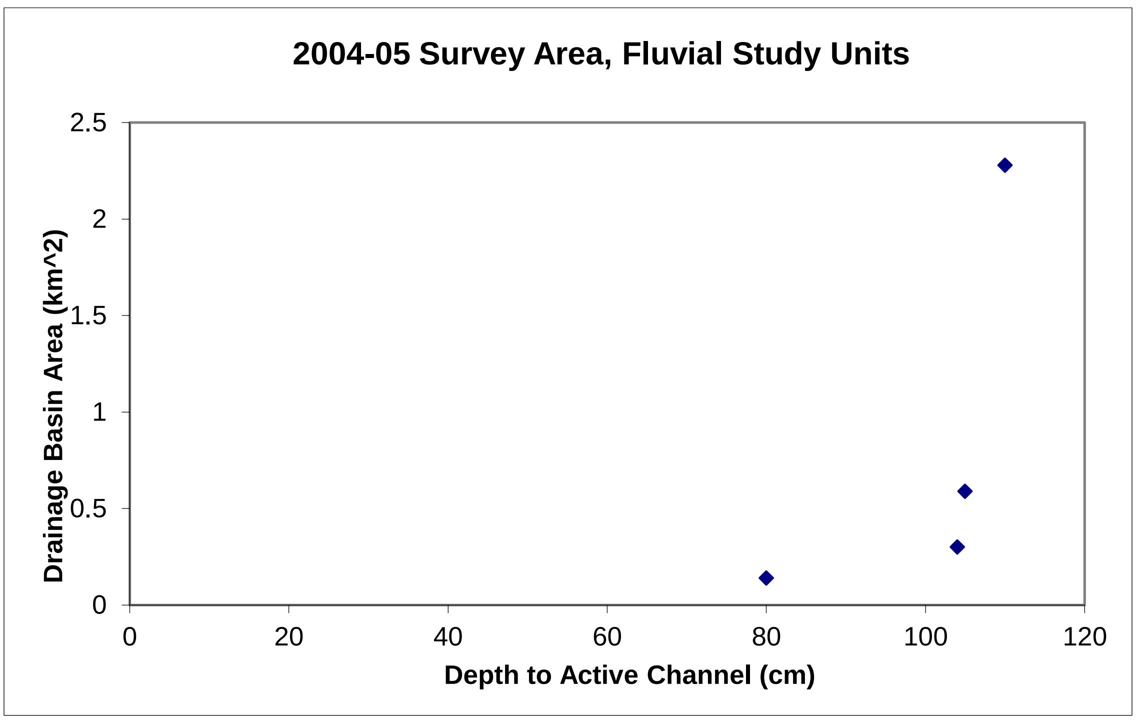

Figure 8.13: Drainage basin area vs. depth to active channel, 2004-05 survey area.

Initial Comparison of Study Areas

Studies of the strata exposed by incised stream channels suggest different histories of landscape change for the 1992 and 2004-05 survey areas. Fluvial strata in the 1992 survey area show a repeated pattern. The basal deposits appear to antedate occupation of the area by agrarian populations. A stone line overlying these deposits reflects the formation of continuous, incised stream channels. The inclusion of temporally diagnostic artifacts and a radiocarbon assay show that these channels formed during or after the occupation of nearby sites in the Islamic and, in the case of study units 3 and 4, the Roman periods. A single-grain OSL age estimate for sediments above the stone line adjacent to study unit 3 suggests channel filling, and probably channel formation, in that basin during the Islamic period. Similarly, OSL dates on correlative strata near study unit 1 show hillslope erosion and channel formation there during the later Islamic period.

Strata immediately above the stone lines generally show moderate degrees of soil development, implying that a protracted period of landscape stability followed arroyo formation. Radiocarbon dates suggest that the channels persisted at stable elevations for three to five centuries, during which time sediments accumulated and soils began to form on the adjacent hillslopes. Similarities in radiocarbon dates from two sites suggest widespread burning, perhaps associated with resettlement of rural areas and episodes of drought during the late Medieval and early modern periods. After sufficient quantities of sediments had accumulated on slopes, providing a source of sediment to the fluvial system, the channels filled and floodplains appear to have remained roughly stable until the 20^{th} century.

The upper 10's of cm of sediments in each of the profiles appear to have been deposited recently, and they exhibit minimal expression of time dependent pedogenic characteristics. They represent renewed hillslope erosion caused by extensive plowing of the hillslopes during the 20^{th} century. Finally, a continuously incised drainage network has formed throughout the surveyed area as erosion caused by mechanical cultivation has removed sediments from hillslopes, leading to an increase in discharge in the stream systems.

Fluvial stratigraphy in the 2004-05 survey area appears superficially similar to that in the 1992 survey area. The basal deposits again appear to have been in place for a period of time on the order of millennia. Stone lines, however, are not present in every case and, where present, are not always immediately above ancient deposits. The variable depth of the stone lines relative to the size of the drainage basins above each profile implies that they do not reflect the past formation of a through-flowing, incised drainage system. In addition, although the expression of pedogenic characteristics in superjacent deposits is variable, clear boundaries between units suggest that the strata above the *in situ* parent material were all deposited recently. Pedogenic characteristics appear to be inherited in most cases, reflecting the removal to the floodplains of well develop soils from nearby slopes. Although not conclusive by itself, a single, recent sherd recorded in deposits immediately above parent material (2004-05 slope 1, stp 5) suggests that initial arroyo formation in the 2004-05 survey area occurred during the 20th century.

In cases where modern channels cut through hillslope deposits, the pedostratigraphic data corroborate the reconstruction of different trajectories of landscape evolution suggested by floodplain strata. The *in situ* soils examined in fluvial study unit 2 in the 1992 survey area exhibit moderate pedogenesis. The degree of development suggests that the sediments in which the soil is forming were deposited relatively recently, within the past several centuries to a millennium. As the sediments rest on bedrock, older sediments must have been stripped from that location prior to deposition. Study unit 8, at the base of a hillslope, exposed ancient deposits at the base. The degree of soil development and measurements of magnetic susceptibility in the superjacent sediments, along with the stratigraphic position of artifacts, suggest erosion roughly a millennium ago, followed by significant deposition within the past decades to century. Both profiles, then, appear to reflect significant erosion roughly a millennium in the past.

By contrast, the *in situ* hillslope soils in fluvial study unit 04-03 in the 2004-05 survey area are among the most strongly developed soils observed in the study area. The pedogenic characteristics are consistent with relative landscape stability and soil formation during multiple millennia, followed only recently by significant erosion. Additional data concerning hillslope deposits adds important information to the

reconstructions of landscape evolution allowed by the studies of sediments exposed by incised fluvial systems, and those data are the subject of the next chapter.

Chapter 9:

Results and Interpretations, Hillslope Contexts

As noted at the beginning of the previous chapter, all data generated during this study are presented fully in appendices. This chapter summarizes pertinent in-field observations and laboratory results for the soil test pits excavated on each of the hillslopes selected for detailed study. Initial interpretations are offered concerning the ages of deposits and what they reveal about the history of landscape change in the study area.

Soil test pits were excavated and the soils and sediments on 11 hillslopes in the surveyed areas were examined and recorded. Soil test pits were excavated on the five geomorphic sections of each slope as described in chapter 6 (i.e., summit, shoulder, backslope, foot and toe of slope). Adjacent to Alcaria Longa and Queimada, additional pits were excavated at the base of the slopes in order provide more exposures and to take samples for OSL dating. In total, 58 soil test pits were excavated and formal soil-stratigraphic descriptions were completed for each.

Five slopes were selected for study in the 1992 survey area. These are designated Alcaria Longa, Queimada, and 1992 Survey Area Slopes 1 – 3. Five analogous slopes were investigated in the southern portion of the 2004 – 05 survey area, identified as 2004 – 05 Survey Area Slope 1 and Slopes 3 – 6. One slope in the northern portion of the 2004 – 05 survey area also was investigated; it is designated 2004 – 05 Survey Area Slope 2. The locations of the catenary studies in the 1992 survey area are shown in figure 9.1, and figure 9.2 shows the locations of the slopes investigated in the 2004 – 05 survey area. The hillslope deposits in the 1992 survey area are discussed first in this section, followed by those in the 2004 – 05 survey area. An initial comparison of the data for the two surveyed areas is presented, highlighting what the hillslope soils reveal concerning the different histories of landscape change in each.

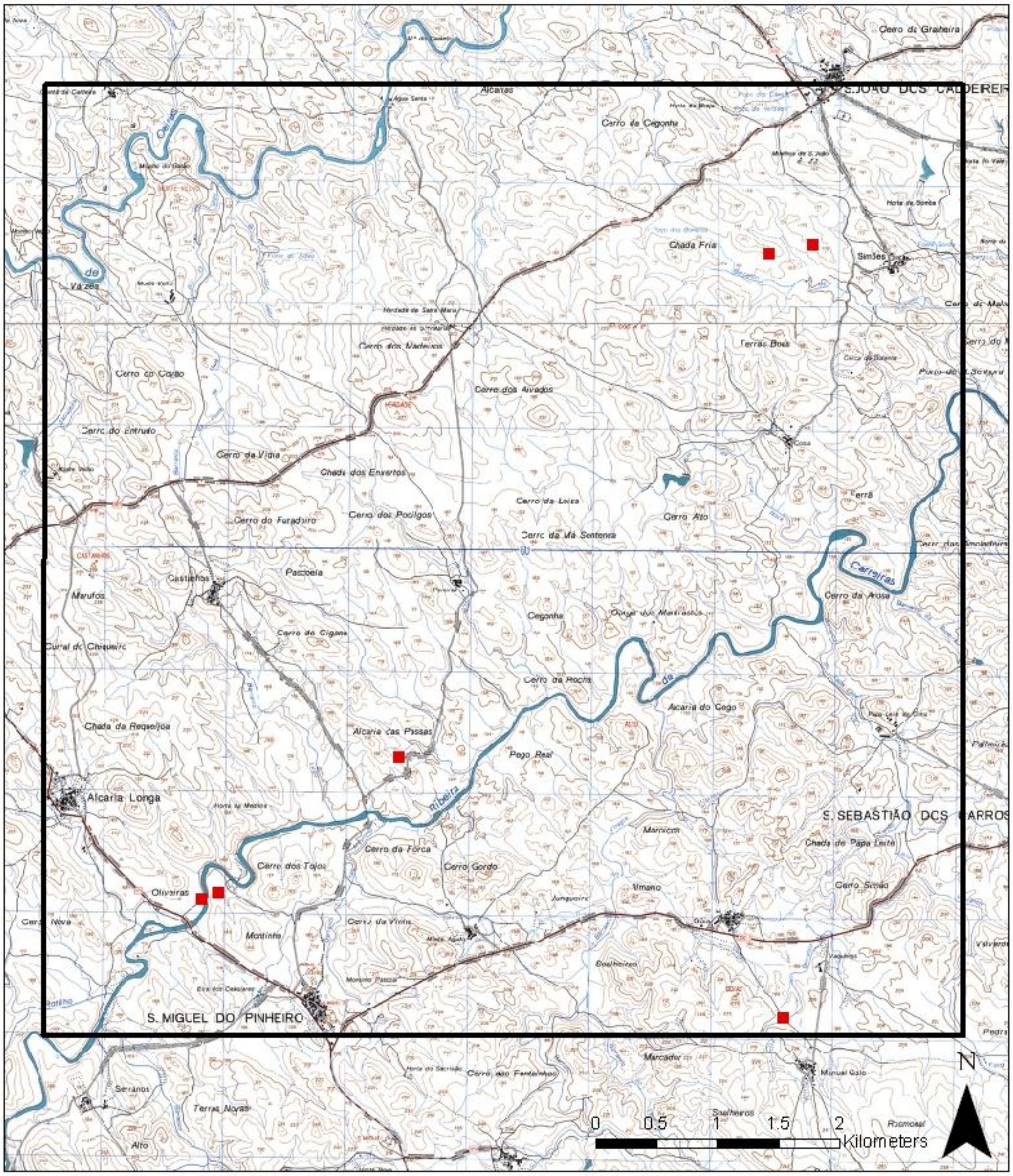

Figure 9.1: Map showing locations of the slopes selected for study in the 1992 survey area.

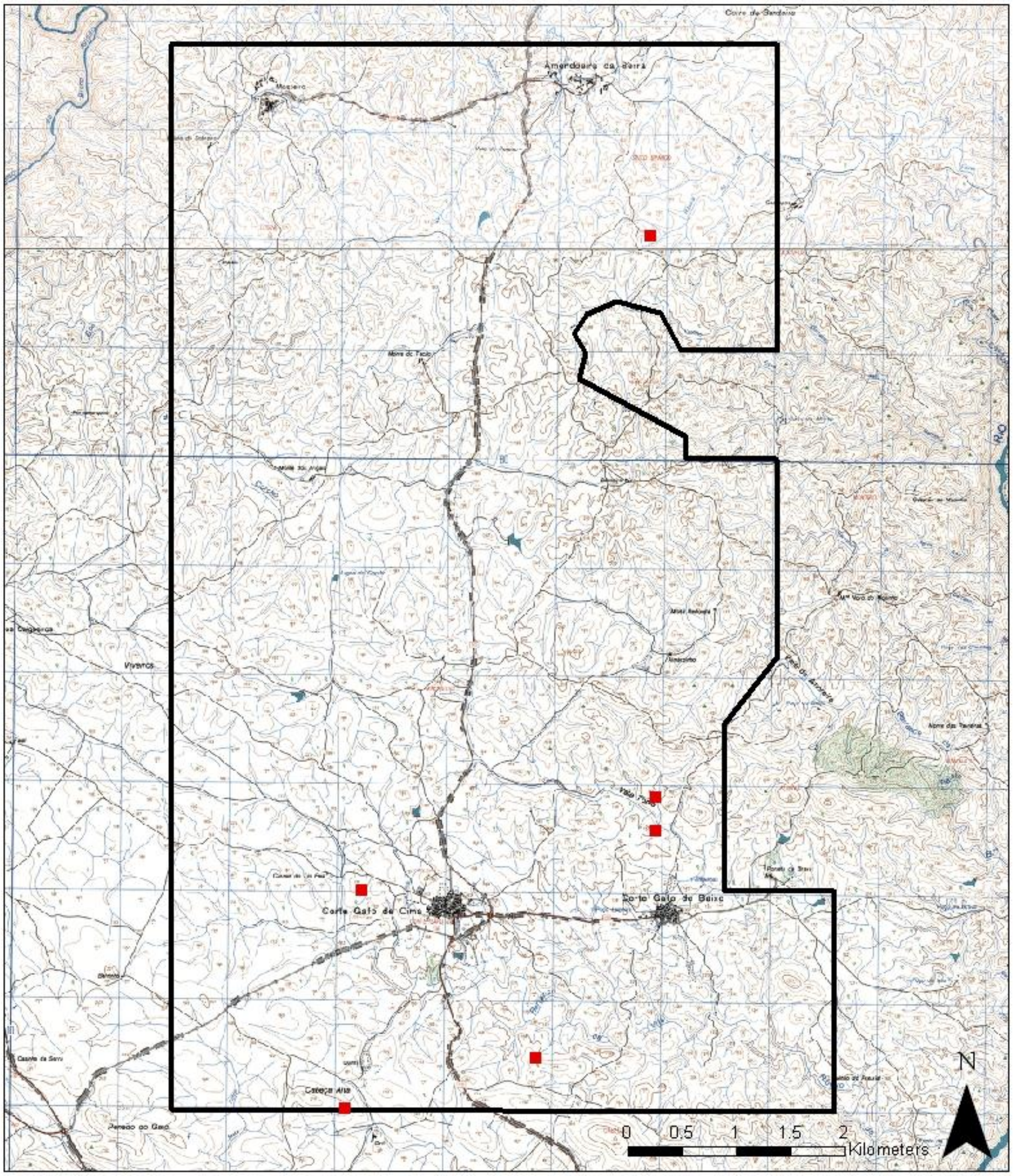

Figure 9.2 Map showing the locations of the slopes selected for study in the 2004 - 05 survey area.

1992 Survey Area

In the 1992 survey area, seven test pits were placed along the slope east of and adjacent to the site of Alcaria Longa and six were excavated on the slope southwest of and adjacent to the site of Queimada. One of the pits at each site was excavated to collect OSL samples. In addition, five test pits were excavated on each of three slopes that were not adjacent to named archaeological sites, for a total of 15 more soil test pits in the 1992 survey area; these soil test pits are numbered 1 – 5 from summit to toe on each slope.

The catenary studies provide clear evidence for a cycle of severe erosion in the past that removed soil and loose sediments from at least the upper portions of slopes throughout the 1992 survey area. The stratigraphic position of artifacts and the degree of pedogenic alteration of sediments in different units suggest that the past cycle of erosion occurred during the Islamic period and OSL assays are consistent with this interpretation. The pedostratigraphic data also reflect recent and ongoing erosion related to widespread mechanical cultivation of hillslopes during the 20th Century.

Alcaria Longa

The soils exposed in this series of test pits generally are thin, exhibiting weak to moderate soil development. They record the removal of the majority of sediments from the hillslope in the past and suggest a moderate degree of ongoing erosion. Figure 9.3 shows measured profile drawings of each test pit and depicts schematically the inferred depositional units.

The soil in test pit 1 at the summit of the slope exhibits the weakest development, with an A horizon resting directly on bedrock. Although magnetic susceptibility data, ped structure, and clay film morphology suggest incipient horizonation, the sediments have not been in place for a sufficient period of time to allow the development of an identifiable B horizon. The soil is only 8 cm thick; deposition and the creation of loose sediments through bedrock weathering have been slow and erosion has continually removed sediment during at least the past millennium. Artifacts were present throughout the soil column. Their presence in contact with bedrock suggests that soils were removed from this location since the artifacts were produced. Because the deposit is thin, however, downward mixing of artifacts through trampling, bioturbation, or other processes could account for their vertical distribution.

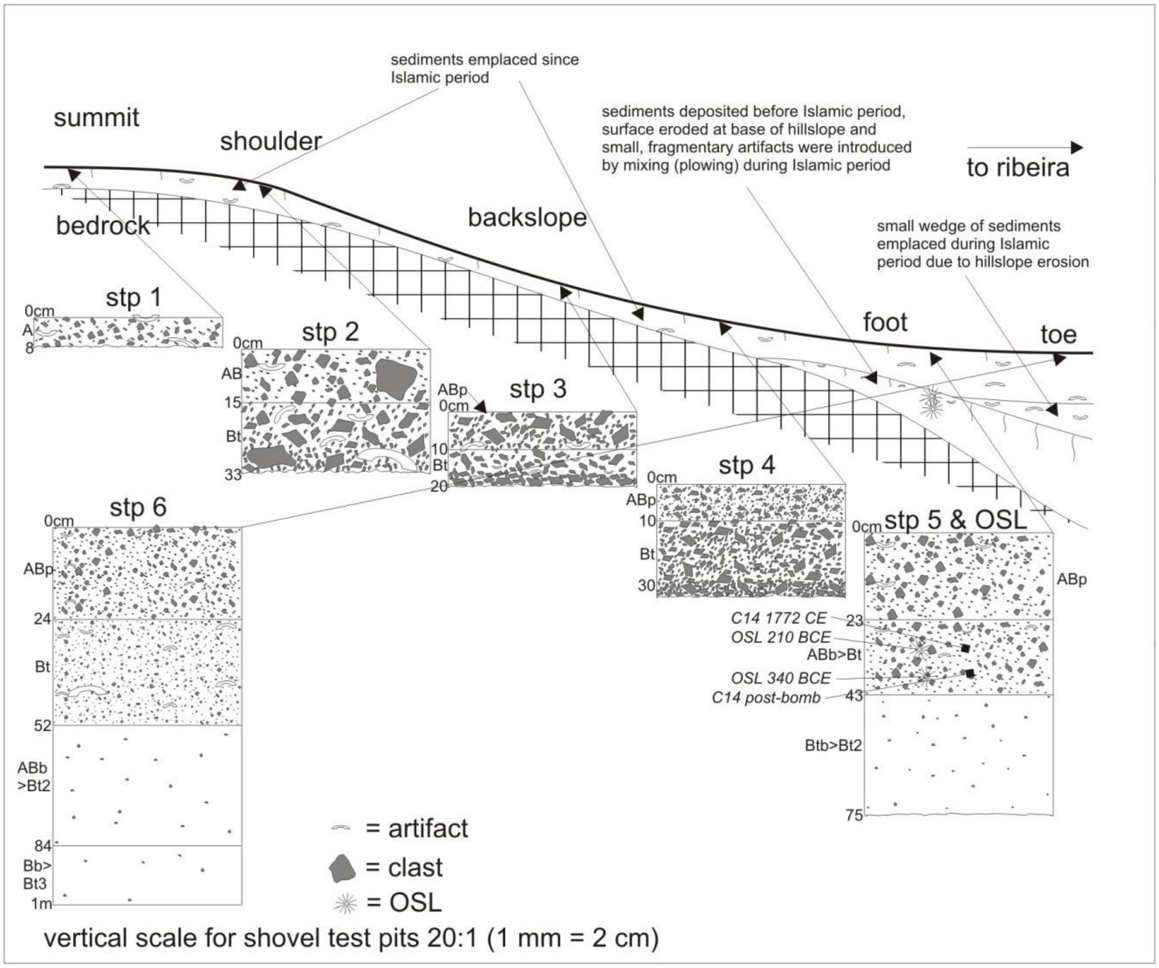

Figure 9.3: Measured profile drawings of soil test pits at Alcaria Longa with inferred depositional units. OSL age estimates are based on single-grain assays.

Lower on the slope, increased inputs of sediment and water due to runoff from above have favored deposition, weathering, and soil formation to a greater extent. Test pit 2 was located in an area that appeared to be particularly stable compared to the rest of the slope based on slope angle and standing vegetation. As expected, it exposed the deepest soil on the upper portion of the hillslope. The expression of pedogenic characteristics is moderate and ped structure, clay film morphology, boundary characteristics, and magnetic susceptibility all indicate pedogenesis in a relatively stable environment with some minor inputs of sediments from higher on the slope.

Artifacts were located at the base of the exposure, immediately above and in contact with bedrock, as shown in figure 9.4. The repeated occurrence of artifacts in contact with bedrock suggests that the slope was stripped of sediments in the past, during or possibly after the Islamic period. It is unlikely that post-depositional mixing would

have redeposited numerous artifacts to the base of the solum in every test pit on the upper portion of the slope.

Figure 9.4: Photograph of Alcaria Longa Soil Test Pit 2. Note large fragments of roof tile in contact with bedrock at the base of the exposure.

Comparison to soils higher on the slope shows that the pedogenic characteristics are not inherited. The degree of soil development therefore suggests that the oldest probable age estimate is the most likely; deposition must have begun soon after the Islamic period occupation, with pedogenesis altering sediments since that time. Test pit 2, then, provides a good example of the high end of the range of sedimentation and soil development that can be expected on a slope in the study area over the course of approximately 850 years. Soils on many hillslopes in the study area may have been similar before the initiation of the most recent cycle of erosion during the 20th Century.

Test pits 3 and 4, on the backslope and at the foot of the slope respectively, also exhibit moderate degrees of soil development but reflect the recent dominance of erosion in addition to past stripping of sediments. The abundance of clasts at the surface suggests recent deflation and sheetwash erosion, and the shallow peaks in magnetic susceptibility

corroborate this impression. In both cases, the physical characteristics of the A horizon, its clear lower boundary, and other observations suggest repeated plowing during the past few decades. Abundant gravels at the base of test pit three suggest a lag deposit. In addition, the weathered appearance of the bedrock and the inclusion of artifacts indicate that this location was stripped of sediments and bedrock was exposed at the surface during or after the Islamic period. The degree of pedogenic alteration of the overlying deposits implies that the severe erosion could not have occurred significantly after the Islamic period.

Similar observations at profile 4 also suggest stripping of sediments in the past and the degree of soil development shows that it was roughly contemporaneous. The angularity of clasts, the higher clay content of the sediments at the base of profile 4, and the relatively flat magnetic susceptibility curve, however, imply either that some remnants of a previous, well-developed B horizon remained or that the lowest parts of the slope were relatively rapidly buried after sediments were stripped. While both may have occurred, it is not necessary to posit the survival of a remnant B horizon; the increased clay content at the base of test pit 4 can be explained as the result of the accumulation of aeolian materials washed off of the bedrock-dominated slope above after the slope was stripped. Ongoing pedogenesis may also favor more rapid accumulation of clays in the B horizon due to increased inputs of water and fine-grained sediment due to runoff from the slope above.

Test pit 5 and the OSL test pit, at the toe of the slope, and test pit 6 between the base of the slope and the ribeira, reveal more complicated soil-stratigraphic relationships that appear to reflect both recent deposition and past landscape change. Figure 9.5 is a photograph of the OSL test pit taken during sampling. In all three cases, the A horizons are thicker and more strongly developed than analogous horizons on the hillslope, probably the result of increased water and sediment inputs below the slope as well as a relative lack of recent erosion in these flatter areas. The depth of these horizons approximates the effective depth of mechanical plowing or disking using the agricultural equipment common in the area; all are designated ABp horizons. The increase in magnetic susceptibility at the base of the A horizon in test pit 6 probably reflects the redeposition of clay-sized particles at the base of the plow zone. The slightly stronger

development of pedogenic characteristics in the A horizon in test pit 6 relative to test pit 5 and the OSL pit likely is related to episodic inputs of water and fine-grained sediments from the ribeira.


Figure 9.5: Alcaria Longa OSL test pit during sampling.

In test pit 5 and the OSL test pit, the inclusion of artifacts in the ABb>Bt horizons below the plowed surface units initially suggested deposition associated with erosion on the adjacent hillslope during the Islamic period. A radiocarbon assay on a charcoal fragment recovered by flotation supported this interpretation, suggesting that the horizon had remained relatively stable at the surface for several centuries before recent cultivation once again initiated hillslope soil erosion. A second radiocarbon date, however, produced a post-atomic bomb age for a charcoal fragment recovered from the base of the same horizon, showing that bioturbation has redeposited organic materials in this location. Additional observations also challenged the initial interpretation of deposition during the Islamic period. First, all of the included artifacts were very small fragments of roof tile, most of them less than 5 mm in maximum dimension. In addition, the abundance of artifacts in the ABb>Bt horizons decreased with depth, and krotovina were noted in test pit 5. These patterns suggest that the artifacts may be intrusive.

OSL analyses showed that partial bleaching and post-depositional mixing are significant problems in this location. Single-grain analyses, which corrected for these problems, documented slow deposition of sediments at the base of the hillslope during the centuries and millennia prior to the Islamic period, presumably due to minor hillslope erosion in the absence of significant human impacts. The age estimates suggest that the ABb>Bt unit was at the surface while Alcaria Longa was occupied, and that fragmentary artifacts were introduced by post-depositional processes, very likely including plowing. This interpretation is consistent with the observed gradual lower boundary of the ABb>Bt horizon and the degree of pedogenic alteration of both of the lower pedostratigraphic units. In addition, it suggests that the high clastic content of both of the upper units reflects mixing and erosion related to plowing and other anthropogenic disturbance.

Unlike the higher exposures, soil test pit 6, located between the base of the hill and the ribeira, revealed more convincing evidence for deposition during the Islamic period. Not only were artifacts more abundant in the Bt horizon, but larger fragments of roof tile measuring several cm in maximum dimension were present significantly below the upper boundary of the stratum. The relatively strong pedogenic alteration of the Bt horizon very likely reflects episodic inputs of fine sediment and water due to overbank flooding along the ribeira as well as inherited characteristics.

No artifacts were encountered in the subjacent strata, which exhibit strong pedogenic alteration. The buried soil was at or near the surface for a period of time on the order of millennia and it almost certainly antedates the occupation of Alcaria Longa. There is no evidence of plowing in the ABb horizon. If the area was plowed in the past, the plowing might have occurred after deposition of the Bt horizon materials started during the Islamic period. Alternatively, evidence of plowing may have been obscured by soil welding. The complete lack of artifacts lends some support to the first scenario. The increase in magnetic susceptibility with depth in the lowest units is puzzling as no other characteristics indicated additional buried soil horizons. Mottling suggests that diagenesis and periodic saturation with groundwater have altered the susceptibility of the deposits.

Considered together, the soils exposed by this series of test pits record two periods of erosion. Prior to the Islamic occupation of Alcaria Longa, the landscape was

apparently stable for an extended period of time, allowing soil development on the hillslopes and in the now-buried ABb horizons at the base of the slope. OSL assays show that minor erosion in the absence of significant human impacts slowly removed sediments to the base of the hillslope, creating deep, cumulic soil profiles there. As suggested by the stratigraphic position of artifacts, this period of stability was followed by an episode of extreme erosion some time during or very shortly after the Islamic occupation, which stripped virtually all loose sediments from the hillslope. Erosion also removed fine sediments from the base of the slope, in the location of test pit 5 and the OSL test pit, where small fragments of roof tiles were incorporated into sediments then at the surface by plowing and/ or other post-depositional processes. Some of these sediments would have been flushed into the ribeira while others were deposited below the base of the slope, becoming the parent material in which more recent soils have formed at test pit 6.

Following the Islamic period, conditions once again favored landscape stability. For several centuries, bedrock weathering combined with aeolian inputs led to the gradual buildup of sediments on the hillslope, and soils formed in those sediments. In relatively undisturbed areas, such as the location of test pit 2, moderately developed soils are present. Finally, most parts of the slope currently are experiencing at least moderate erosion, very likely related to the regime of plowing for cultivation of cereal crops initiated during the 20th Century.

Queimada

As at Alcaria Longa, the soils and sediments exposed in test pits on this slope reflect two episodes of severe erosion, one in the past and the second ongoing. Figure 9.6 shows measured profile drawings of each of the test pits along with inferred depositional units. The soils exposed in test pits one and three, at the top of the slope and on the back slope, respectively, are thin and weakly developed. They consist of plowed mixtures of A and B horizon materials over weakly developed cambic B horizons that are present in the interstices in bedrock. This pattern suggests that surface sediments were completely stripped in the past in both locations. The degree of soil development is consistent with the erosion having occurred during roughly the past millennium.

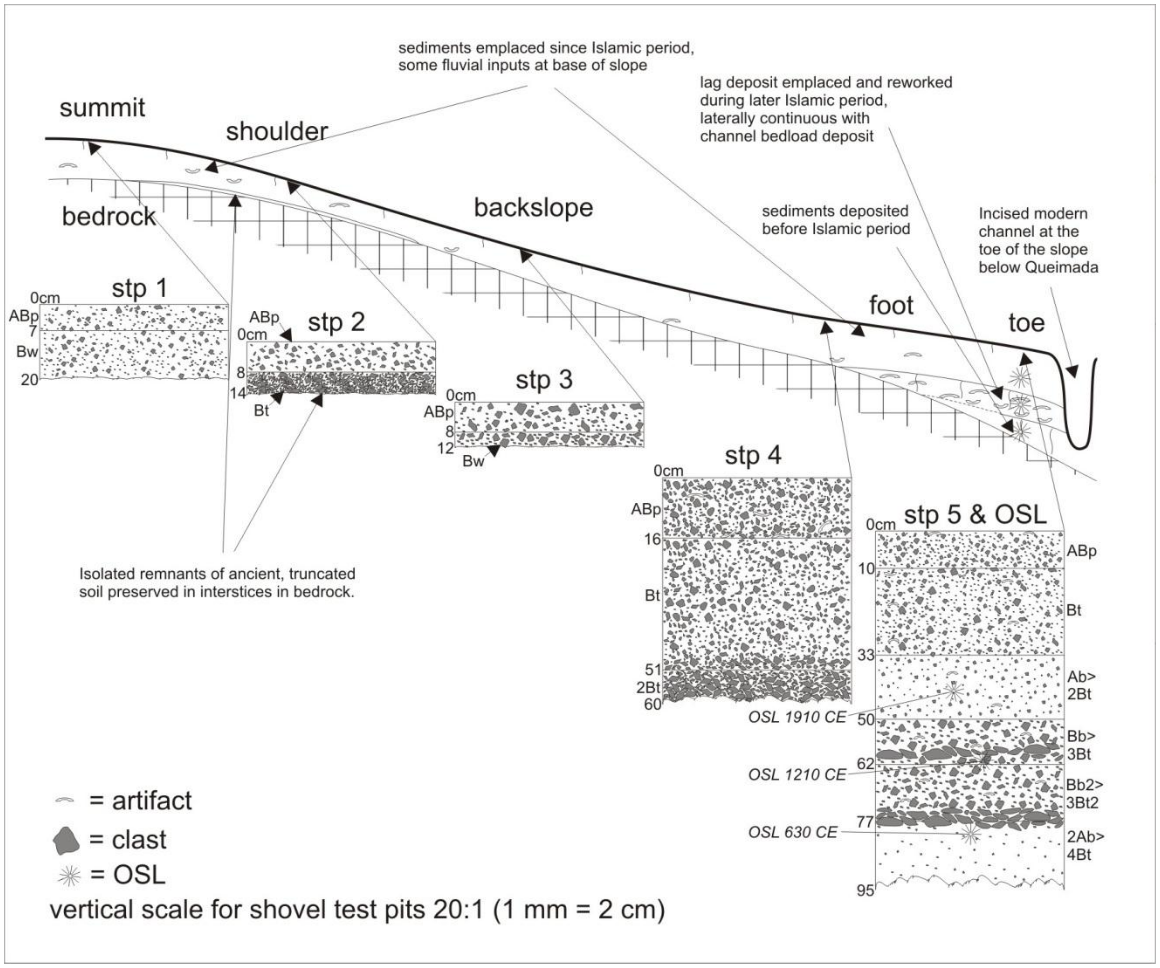

Figure 9.6: Measured profile drawings of soil test pits at Queimada with inferred depositional units. OSL age estimates based on single-grain assays.

The sediments exposed in test pit two, on the shoulder of the slope, include a similar weakly-developed ABp horizon. The physical similarities between the ABp horizons in all three pits suggest that these deposits are of the same age and origin. In test pit two, however, the surface horizon is underlain by a well-developed Bt horizon preserved in the interstices in the bedrock. The ped structure, texture and clay film morphology suggest a significantly greater age for the lower soil horizon; the cycle of hillslope erosion in the past evidently left some discontinuous areas of remnant hillslope soils intact in interstices in the bedrock. In all three test pits, soil characteristics and especially the monotonic decrease in magnetic susceptibility with depth suggest that a second episode of slope instability and erosion was initiated in the recent past and continues in the present.

Test pit 4 at the foot of the slope exposed a weakly developed cumulic soil. The ABp horizon at the surface is similar to the surface deposits higher on the slope, suggesting a similar age and origin. The slightly stronger expression of ped structure and clay films is attributable to increased inputs of water and fine sediments at the base of the hillslope. The subjacent Bt deposit exhibits relatively weak pedogenic modification, implying original deposition within the past century or few centuries at most. The relatively flat magnetic susceptibility curve is consistent with recent deposition. Pedogenesis has not created a noticeably enhanced signal at or near the surface, although there is a slight peak in susceptibility at the base of the ABp horizon, probably reflecting redeposition of clays to the base of the plow zone.

The color of and the lack of artifacts in the unit suggest that it may include sediments deposited by the fluvial system. There is a gravelly lag deposit at the base of the weak argillic horizon and in contact with bedrock at the base of test pit 4, suggesting that erosion removed sediments from this location in the past. The clay film morphology exhibited by the materials in the interstices in the bedrock suggests that they may be a preserved remnant of an ancient soil. Clay films may have formed rapidly in this location, however, due to inputs of water and fine sediments from the fluvial system. Similarities to the overlying unit in terms of color and texture imply at least some admixture with sediments deposited recently.

The polygenetic soils exposed in test pit 5 and the OSL test pit at the base of the slope record two episodes of deposition, corresponding with erosion on the hillslopes and channel formation on the floodplain, as well as periods of relative stability before and between the erosional events. The uppermost 30 cm of deposits correlate with the current hillslope soils, with similarly weak expression of pedogenic characteristics. These surface deposits probably have been accumulating at the base of the hillslope during the past decades, since the initiation of the most recent cycle of erosion; their relatively high magnetic susceptibility is likely an inherited characteristic. The physical characteristics of the subjacent horizon, including color, texture, ped structure, and clast rounding, suggest that it was exposed at the surface during a protracted period of landscape stability in the past. Alternatively, these may be more recent (i.e., early 20th Century) deposits with the relatively strong evidence of pedogenic alteration reflecting a combination of

inherited characteristics and increased inputs of fine sediments and water by the stream system. The inclusion of a few artifacts in this stratum shows that it was emplaced after occupation of the adjacent site during the Islamic period.

Characteristics of the two subjacent horizons (described as a single horizon with internal variation in the OSL test pit), especially the deposits of imbricated clasts, suggest that these lag deposits were emplaced and/ or reworked by a canalized fluvial system similar to the modern incised seasonal stream at the base of the slope. Inclusion of artifacts shows that these channels were active during or after the Islamic period occupation, and the relatively high magnetic susceptibility readings imply subsequent stability at this elevation for a protracted period of time. These strata appear to represent hillslope erosion and channel formation during the Islamic period.

Three single-grain OSL dates constrain the timing of channel formation in this location. Sample Q-2 from the OSL test pit was collected above the stone line in the 2AB>Btb unit. It yielded an optical age of 90 +/- 10 BP, corresponding to 1910 C.E. The date suggests that the surface remained stable in this location after channel filling, until changes in land use practices in the early 20th Century initiated widespread erosion. Sediments collected from within and below the upper stone line in test pit 5 yielded a single-grain optical age of 790 +/- 70 BP, corresponding to 1210 C.E., showing that erosion was significant and the channel was active during the later Islamic period. The existence of two stone lines in that exposure but not in the OSL pit or in the nearby fluvial profile most likely reflects changes in channel location or morphology related to initial channel formation; a shallow channel may have moved laterally across the floodplain prior to the deeper and longer-lasting incision of the channel reflected in the fluvial profile. Pedogenic characteristics of sediments immediately above, within, and below the upper stone line to the base of the lower stone line are nearly identical, suggesting similar ages and depositional processes.

Sample Q-3, from the basal stratum in the OSL test pit, returned a single-grain optical age of 1370 +/- 100 BP, corresponding to a calendar date of 630 C.E. The close correspondence of this date with the earliest radiocarbon dates from the site of Queimada suggests that the occupants' activities probably increased hillslope erosion to some extent. The homogeneity of the stratum, however, implies that anthropogenic erosion

initially was relatively minor, with more significant erosion and channel formation occurring during the later Islamic period. Pedogenic characteristics and clast content also are consistent with slow, long-term accumulation of sediments at the base of the hillslope, reflecting a long period of relative landscape stability. Interestingly, the position in this location of the channel or lag deposits above the sediments exposed at the surface during the late Roman period suggests that large quantities of soil eventually were redeposited at the base of the slope before the channel formed through them.

Overall, the pedostratigraphic evidence from the test pits excavated along the slope adjacent to Queimada is consistent with landscape stability prior to occupation of the area by agrarian populations. Subsequently, the rate of erosion appears to have increased somewhat during the early occupation of the site; the temporal correlation implies that human activities caused localized, minor hillslope erosion. During or near the end of the Islamic period, large quantities of sediments were removed to the base of the slope and these were then reworked and partially removed by the fluvial system that cut a channel through them; the formation of a canalized stream system appears to correspond to stripping of soils from the slopes. It is important to note that the major erosion and channel formation post-dated the latest radiocarbon dates from the adjacent site by as much as three centuries, reflecting regional landscape change as opposed to localized anthropogenic impacts adjacent to residential sites. Later, conditions facilitated a return to relative stability for several centuries, during which time sediments once again accumulated and soils began to form on the slopes. Finally, the deposits near the surface suggest a return to conditions of rapid hillslope erosion, burying the filled channel in the early 20th Century. The recent formation of an arroyo at the bottom of the slope probably is due to increased runoff because slopes are now only thinly mantled with sediments.

Slope 1

The soils on and at the base of this slope indicate at least two periods of severe erosion, one in the past and the second recent and ongoing. Figure 9.7 shows measured profile drawings of each of the test pits, along with inferred depositional units. Test pit 1, at the summit of the hill, exposes a thin, rocky, weakly-developed, and plowed soil resting directly on bedrock. The lack of evidence for stronger pedogenic alteration and the observation that the sediments continue unaltered into the interstices in the bedrock

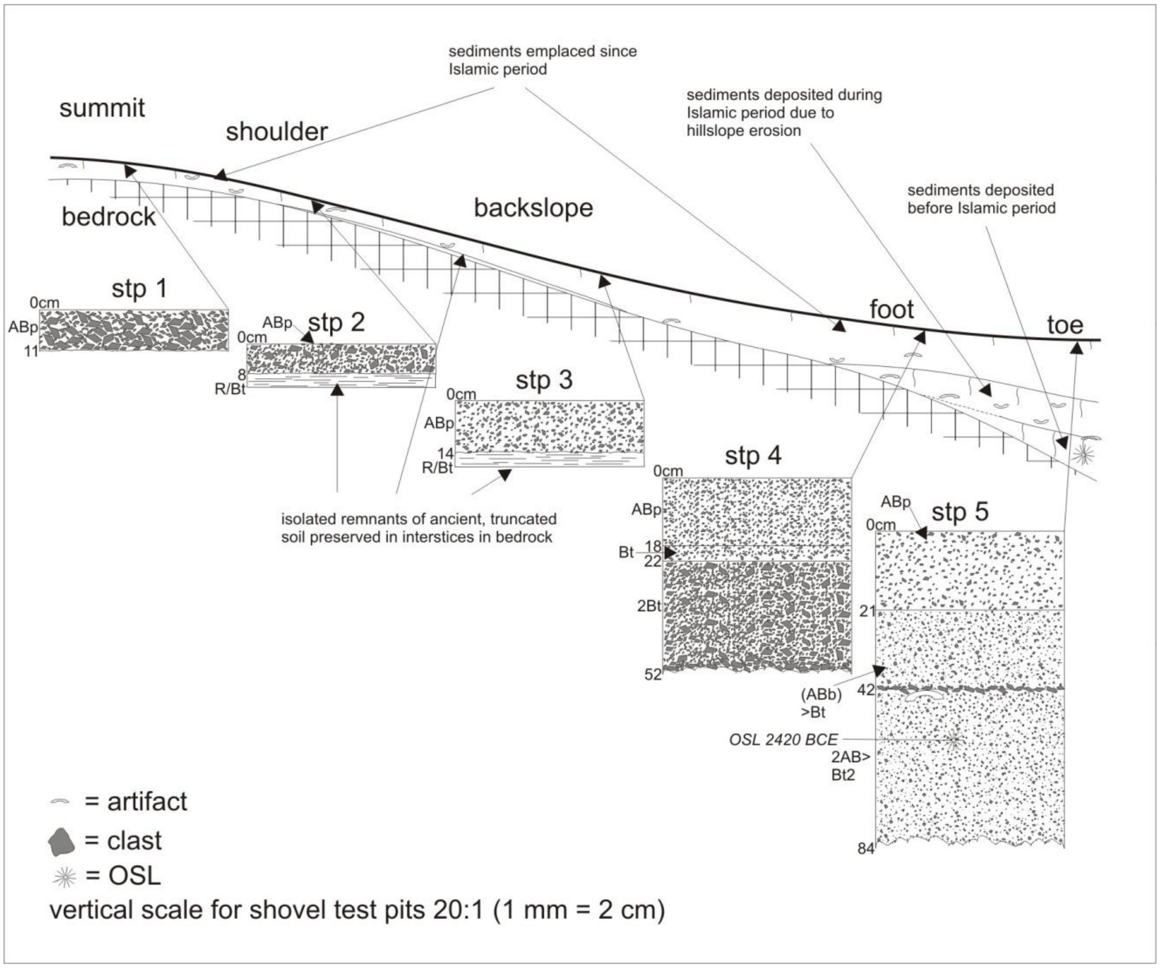

Figure 9.7: Measured profile drawings of soil test pits at 1992 survey area slope 1 with inferred depositional units. OSL age estimate based on a multi-aliquot assay.

suggest that loose sediments were removed from this location by severe erosion within approximately the past millennium. The presence of a few distinct ped face clay films suggests moderate pedogenesis following the renewed accumulation of sediments. The peak in magnetic susceptibility at the surface is consistent with recent erosion and exhumation of the soil B horizon.

Test pits 2 and 3 expose surface deposits that are almost identical to those in test pit 1, with the only significant differences being that soil thickness increases and gravel content decreases lower on the slope. These patterns are typical given that fine grained sediments are more easily transported to lower points on the slope than larger clasts by processes such as rainsplash and sheetflow. Test pits 2 and 3 also expose strongly developed remnant argillic horizons, preserved in interstices in the bedrock beneath the

plowed surface horizons. Ped structure, clay film morphology, and increased magnetic susceptibility indicate that the remnant deposits are significantly older than the surface deposits. As on the Queimada hillslope, a past cycle of erosion apparently left discontinuous areas of hillslope deposits intact where these were protected by the roughness of the bedrock. In all three pits, the surface deposits have been affected by mechanical mixing, and admixture with the underlying Bt horizon in pits 2 and 3 has transferred a few peds with strong clay films into the surficial horizon. Nonetheless, the pedogenic characteristics in the surface deposits are consistent with deposition and soil formation during the past millennium. Soils in all three test pits also show evidence for recent and ongoing erosion in their physical characteristics and particularly in the weak pedogenic alteration of surface sediments.

Soil test pit 4, at the foot of the slope, presents evidence for severe erosion in the past followed by at least two periods of deposition. The bedrock at the base of the test pit appears weathered and is capped by a lag deposit consisting of imbricated clasts derived from the local bedrock. It appears that erosion in the past removed soil and loose sediments from this location and transported larger clasts to the base of the slope.

The overlying 2Bt stratum is a moderately well-developed argillic horizon, with moderate ped structure and strong clay films. The timing of deposition and the length of time during which soil formation has occurred are difficult to infer from pedogenic characteristics alone. The clay loam texture of the unit probably has facilitated rapid formation of clay films. No horizonation within the unit is preserved. This could be due to rapid deposition and deep burial in the past or it could reflect a relatively long period of steady accumulation; cumulic soils often exhibit weak or no horizonation. Either scenario is consistent with the geomorphic position at the base of the slope, but the texture is suggestive of steady accumulation of fine aeolian materials and weathering products below a bedrock dominated slope. Alternatively, the lack of horizonation could be due to soil welding and/ or the effects of groundwater; gleying and mottling indicate repeated saturation of the stratum. The decrease in magnetic susceptibility to almost zero at depths below 35 cm provides weak support for accumulation of minimally altered sediments, but susceptibility also has almost certainly been affected by the presence of groundwater. In any case, the overall degree of soil development is broadly consistent

with deposition within the past millennium, assuming relatively rapid pedogenesis in geomorphic contexts where there are increased inputs of water and fine sediments (compare to e.g. Alcaria Longa test pit 2). The characteristics are consistent with deposition after erosion stripped sediments from the hillslope during the Islamic period.

The superjacent Bt and ABp horizons in test pit 4 reflect recent deposition and mechanical mixing. Clay films and ped structure are moderately well developed in the Bt horizon, implying a relatively long period of stability and illuviation but also reflecting increased inputs of water and fine sediments at the base of the slope. Its stratigraphic position, thickness and clear lower boundary suggest that it may be the lower portion of an older plow zone, now buried by more recent deposition below the depth affected by current plowing/ disking. A minor peak in magnetic susceptibility suggests that the horizon at least includes some illuviated materials initially deposited in a B horizon by pedogenic processes. The ABp horizon is similar to those higher on the hill, with physical characteristics and magnetic susceptibility indicating that it is composed of mixed A and B soil horizons. The thickness of the horizon and the presence of the separate Bt horizon indicate significant recent deposition at the base of the slope due to erosion of soils from higher positions.

The soils exposed in test pit 5, at the toe of the slope, provide evidence for at least two periods of erosion and deposition. The bedrock at the base of the pit does not appear to have been exposed at the surface. The basal 2AB>Bt2 deposit exhibits a moderate degree of soil development but the timing of deposition is difficult to infer from pedogenic characteristics. Mottling and gleying indicate that the unit has been altered by groundwater, and no horizonation is evident although an increase in clay content with depth was noted, prompting the AB designation which indicates that this may be a buried soil. It is possible that the unit was deeply buried for millennia in the past, inhibiting pedogenic alteration despite landscape stability. A single rooftile fragment in the upper 3 cm of the stratum suggests that it was exposed at the ground surface during or after the Islamic period. A multi-aliquot OSL age of 4420 +/- 480 BP (2420 B.C.E.) for sediments from the upper portion of the unit almost certainly overestimates the time elapsed since those sediments were exposed to light. It does, however, provide a maximum age for the deposit and it is consistent with slow accumulation of sediments at the base of the

hillslope prior to significant erosion during the Islamic period. The 2AB>Bt2 unit is capped by a lag deposit indicating past removal of an unknown quantity of fine sediments from this location; the lag deposit likely correlates with the erosion of sediments from higher on the slope. The rooftile fragment suggests that this may have occurred during the Islamic period, and this interpretation is consistent with the OSL age estimate.

As indicated by its designation as an (ABb)>Bt horizon, the overlying stratum exhibits characteristics of both a buried soil and a zone of illuviation of pedogenic clays. The expression of time-dependent pedogenic characteristics is consistent with deposition in the past millennium, and the texture and lack of variation within the deposit suggest steady accumulation of fine sediments eroded from higher on the slope. On the other hand, these may be relatively recent deposits (as little as a century old) with inherited characteristics and accelerated pedogenesis due to increased inputs of water and fine sediments at the base of the slope. Given that the clear lower boundary corresponds to a stone line and textural change, it does not allow for differentiation between these two possibilities.

The ABp horizon at the surface is similar to those higher on the slope, although more yellow in color; the color difference could be due to increased exposure to water and inputs from the fluvial system at this low point on the landscape. The thickness of the deposit, its relatively high magnetic susceptibility, and the degree of pedogenic alteration clearly show that these sediments are sediments redeposited from higher on the hillslope during the 20th Century.

Although the ages of some strata remain ambiguous, the soils exposed by test pits on Slope 1 clearly reflect an episode of severe erosion in the past, followed by deposition and pedogenesis, and then recent remobilization of surface materials. Test pits 1 – 4 show that the past erosion removed the majority of loose sediments from the hillslope, and an unknown quantity of sediment also was removed from the location of test pit 5. The relict argillic horizons in interstices in the bedrock in test pits 2 and 3 provide evidence that the soil that was largely removed was very well developed, reflecting millennia of landscape stability. The timing of the past episode of erosion is difficult to infer due to recent plowing and ambiguities in interpreting the ages of deposits below the plow zone in test pits 4 and 5. The thickness of deposits on the hillslopes and the general

degree of soil formation, however, show that the previous erosion cannot have been recent or extremely ancient. Comparisons to other soils in the study area suggest that the erosional event occurred roughly within the past millennium. The stratigraphic position of a single rooftile fragment suggests that it likely occurred during the Islamic period, and this interpretation is consistent with a multi-aliquot OSL age estimate for the underlying sediments. Cumulic soil profiles in test pits 4 and 5, as well as the observed profile thicknesses, magnetic susceptibility data, and gravel content in test pits 1 – 3, show that recent plowing is causing renewed erosion of hillslope soils.

Slope 2

This catenary sequence indicates two episodes of severe erosion, one in the past and the second recent and ongoing. Figure 9.8 presents measured profile drawings of each of the test pits, as well as inferred depositional units. Test pits 1 and 2 expose thin, rocky soils with weak to moderate development, resting directly on bedrock. In both cases the continuation of the same weakly developed soils into interstices in the bedrock suggests that soils and loose sediments were completely removed from the upper portions of the slope in the past. It also implies that the stratigraphic location of artifacts throughout the profiles and in contact with the bedrock is probably not due to the downward movement of those artifacts from a former surface because of post-depositional mixing. The degree of soil development and the presence of artifacts most likely originating on a small nearby Islamic period site suggest that the past erosion was temporally correlated with the Islamic period. Lag deposits of gravel at the surface indicate ongoing erosion associated with wheat cultivation on the hillslopes.

Test pit 3, on a concave section of the backslope, provides evidence for two separate cycles of erosion. The clay film morphology, color, and ped structure of the Bt2 horizon, in contact with bedrock at the base of the exposure, suggest an age on the order of multiple millennia for this deposit; it has among the strongest expressions of time dependent pedogenic characteristics of any of the soils recorded in the study area. The overlying Bt horizon is moderately well developed, exhibiting pedogenic characteristics consistent with a period of soil development on the order of a millennium. The gradual lower boundary of the Bt horizon is probably due to soil welding, which may also have obscured horizonation in the subjacent deposit.

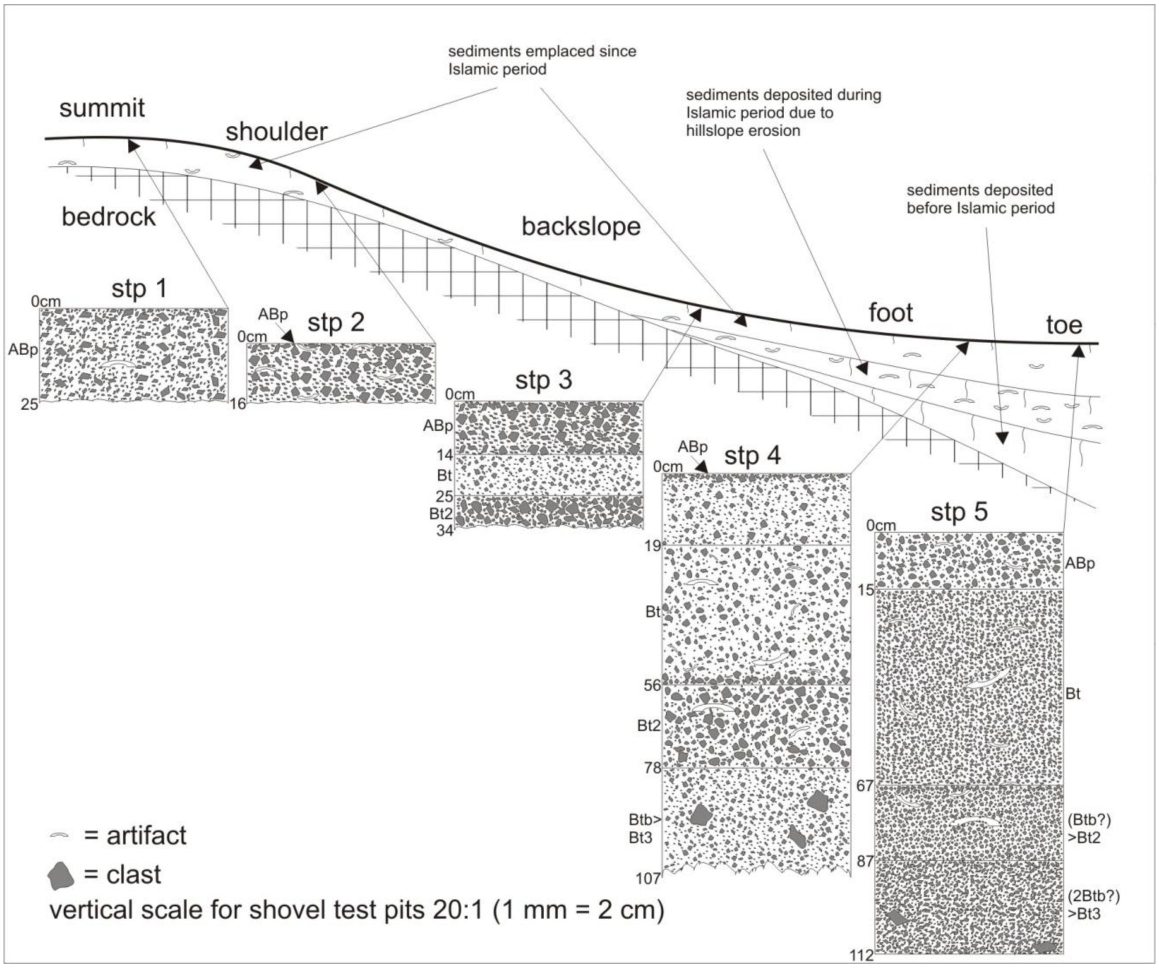

Figure 9.8: Measured profile drawings of soil test pits at 1992 survey area slope 2 with inferred depositional units.

Although no artifacts were encountered in the Bt horizon, pedogenic characteristics suggest that it correlates with the Bt and Bt2 horizons lower on the slope that include artifacts derived from the nearby Islamic period site. The Bt horizon in test pit 3 most likely formed in sediments that were eroded from higher on the slope and redeposited during the Islamic period. A weak peak in magnetic susceptibility at 20 – 25 cm is consistent with this interpretation. The overall pattern suggests that the overlying stratum was emplaced recently; the ABp horizon is similar to that at other points on the slope. A second peak in magnetic susceptibility at the surface, in addition to the gravelly lag deposit, indicates recent and ongoing erosion.

The pedostratigraphy in test pits 4 and 5 is somewhat more complicated but also is consistent with hillslope erosion during the Islamic period and recently. The stratum at the base of each pit is similar to that at the base of test pit 3, with strong expression of

ped structure. Clay film morphology is not as strongly developed in test pit 5, either because of the effects of frequent saturation with groundwater or because it was deeply buried in the past. In both pits, there are two Bt horizons above the stratum at the base, each with moderately well-developed ped structure and weak clay films. The timing of deposition is somewhat ambiguous, given that groundwater has affected these horizons, that some pedogenic characteristics may be inherited, that soil welding is likely, and that there is a weak stone line at the boundary between the two. The inclusion of numerous artifacts and the magnetic susceptibility data, however, support deposition of both units during the Islamic period, as does the lack of observable internal differentiation in the basal units.

The stone line between the Bt horizons may be related to the test pits' position on an alluvial fan that currently is crossed by a small incised channel; a similar channel in the past may have migrated across the surface of the fan and eroded or reworked deposits. Alternatively, it may reflect a short period of erosion of the lower hillslopes during the Islamic period, between two periods of deposition due to erosion of sediments from higher on the slope. In any case, the surface deposits are similar to the ABp horizons at other positions on the hill, with the exception of fewer clasts at the surface at test pit 5. The lack of a lag deposit is consistent with ongoing deposition of materials eroded from higher positions as well as fining of the surficial deposit away from the foot of the slope.

The soils exposed by test pits on the upper portions of this slope clearly reflect a past episode of extreme erosion that removed the majority of loose sediments and transported them to lower points on the slope or beyond. The thickness of extant sediments, included artifacts, and the degree of soil development are consistent with that erosion having occurred during the Islamic period. Strata at the base of test pits low on the slope and at the base of the hill are remnants of a very well-developed soil. They show that erosion in the past removed a soil that developed during millennia of landscape stability. The timing of deposition of the superjacent strata in the lower soil test pits is somewhat ambiguous, but the stratigraphic position of artifacts and the pedological data are consistent with the deposition occurring during the Islamic period. Gravelly lag deposits at the surface and magnetic susceptibility data show that recent cultivation is causing another cycle of erosion on the hillslope.

Slope 3

The soils on and at the base of this hillslope reflect severe, ongoing erosion and provide some evidence of an episode of erosion in the past as well. Measured profile drawings of each test pit and inferred depositional units are shown in figure 9.9. Test pits 1 – 3 expose thin, rocky, plowed soils with weak to moderate development. The soils rest on bedrock and continue unaltered into the interstices; the lack of sediments exhibiting stronger pedogenic alteration in the interstices in the bedrock suggests that all loose sediments were removed from the slope in the past. Physical characteristics of the Bt horizons, including color, ped structure, and clay film morphology, are consistent with deposition and soil formation during roughly the past millennium. Magnetic susceptibility data for STP 3 show peaks in susceptibility at the surface and at 10 – 15 cm, suggesting that the Bt horizon has developed *in situ*, that mechanical mixing incorporates B horizon materials into the ABp horizon and facilitates translocation of clays to the base of the plow zone, and that there is significant, ongoing erosion on the hillslope.

In test pit 4, at the foot of the slope, the ABp horizon rests directly on bedrock. The sediments are similar to the ABp horizon elsewhere on the slope except that they incorporate more sand-sized particles. This textural change is likely due to the inclusion of mechanically crushed bedrock in the soil; the top of the bedrock appears to have been planed off by agricultural equipment in this location (probably a disk cultivator). The lack of a distinct, preserved B horizon or of appreciable sedimentation at the foot of the slope is likely due to slope geometry. This slope is relatively straight, so erosive potential would generally increase at lower points on the slope due to increased catchment areas and correspondingly higher runoff. In addition, the incised ephemeral stream immediately at the base of the slope probably effectively removes mobilized surface sediments from the area, preventing buildup of a wedge that otherwise would favor deposition.

At the toe of the slope, test pit 5 exposes a plow zone over a thick, weakly developed argillic horizon. The ABp horizon is similar to analogous deposits at other points on the slope. The color and clay film morphology in the subjacent Bt horizon indicate minimal pedogenic alteration. The lack of soil development or differentiation

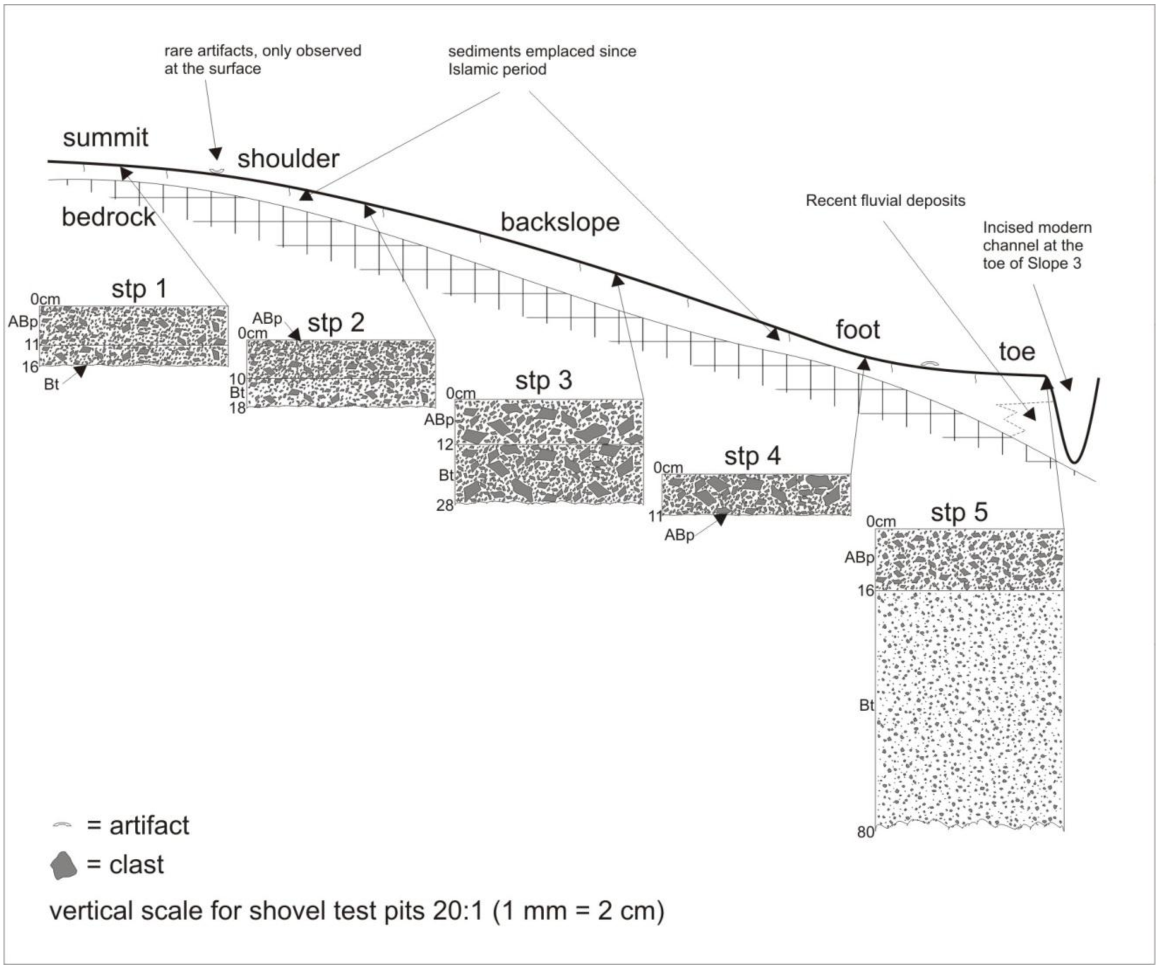

Figure 9.9: Measured profile drawings of soil test pits at 1992 survey area slope 3 with inferred depositional units.

within the horizon, together with its thickness, suggest that the Bt horizon is cumulic and composed of sediments removed to the base of the hillslope by recent erosion (i.e., 20th Century). The lack of older preserved sediments is probably due to the presence of an incised stream that presumably removed older sediments and continues to flush mobilized sediments into the ribeira. Bedrock is exposed at the base of the channel in most of the nearby area. The magnetic susceptibility data for STP 5 show peaks at the surface, at 15 – 20 cm and at 30 – 35 cm. These data may be affected by seasonal saturation by groundwater, as suggested by mottling in the deposit. They do, however, also imply multiple recent episodes of deposition as well as the accumulation of pedogenic clays at the base of the plow zone. The deepest peak may be an inherited characteristic, or it could be related to *in situ* development of a weak B horizon or the

lower limits of a previous plow zone; none of these possibilities rules out recent deposition.

The profile exposed in STP 5 presents evidence for recent erosion and deposition at the base of the hillslope. No preserved sediments at the base of the slope appear to have been in place for more than approximately the past century. Because of the lack of older preserved sediments and temporally diagnostic artifacts at low points on the slope, the pedostratigraphy does not provide particularly strong evidence for erosion prior to the ongoing removal of hillslope sediments due to modern mechanized agriculture. The lack of well-developed soils anywhere on the slope, however, is consistent with an episode of extreme erosion in the past, and the degree of soil development observed in the Bt horizons is broadly consistent with that erosion being temporally correlated with the Islamic period occupation of the area.

Discussion

The five catenary studies completed in the 1992 survey area consistently produced evidence that corroborates the history of landscape change suggested by studies of floodplain strata. In the majority of soil test pits located high on the slopes (i.e. summit, shoulder, backslope), weakly to moderately developed soils rest directly on bedrock. Soils were removed from these locations by erosion at some time in the geologically recent past. Artifacts in contact with bedrock at many locations suggest that the past erosion occurred during or after the Islamic period, and an episode of severe erosion approximately during the Islamic period is consistent with the observed degree of pedogenic alteration in surficial deposits. In several cases, the weakly developed soils are underlain by well-developed argillic horizons preserved in interstices in the bedrock. No artifacts were present in these strata. The expression of time dependent pedogenic characteristics in these horizons is significantly stronger than in the surficial deposits, implying a greater age. Differences in color, texture, and clast content suggest that the ABp and Bt horizons are not genetically related in those settings; the B horizons are truncated remnants of the ancient, well-developed soils that mantled hillslopes in the study area prior to the Islamic period.

Test pits at lower points on the slopes (i.e. foot and toe) exposed somewhat more complicated stratigraphy. Although all profiles were consistent with the same history of

landscape change, the strata exposed by the profiles were varied due to variations in slope geometry, the presence or absence of an incised stream at the base of the slope, and other differences between hillslopes. In most cases, the basal strata appear to antedate significant occupation of the area by agricultural populations and they often exhibit evidence for a protracted period of relative landscape stability, pedogenesis, and slow accumulations of sediment at the base of slopes in the past. Several OSL dates are consistent with relatively slow accumulation continuing through the late Roman period. The overlying deposits generally include artifacts produced during the Islamic period; they reflect hillslope erosion during or after the Islamic period. OSL data from the hillslope adjacent to Queimada imply erosion and channel formation there during the later Islamic period. Pedogenic characteristics and OSL assays suggest that the past erosion was followed by another period of relative stability and soil formation. Finally, strata now at the surface at lower points on the slopes were deposited recently due to ongoing erosion related to cultivation of the hillslopes during the 20th Century.

2004-05 Survey Area Hillslope Soils

In order to provide data for comparison to the 1992 survey area, test pits were excavated on six slopes in the 2004-05 survey area and the soils and sediments were examined and recorded. Five of the slopes selected for catenary studies were located in the southern portion of the 2004-05 survey area where bedrock and soil types are similar to those in the 1992 survey area. In addition, one set of test pits was excavated on a hillslope west of Cachopos in the northern part of the 2004-05 survey area. The bedrock and soil types in that location are different from those in the 1992 survey area, but the catenary study provides complementary information about the trajectory of landscape evolution in that geologically different setting. As in the 1992 survey area, test pits were excavated on the five geomorphic segments of the slopes and they are numbered 1 to 5 from summit to toe. The soils and sediments exposed on hillslopes in the 2004-05 survey area reflect an extended period of landscape stability and pedogenesis followed by recent erosion. None of the studies yielded evidence for an episode of significant erosion prior to the 20th Century.

Slope 1

The soils on and at the base of slope one reflect significant recent and ongoing erosion associated with cultivation. Measured profile drawings of each test pit and inferred depositional units are shown in figure 9.10. While the timing of deposition of some of the strata is somewhat ambiguous, there is no evidence for hillslope erosion during the Islamic period. The plowed soil exposed in test pit 1, at the summit of the hill, is thin and rocky with a gravelly lag deposit at the surface indicating ongoing erosion. While it is similar to the degree of soil development observed in sediments deposited since the Islamic period in the 1992 survey area, the expression of pedogenic characteristics by itself does not adequately constrain the age of this deposit. Cultivation has planed off the bedrock, so the sediments cannot be compared to those that otherwise might be preserved below the plow zone. The color and ped structure of the soil suggest that it incorporates remnants of a moderately to well-developed soil. The relatively weak overall soil development may be the result of severe recent erosion combined with mechanical mixing and cultivation of an exhumed B horizon.

Soil test pit 2 provides better evidence concerning the history of landscape change in this location. A similar ABp deposit is present at the surface, overlying a well-developed argillic horizon that continues into the interstices in the bedrock. The ped structure and clay film morphology of the Bt horizon suggest a period of pedogenesis on the order of several millennia, and there is no evidence that the bedrock has been exposed at the surface in this location. This pattern is superficially similar to that seen in analogous geomorphic positions on two slopes in the 1992 survey area. In this case, however, similarities between the ABp and Bt horizons in terms of color, texture, and clast content suggest that the two strata are of similar age and origin. The magnetic susceptibility data, with a weak peak at 10 – 15 cm below the surface, support this interpretation and reflect churning of the upper portion by plowing. This soil profile records recent erosion and cultivation of the exhumed argillic horizon. There is no evidence of significant erosion in the past and no characteristics of either deposit suggest that the ABp horizon is comprised primarily of sediments emplaced since the Islamic period.

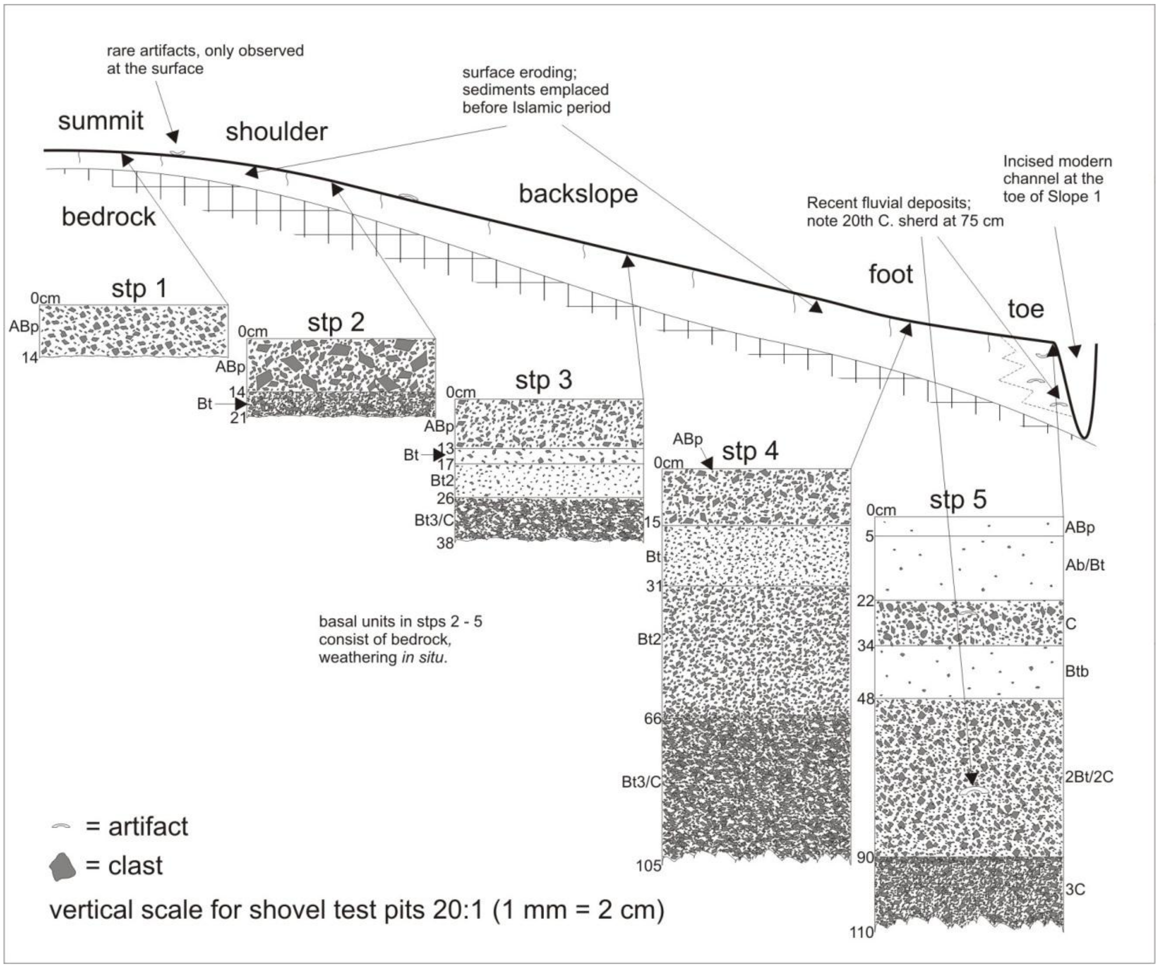

Figure 9.10: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 1 with inferred depositional units.

The bedrock at the base of the exposure in test pit 3, on the backslope, has not been exposed at the surface in recent millennia and the C>Bt3 horizon in contact with the bedrock clearly is the product of *in situ* bedrock weathering. A moderate degree of pedogenic alteration is observable, consisting primarily of the presence of illuvial pedogenic clays. The color, gradual lower boundary, and clast characteristics of the superjacent Bt2 horizon suggest that it is genetically related to the C>Bt3 horizon. Although pedogenic characteristics are only moderately expressed, this relationship implies that the Bt2 horizon has been in place for multiple millennia.

The lack of stronger evidence for soil development (i.e. in terms of clay films and ped structure) in the Bt2 horizon likely is related to geomorphic position and soil texture. The backslope is particularly susceptible to sheetflow erosion because of the relatively steep slope angle and the generation of runoff from areas upslope. It is likely that

sediments were thicker in this location prior to recent cultivation and that deep burial retarded pedogenesis in the lowest strata. In addition, the long-term, gradual movement of surface sediments downhill through processes such as creep also tends to diminish soil development on the backslope. Finally, the high clay content of the Bt2 and Bt3/ C strata probably favors the movement of groundwater downslope as opposed to downwards through the soil profile, further inhibiting pedogenesis in the lowest strata. The magnetic susceptibility data, with a peak at 20 – 25 cm below the surface, are consistent with the Bt2 horizon being ancient and *in situ* and the second, minor peak at the surface implies recent movement of soils downhill.

The color, variable clay films, and clear lower boundary of the superjacent Bt horizon imply that it was deposited recently and subjected to mechanical mixing when the hillslopes were plowed. The color and ped structure of the ABp horizon and the lack of a gravelly lag deposit at the surface also appear to reflect recent addition of surface materials from higher on the slope. Although the expression of time dependent pedogenic characteristics in the Bt2 and C>Bt3 horizons is not as strong as might be expected, the simplest explanation that accounts for these data is that the two strata nearest the surface were emplaced by recent movement of sediments down the hillslope. The deeper horizons are significantly older, the truncated remnant of a deeper, older soil. The clear boundary between the two pairs of strata shows that landscape changes have been recent. There is no clear evidence for erosion prior to the cultivation of hillslopes during the 20th Century.

The pedostratigraphy in test pit 4, at the foot of the slope, mirrors that in test pit 3. The strong expression of time dependent pedogenic characteristics in the basal deposit is consistent with its inferred age on the order of multiple millennia. The differences from test pit 3 reflect increased infiltration and diminished erosion at the base of the slope. The weaker soil development in the Bt2 horizon creates some ambiguity regarding the timing of deposition, but the color, gradual lower boundary, and magnetic susceptibility data indicate that it is genetically related to the deeper horizon, implying that it has been in place for multiple millennia. The overlying Bt and ABp horizons reflect recent deposition and mixing due to plowing of the hillslopes. The magnetic susceptibility data suggest that the plowing affected a relatively well-developed soil and that erosion

continues to impact the hillslope. The surface is furrowed perpendicular to the hillslope. This "contour plowing," rarely observed in the study area, implies a concern with ongoing erosion.

Test pit 5, at the toe of the slope, exposes fluvial strata. The ped structure, texture, and color of the stratum at the base of the exposure indicate a similar age and origin to the ancient deposits exposed at the base of test pits 4 and 3. As in the other two cases, the basal stratum clearly grades downward into decomposing bedrock. The overlying deposit reflects channel formation and filling, as indicated by the presence of a stone line at its base. It appears to be composed predominantly of reworked parent material from the deepest stratum. As noted above (2004-05 Fluvial Contexts, Discussion) a somewhat-rounded sherd in the channel fill is of a type produced as late as the mid-20th Century. Although not conclusive, this implies channel formation and filling in the 20th Century, associated with the advent of extensive, mechanized agriculture in the area. Characteristics of the overlying strata show that they all were deposited rapidly and buried before significant pedogenesis occurred. In sum, the strata reflect a long period of landscape stability followed by channel formation during the 20th Century. Subsequently, the channel filled and sediments were deposited on the floodplain prior to the formation of the deeper, through-flowing modern channel.

Characteristics of the soils exposed by test pits on and at the base of slope one reflect ongoing erosion associated with changes in land use initiated during the 20th Century. The soil exposed in test pit 1, at the summit of the hill, is the cultivated remnant of a mixed soil truncated by ongoing erosion. Test pit 2 exposes the recently plowed remnants of a truncated, well-developed argillic soil horizon. The degree of pedogenic alteration indicates landscape stability on the order of several millennia prior to the recent erosion. The deposits at the base of test pits 3 and 4 also provide evidence for long-term landscape stability in the past, although the degree of expression of time dependent pedogenic characteristics is somewhat less than might be expected in test pit 3. The overlying deposits are associated with hillslope erosion due to recent cultivation; they reflect recent and ongoing removal of hillslope soils to the base of the slope. Finally, the fluvial stratigraphy exposed in test pit 5 reflects channel formation and floodplain deposition associated with changes in land use during the past century.

Slope 2

Slope 2 is located in the northern portion of the 2004-05 survey area, in a region dominated by red schist bedrock and red clay soils. Figure 9.11 presents measured profile drawings of each test pit as well as inferred depositional units. Although the bedrock geology and soils are different from other locations in the study area, the soils and sediments exposed by the test pits reveal a history of landscape change similar to that in the southern portion of the 2004-05 survey area: the data indicate recent and continuing severe erosion. There is no evidence for hillslope erosion in the past, including during the Islamic period.

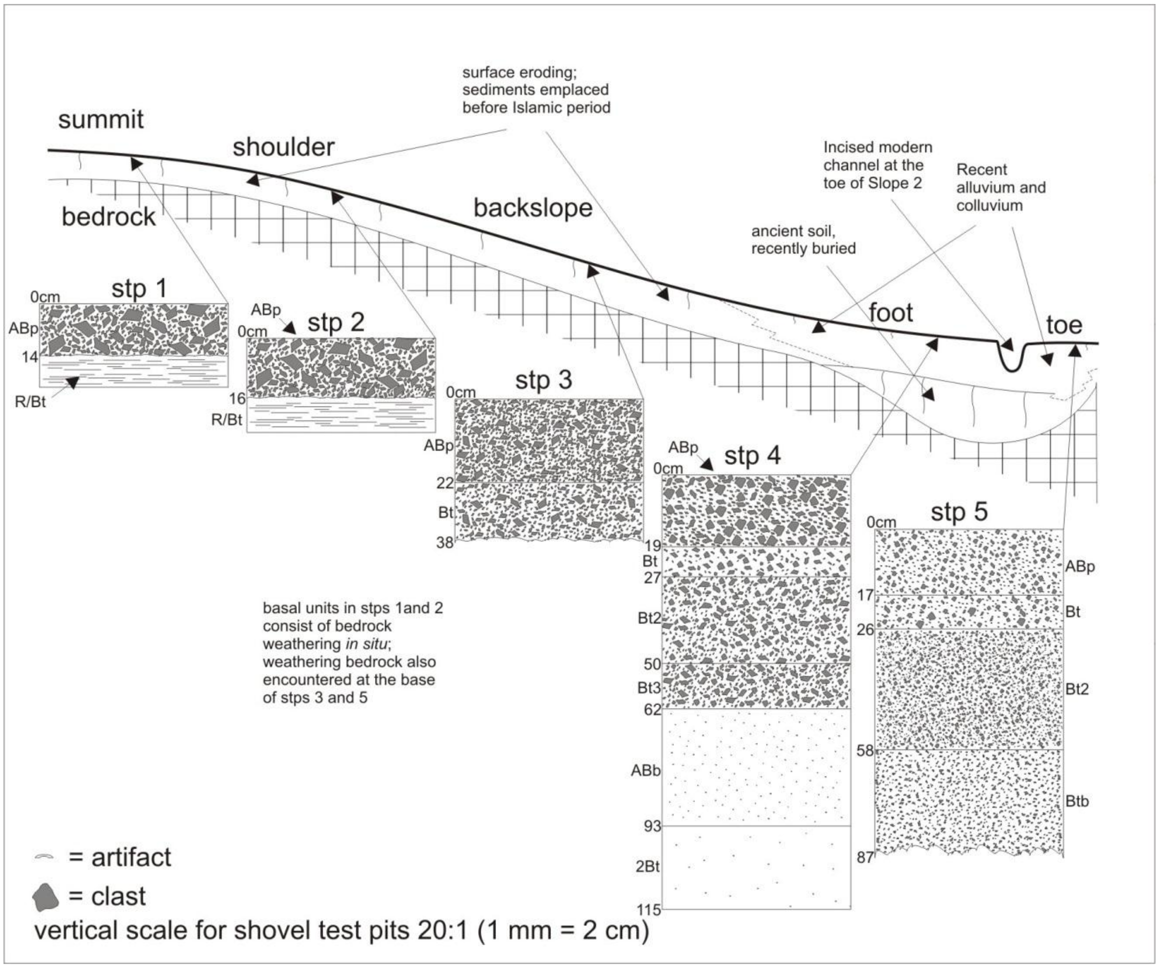

Figure 9.11: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 2 with inferred depositional units.

The color and clay film morphology of the thin, plowed, rocky soil in test pit 1, at the summit of the hill, indicate that it incorporates the remnants of a well-developed soil.

The plowed sediments are remarkably similar to the subjacent decomposing bedrock, differing only in clay film morphology and, very slightly, in color and gravel content. This suggests that the soil at the summit of the hill has been truncated by severe erosion. The remnants of a well-developed argillic horizon have been mechanically mixed into the friable bedrock to create the substrate in which wheat is cultivated.

The ABp horizon exposed in test pit 2, at the shoulder of the slope, is similar to that exposed at the summit. In this location, it overlies remnants of a very well-developed Bt horizon, preserved in the interstices in bedrock. The remnants indicate a period of landscape stability and pedogenesis on the order of several millennia. Similar stratigraphic relationships and relict deposits on several slopes in the 1992 survey area indicated severe erosion in the past. In this case, however, similarities of color, clast content, texture, and clay film morphology between the Bt horizon and the plowed deposits suggest that the two are genetically related. The relatively minor differences between them are likely due to recent plowing and mobility of hillslope sediments, and they imply that a somewhat larger amount of the older soil is incorporated into the plowed deposits here relative to higher on the slope. Recent plowing has mixed and eroded a well-developed soil that previously had been stable at the surface for millennia.

The color, ped structure and clay film morphology exhibited by the Bt horizon superjacent to bedrock in test pit 3 indicate moderate pedogenic alteration. As in the backslope test pit on slope 1 in the 2004 – 05 survey area, the orientation of clasts and the presence of the same sediments in the interstices in the highly friable bedrock show that the horizon is comprised of weathered bedrock. The thickness of the zone of weathering and decomposition suggests that the sediments have been *in situ* for a period of time on the order of millennia. The lack of stronger expression of time dependent pedogenic characteristics may be due to geomorphic position in a location that is susceptible to a high degree of mobility of surface sediments, implying deeper burial prior to the recent initiation of erosion.

Similarities between the Bt and the overlying ABp deposits in terms of color, clast content and clay film morphology indicate that the two are genetically related. The relatively flat magnetic susceptibility curve suggests that plowing has thoroughly mixed any remnants of an A horizon into the argillic horizon of a moderately well-developed

soil. It also is consistent with ongoing mobility of surface sediments as well as the preferential accumulation of pedogenic clays at the base of the plow zone. The increased silt content relative to higher portions of the slope and the greater overall thickness of deposits above bedrock suggest recent sediment inputs from higher on the slope[50]. The ABp horizon apparently incorporates a greater quantity of an original A horizon than the analogous deposits higher on the slope.

The strata in test pit 4, at the foot of the slope, reflect an extended period of landscape stability in the past followed by rapid, recent deposition of large quantities of hillslope soil mobilized from higher positions. The color, ped structure, clay film morphology, and clast content of the two deepest strata indicate that the ABb horizon was at or near the surface during a period of landscape stability that lasted on the order of multiple millennia. With the underlying 2Bt horizon, this is among the most strongly developed soils recorded in the study area.

The color, ped structure, and abrupt lower boundary of the superjacent Bt3 deposit indicate that it originated on the nearby hillslope and was deposited recently. The overlying Bt2 and Bt deposits are similar to each other in physical characteristics, with the exception of an increase in clay films in the lower horizon. Color, ped structure, and clay film morphology indicate moderate to strong pedogenesis. Because there is no change in texture, however, the abrupt lower boundary of the Bt2 deposit shows that the Bt and Bt2 horizons were deposited recently and that the pedogenic characteristics are largely inherited. These are well-developed hillslope soils that were removed from their original position and transported to the base of the slope by erosion. Similarly, the ABp horizon is comparable to that in test pit 3, implying recent mixing and deposition. The magnetic susceptibility data for test pit 4 are consistent with the upper 50 cm of deposits having been emplaced by multiple episodes of deposition separated by relatively short intervals of time. Mottling in the Bt3 horizon indicates frequent saturation with groundwater, explaining the falloff to nearly zero in magnetic susceptibility in that and deeper strata.

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[50] Erosion by sheetflow often preferentially mobilizes silt-sized particles as sand is larger and heavier and the platy shape of clay particles and strong cohesion between individual grains makes them difficult to entrain [e.g., Ritter *et al.* 1995: 200-201].

The strata in test pit 5 correlate with those in test pit 4, with the exception that the ABb and Bt3 horizons are not present in test pit 5. This difference probably reflects erosion at the toe of the slope, and possibly the formation of a shallow incised channel prior to deposition of the overlying strata. As in test pit 4, pedogenic characteristics of the deepest stratum suggest a period of soil formation on the order of millennia. The superjacent Bt2, Bt, and ABp horizons are analogous to those in test pit 4, reflecting recent erosion and downward movement of hillslope soils. The magnetic susceptibility data reflect at least two recent episodes of deposition, separated by a short interval of time.

The soils on hillslope 2 reflect recent and ongoing erosion associated with changes in land use initiated during the 20th Century. The sediments exposed in test pits 1 and 2 suggest that the majority of soils have been removed from the upper portions of the slope and that lower soil horizons and decomposing bedrock are currently being cultivated. The pedostratigraphic data from test pit 3 indicate recent and ongoing mobility of surface deposits that incorporate well-developed soils, which are genetically related to the deeper, *in situ* deposits. Finally, the deposits at the foot and toe of the slope record an extended period of landscape stability and soil formation in the past, followed by rapid, recent deposition as soils were eroded from the adjacent hillslopes. There is no evidence for significant erosion prior the 20th Century.

Slope 3

The soils exposed in the series of test pits along slope 3 indicate significant recent erosion. Figure 9.12 includes measured profile drawings of each test pit and shows inferred depositional units. Abundant gravels at the surface along the entire slope are a lag deposit created by ongoing plowing and removal of fine sediments. A thin, rocky ABp horizon also is present at the surface in each pit. The only notable difference between the ABp sediments and the subjacent Bt deposits in the interstices in the bedrock is the incorporation of small quantities of sand-sized particles in the former. The appearance of the “sand” suggests that it is small fragments of bedrock, most likely present because mechanical cultivation has crushed pieces of the friable stone. Minimal color and texture differences suggest that minor remnants of an A horizon are mixed into the plowed deposits. The two horizons clearly are genetically related, and in each

exposure the expression of ped structure and the clay film morphology indicate that the plowed sediments are comprised primarily of a well-developed, exhumed B horizon. The degree of pedogenic alteration suggests landscape stability on the order of millennia prior to the initiation of the current cycle of erosion.

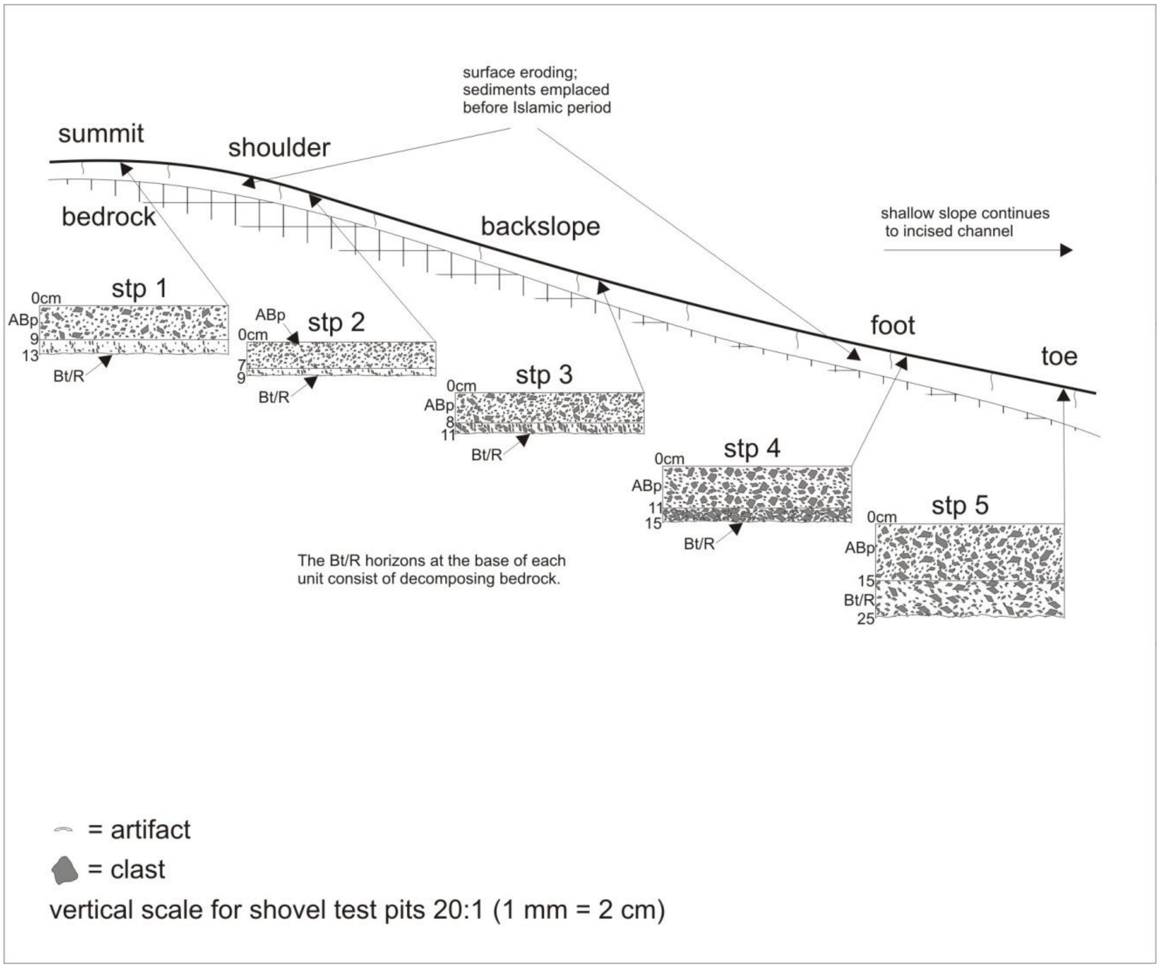

Figure 9.12: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 3 with inferred depositional units.

The strata exposed in each test pit are remarkably similar along the slope. There are minor differences in the thickness of the ABp horizon that are consistent with the expected severity of erosion at each geomorphic position. Even at the toe of the slope, however, the depth of loose sediments is not greater than the effective depth of plowing. The lack of deeper deposits at the base probably is related to slope geometry; a gentle slope continues downward to the incised, ephemeral stream located a few meters beyond the break in slope. Presumably, the stream system has removed sediments previously eroded from higher positions. It also is possible that the south aspect has increased the

slope's susceptibility to erosion because of increased evapotranspiration and decreased plant cover. The magnetic susceptibility profile for test pit 5 is flat, with no significant increase in the signal at the surface and no appreciable changes with depth. This suggests that all of the sediments are of the same age, that they are thoroughly mixed, and that they have only recently been exhumed by erosion. In sum, observations at each pit suggest recent and ongoing erosion of soils that previously had been in place for millennia. There is no evidence for erosion prior to the 20th Century.

Slope 4

Slope 4 was selected for study because there is a small, unexcavated Islamic period site located at the summit. Measured profile drawings of each test pit and inferred depositional units are shown in figure 9.13. Artifacts from the site, observed in the soil test pits, provide chronological points of reference useful for reconstructing the history of sediment movement on the slope. Overall, the soils reflect significant recent erosion. There is no evidence for an episode of erosion prior to the 20th Century.

Test pits 1 – 3, on the upper portion of the slope, expose pedostratigraphy similar to that observed on Slope 3. In each case, a thin (9 – 12 cm), plowed horizon is present over bedrock. Similarities of color, texture, clay film morphology, ped structure, and clast content between the plowed deposit and the Bt sediments preserved in the interstices in the bedrock show that the two horizons are genetically related. The plowed deposits consist primarily of an exhumed B horizon mixed with minor remnants of an A horizon and they include sand-sized particles created by mechanical crushing of bedrock during cultivation. The expression of time-dependent pedogenic characteristics, particularly clay films, is consistent with millennia of landscape stability and soil formation prior to plowing.

In each case, artifacts were present only within the upper few cm of the plowed deposits. This pattern suggests that erosion did not expose bedrock in this location during or at any time after the Islamic period occupation of the site at the summit of the hill. In addition, it suggests that soil loss in this location has been recent and severe; if the erosion had been occurring slowly for a long period of time, repeated plowing likely would have mixed at least some artifacts downwards to the base of the plow zone. The presence of artifacts only in the upper portion of that zone suggests that the plow zone

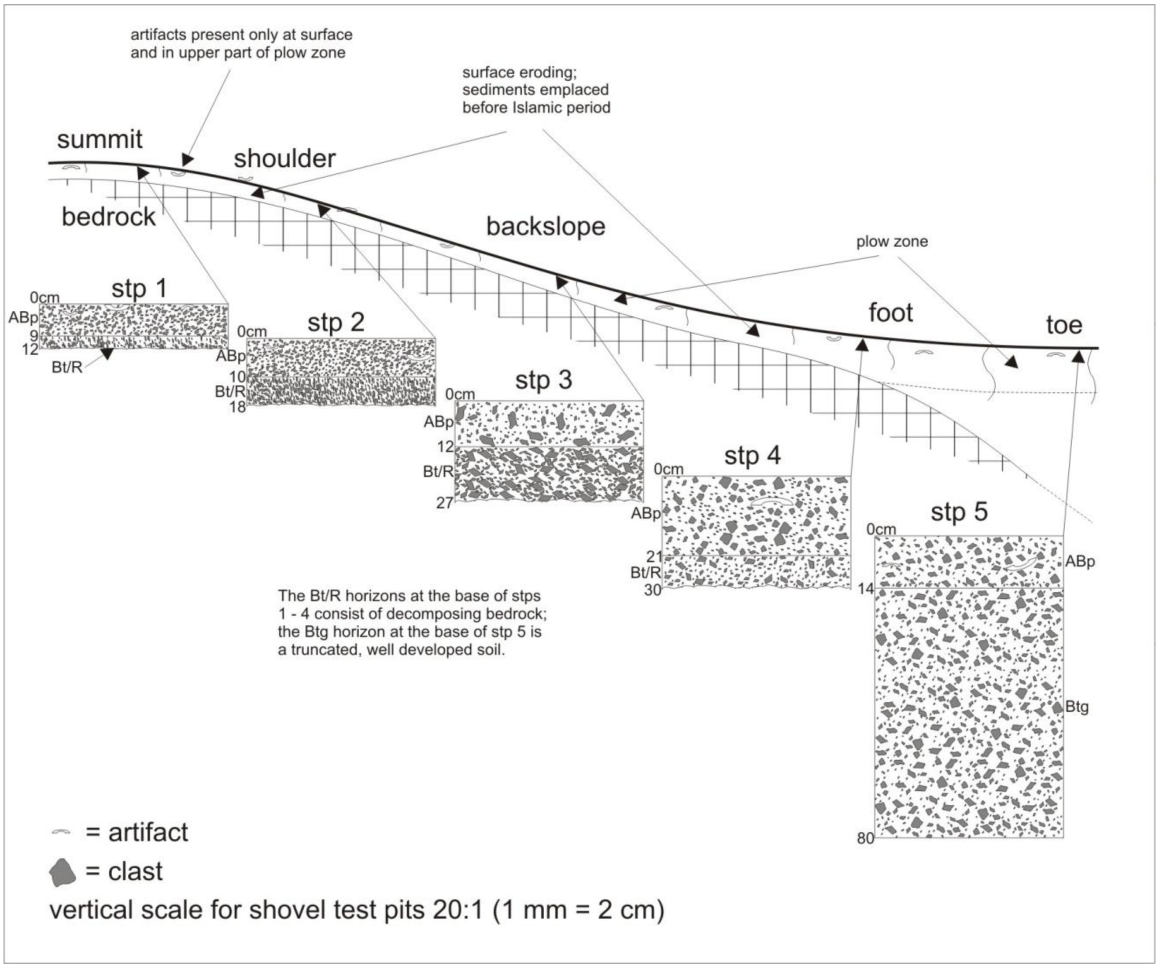

Figure 9.13: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 4 with inferred depositional units. Note the position of artifacts only in the upper portions of plowed deposits.

itself has been moving downward rapidly through the soil column as sediments are removed by erosion.

Soil test pit 4 at the foot of the slope exposes similar stratigraphy, with the exception that the ABp horizon is 21 cm thick. Because of similarities between the plowed horizon and the sediments preserved in interstices in the bedrock, it is reasonable to infer that the origins and age of the surface deposits are the same as higher on the slope. The increased thickness of the unit probably represents deposition at this location due to erosion higher on the slope. This suggestion is corroborated by the presence of rooftile fragments at depths of up to 8 cm. The uppermost 15 cm of sediment exhibit slightly lower magnetic susceptibility than the deeper deposits. This is consistent with recent deposition in this location of sediments from higher on the slope that were relatively deeply buried in the past. In addition, it shows that the sediments have not

been exposed at the surface for an extended period of time. The lack of changes in susceptibility below 15 cm suggests that these sediments were more deeply buried before erosion removed the A horizon from this location.

At the toe of the slope, the plowed deposits exposed in test pit 5 are essentially the same as those higher on the slope, consisting primarily of a mixed, exhumed B horizon. The increased expression of ped structure is attributable to locally increased inputs of water and fine sediment in the form of slope runoff. As in test pit 4, the thickness of the plow zone suggests recent accumulation of sediments from higher on the slope, and rooftile fragments again are present at depths of as much as 8 to 9 cm. The low magnetic susceptibility of the surface sediments and the slight increase below 10 cm are consistent with recent deposition of B horizon materials from higher on the slope. The pattern also suggests that the buried deposits may incorporate some remnants of an A horizon.

No artifacts were encountered in the lower portion of the plow zone, and none was present in the subjacent horizon, suggesting that it was emplaced prior to the Islamic period and that it was and has remained buried since that time. The slightly enhanced magnetic susceptibility to a depth of 30 cm is consistent with a very long period of soil formation. The random size and orientation of clasts in the deposit may reflect initial emplacement by a mass movement. The degree of pedogenic alteration is as strong as any observed during the study, suggesting a subsequent period of landscape stability and pedogenesis on the order of millennia; initial deposition may have been related to climate changes during the Pleistocene – Holocene transition. Excavation to a depth of 80 cm did not expose bedrock.

Characteristics of the soils and sediments exposed in test pits on slope 4 indicate severe recent erosion. Artifacts were encountered in each test pit. Their vertical locations, in addition to soil characteristics, provide no evidence for significant erosion while the adjacent site was occupied during the Islamic period. Test pits 4 and 5 are particularly revealing in that both show evidence for recent accumulation of sediments due to erosion higher on the slope. There are not, however, analogous older deposits that would indicate erosion in the past, and pedogenic characteristics of the plowed deposits at the surface suggest that such deposits probably were not obliterated by recent plowing and erosion.

Slope 5

The soil catena on slope 5 is similar to that observed on other slopes in the 2004 – 05 survey area, particularly slopes 3 and 4. Measured profile drawings of each test pit and inferred depositional units are shown in figure 9.14. Test pits 1, 2, and 3 on the upper portions of the slope all expose thin (8 – 10 cm), rocky, plowed horizons over bedrock. In each case, similarities of color, ped structure, texture, clay film morphology, and clast content between the plowed soils and sediments in the interstices in the bedrock show that these are genetically related soil horizons. The minor differences between them suggest that a slightly larger quantity of the remnant A horizon is present here than on slopes 3 and 4, perhaps reflecting the greater distance from the village of Corte do Gafo and, consequently, fewer episodes of plowing during the 20th Century. Differences in clay film morphology between the horizons exposed in test pit 1 suggest that bedrock was significantly more deeply buried in the past and that the current surface deposits are comprised primarily of remnants of a well-developed B horizon. Recent erosion appears to have been somewhat less severe at the location of test pit 2. A dark layer of organic-rich sediment at 4 cm in test pit 3 very likely is a former surface that was buried by sediments mobilized from higher on the slope after the most recent plowing.

The soils exposed in test pits 1 – 3 reflect significant recent erosion. The overall degree of pedogenic alteration of the sediments is moderate and does not rule out severe erosion in the past, perhaps as recently as during the Islamic period. The unweathered appearance of the bedrock, however, suggests that it has not been exhumed in the geologically-recent past. In addition, the moderate degree of soil development can be attributed to geomorphic position and need not reflect previous removal of loose sediments during the later Holocene. The relatively fine texture of surface sediments, aside from at the summit where recent erosion has created a lag deposit, implies rapid runoff and slow infiltration. Also, the slow, long-term downhill movement of sediments due to processes such as creep would further retard soil development at geomorphic positions high on the slope. No artifacts were encountered that could help to constrain the timing of initial deposition or subsequent movement of sediments on the slope.

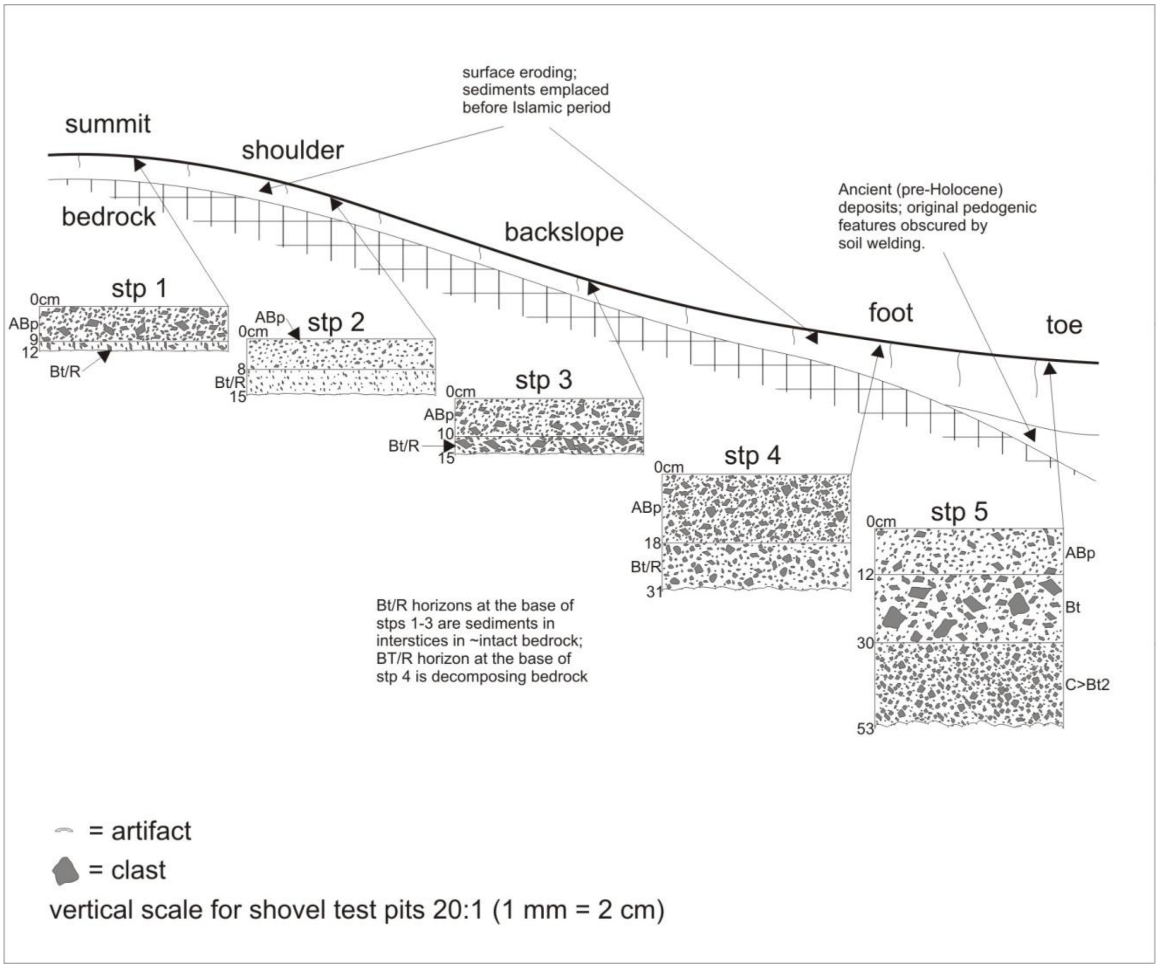

Figure 9.14: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 5 with inferred depositional units.

The soil exposed in test pit 4, on the other hand, provides clear evidence for a single, recent episode of erosion following millennia of landscape stability. The plowed sediments at the surface are thicker than those higher on the slope, and their thickness and somewhat browner color suggest both accumulation of sediments on lower portions of the slope and the incorporation of larger quantities of A horizon material in this location. The enhanced magnetic susceptibility of the upper 20 cm of sediments corroborates this interpretation. Clay film morphology, however, indicates that the plowed deposits also incorporate large quantities of a well-developed argillic horizon, consistent with recent erosion of an intact soil. The subjacent Bt horizon is composed of deeply weathered and pedogenically altered bedrock. The clay film morphology and ped structure indicate landscape stability for millennia and show that bedrock has not been exposed at the

surface in this location in the geologically recent past. The significant reduction in magnetic susceptibility suggests that this horizon was more deeply buried in the past. There are no strata present that reflect significant movement of hillslope sediments prior to recent plowing.

Test pit 5 exposes somewhat more complicated stratigraphy. The plowed sediments at the surface again consist of a mixture of an exhumed B horizon with relatively small quantities of an A horizon, much of which probably originated higher on the hillslope. The relatively low magnetic susceptibility of the uppermost 10 cm of sediments suggests either that it incorporates materials with very low susceptibility emplaced by the stream or that increased water inputs have diminished the signal.

Clay film morphology and ped structure in the subjacent Bt horizon reflect millennia of soil formation. The gradual lower boundary, smooth drop-off in magnetic susceptibility, and textural similarities suggest that it is genetically related to the underlying C>Bt2 horizon, in which the somewhat weaker pedogenic alteration probably is due to the depth of burial in the past. The random orientation and lack of size sorting of clasts in these deposits imply that they were emplaced by a mass movement. The degree of pedogenic alteration and the continuation of the sediments essentially unaltered into the interstices in the bedrock show that the mass movement occurred millennia in the past. The mass movement likely was triggered by landscape adjustment to changing climatic conditions at the Pleistocene – Holocene transition. Soil welding has obscured any differences that may have been present between the C>Bt2 sediments and those in the interstices in the bedrock.

In sum, the soils exposed in test pits high on slope 5 reflect significant recent erosion, but the timing of the initial emplacement of sediments in those geomorphic positions is poorly constrained. The test pits at the foot and toe of the slope, however, reflect millennia of landscape stability followed only recently by erosion. There are no strata at these lower locations that reflect hillslope erosion during the later Holocene, prior to mechanical cultivation during the 20th Century.

Slope 6

The final catenary study included in this research was undertaken on the north-facing slope of a prominent hill near the southwestern corner of the 2004 – 05 survey

area. Three sites located nearby increased the likelihood of encountering artifacts during soil studies. Adjacent to the base of the slope, to the northwest, is a small, unexcavated Islamic period site that was severely impacted by mechanical cultivation at some time between the summers of 2005 and 2007. Along the drainage to the northeast is a large residential compound and walled garden that was occupied until the second half of the 20th Century. Southeast of the hill, there is a large *quinta* (household compound with outbuildings belonging to a large landowner, more or less equivalent to a *hacienda*). Although the history of this particular one is unknown, several of the *quintas* in the study area appear to have been occupied at least episodically since the Roman period, and others were founded shortly after the Christian *reconquista*.

In addition to the nearby sites, portions of the hill are ringed by low alignments of rocks placed perpendicular to the slope. These appear to be the remains of shallow terraces or walls, perhaps animal pens. Aside from small, recently-constructed check dams across minor drainages, these are the only terrace-like features encountered in the study area. Unfortunately, despite careful investigation no temporally diagnostic artifacts were recovered from the surface and none was present in any of the soil test pits. Given the lack of artifacts other than recent refuse, it seems reasonable to conclude that the lithic alignments are probably recent features. A portion of one of the features is shown in Figure 9.15.

Figure 9.15: Photograph showing low stone alignment across slope 6, 2004 - 05 survey area.

Beyond the nearby sites and the enigmatic alignments of stone, this location was selected for study because the geomorphology and bedrock geology are somewhat unusual. The hill is one of a line of high hills trending east-west near the southern boundary of the 2004 – 05 survey area. The geologic map of the area shows resistant

units interbedded with the more highly erodible, weakly metamorphosed turbidites (flysch and greywacke) that are typical in the two surveyed areas. Outcrops of silicified stone and several prehistoric tools made from that material were recorded during survey along the line of hills. These observations suggest that the high hills are present because the finer-grained bedrock units are more resistant to weathering than the bedrock in other locations. The lithic alignments across slope 6 are, for the most part, oriented parallel to the bedding in the bedrock and in several places they appear to augment natural outcrops of fine-grained stone. As expected, given the bedrock and the lithic features, the soils exposed in test pits along the slope are somewhat different from those observed in other locations. Figure 9.16 presents measured profile drawings of the soil test pits, along with inferred depositional units.

The plowed soils exposed in test pits 1 and 2, at the summit and shoulder of the hill, are deeper (17 and 14 cm thick, respectively) than those in analogous locations on other hills in the study area. Their color, texture, and clay film morphology suggest that they also incorporate larger quantities of an A horizon than on other slopes. At the same time, gravels at the surface indicate at least some ongoing erosion. Similarities to the underlying sediments in terms of color, ped structure, texture, and clay films show that the horizons are genetically related. The subjacent deposits, in the interstices in the unweathered bedrock, exhibit moderate ped structure and strong clay film development, implying millennia of landscape stability prior to recent plowing.

Test pit 3, on the backslope, exposes surprisingly deep soils, with approximately 40 cm of pedogenically altered material over bedrock. The relative lack of erosion in this location may be related to the alignments of stone across the slope; whatever their origin or intended function, they effectively discourage plowing down the slope as is common in the region and they may have discouraged any mechanical plowing at all on some portions of the hill. Contour plowing (plowing across the slope) is a simple and effective method of reducing soil erosion associated with cultivation, and the depth of the soil may reflect, at least in part, this difference in land use practices. It also is possible that the frequent use of this area for winter pasture has increased organic inputs (i.e., manure) and that it has been less frequently cultivated than other slopes, again reducing erosion.

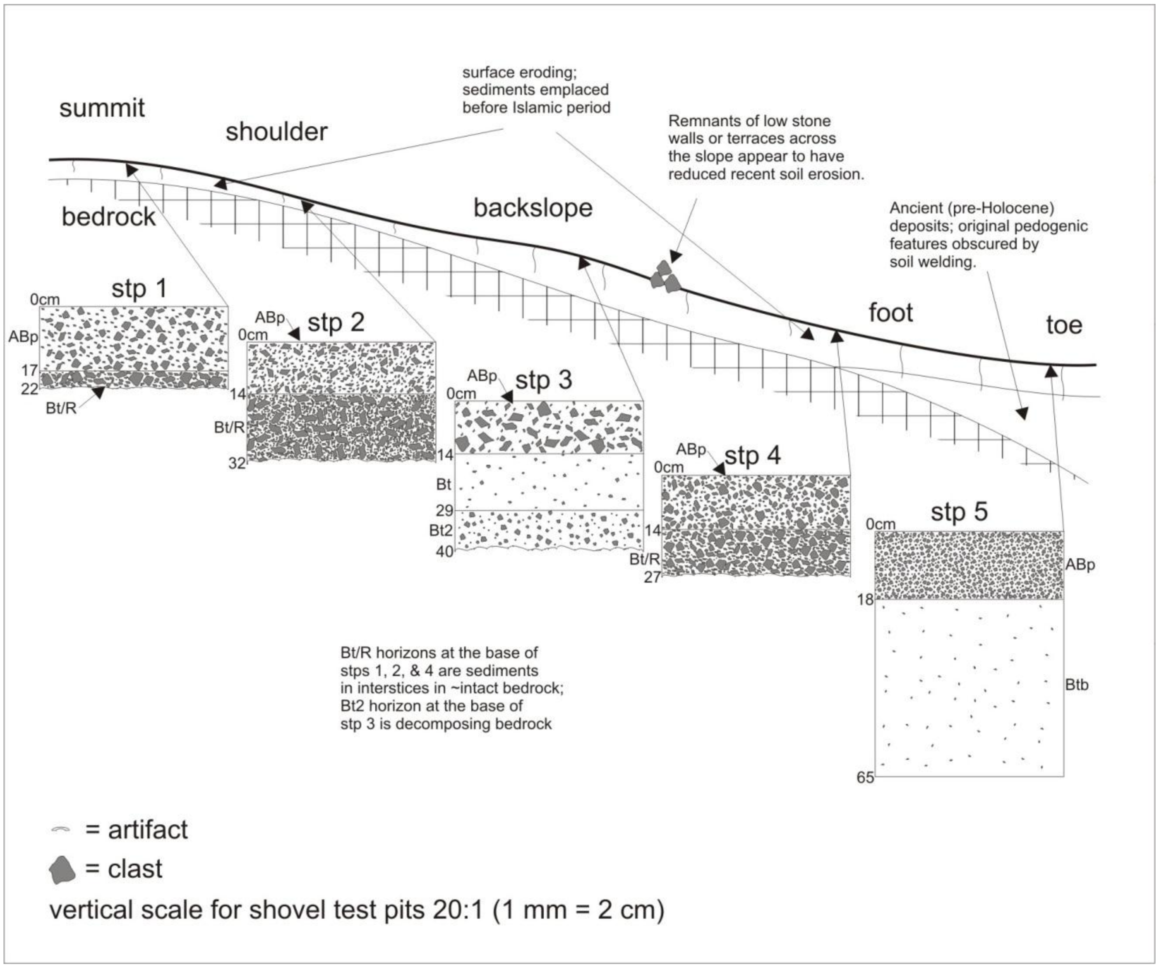

Figure 9.16: Measured profile drawings of soil test pits at 2004 - 05 survey area slope 6 with inferred depositional units.

Gravels at the surface and the sandy texture of the plowed deposits do suggest, however, some degree of recent and ongoing erosion. The peak in magnetic susceptibility at 10 – 20 cm is consistent with recent deposition of sediments that incorporate B horizon materials. As at the higher positions, however, the color and clay film morphology of the plowed deposits indicate the preservation and incorporation of significant quantities of an A horizon; the recent erosion has not been severe. In addition to recent deposition, the peak in susceptibility probably reflects accumulation of clays at the base of the plow zone.

As in other locations, soil characteristics show that the surface deposits are genetically related to the subjacent Bt horizon, which exhibits moderate to strong pedogenic alteration. Its gradual lower boundary and similarities of color, ped structure, clay film morphology, clast content, and texture indicate that the Bt and Bt2 horizons are

the lower portions of an intact, monogenetic soil. The weak secondary peak in magnetic susceptibility at 30 – 35 cm, coincident with the uppermost portion of the Bt2 horizon, very likely can be attributed to the increased clay content in the lower horizon. Clast orientation and the presence of only one lithic material type suggest that both units are comprised of bedrock that is weathering *in situ*; the bedrock in this location is highly friable and thinly bedded, unlike the more blocky and resistant bedrock higher and lower on the slope. The degree of pedogenic alteration in the lower horizon is as strong as any observed in the study area and indicates millennia of landscape stability.

Test pit 4 exposed sediments that are more typical of this geomorphic position across the 2004 – 05 survey area. Importantly, it is located well below the lowest of the stone alignments that cross the upper portions of the slope, again indicating that these played a role in reducing erosion at the higher positions. The plowed sediments are 14 cm thick and overlie blocky, fine-grained bedrock. Clay film morphology and soil texture indicate that the sediments are comprised primarily of an exhumed B horizon. Quartz clasts in the sediments and as a gravelly lag deposit at the surface reflect significant recent and ongoing erosion, as they are not present in the bedrock at the base of the profile. The peak in magnetic susceptibility at the surface and the relatively minor enhancement of surface deposits is consistent with this interpretation. Similarities of color, texture, clay film morphology, and clast content to the sediments in the interstices in the bedrock imply that the two are genetically related. The Bt horizon exhibits strong pedogenic alteration, implying millennia of landscape stability prior to the recent erosion.

At the toe of the slope, the soil exposed in test pit 5 reflects recent mobility of surface sediments but there are no preserved strata indicative of analogous erosion and deposition in the past. The abundance of gravels at the surface and in the plow zone suggests significant recent erosion, while the range of lithic types and the color of the sediments imply redeposition of materials, including a mobilized A horizon sediments, from higher on the slope. The weak peak in magnetic susceptibility at 5 – 10 cm is consistent with significant recent erosion followed by recent deposition of B horizon materials mobilized from higher on the slope. The clay film morphology also suggests that the deposit incorporates an exhumed B horizon, and the thickness of the horizon is

approximately the depth of plowing typical in unconsolidated sediments with the types of equipment generally in use in the area.

The strong pedogenic alteration of the subjacent deposit reflects millennia of landscape stability prior to the recent plowing and erosion. The sediments continue unaltered to a depth of 65 cm, where excavations were abandoned without reaching bedrock. Clasts within the lower horizon are randomly oriented and include several types of material, all relatively resistant to weathering. The mixture of rock types and the random orientation and lack of size-sorting of clasts suggest that the sediments initially were emplaced by a mass movement. As at other locations, the degree of pedogenic alteration suggests that the movement may have been triggered by significant climate changes at the Pleistocene-Holocene transition.

Interestingly, the sediments at the base of test pit 5 were identified as "*barro*" by Edgar, one of the local field crew. *Barro* is a generic term for clay, but it also denotes in this case a type of clay used widely across the 2004 – 05 survey area to build *pisé* (rammed earth) structures, and the word can also refer to the structures themselves. The ubiquity of *pisé* as a building material in the 2004 – 05 survey area may suggest that similar deposits are widely distributed in that area; masonry structures are far more typical in the 1992 survey area.

There is an anomalously high peak in magnetic susceptibility at a depth of 25 – 30 cm that is puzzling in that it is not correlated with any obvious changes in soil characteristics. An examination of the data reveals that the measurement is driven primarily by the readings on one aliquot (25 – 30 a) that was much smaller than the average aliquots, at only 2.9g. It is likely that correcting for mass effectively amplified a small error. With the readings on that aliquot removed, the other two aliquots at that depth yield an average susceptibility measurement that is only very slightly higher than the subjacent and superjacent 5 cm sample strata. If this is a more accurate measurement, the minor increase may be due to the accumulation of clays just below the plow zone. Alternatively, given the highly weathered nature of many clasts in the base unit and the range of lithic types present, it is possible that the anomalous aliquot included rock decomposing *in situ* that contained relatively high quantities of magnetic minerals. The data are insufficient to distinguish between the alternatives, but the anomalous reading

does not significantly alter the overall interpretation of the history of erosion and deposition at this location.

In sum, test pits on the upper portions of slope 6 expose soils that are unusually deep and well-preserved compared to others in similar geomorphic positions across the 2004 – 05 survey area. The differences appear to be related to a series of low stone alignments positioned across the upper portions of the slope. While the intended purpose of these alignments remains unknown, they have made plowing down the slope impractical and thereby contributed to soil retention both by altering cultivation techniques and directly by trapping sediment. In any case, the soils reflect some degree of recent erosion and there is no evidence for earlier erosion in the geologically recent past. The pits at lower positions, below the alignments, reveal evidence for more significant recent erosion. Like those higher on the slope they do not preserve any evidence for previous erosion during the middle to late Holocene.

Discussion

The data produced by catenary studies in the 2004 – 05 survey area support the reconstruction of landscape history suggested by studies of floodplain deposits; they reflect a protracted period of landscape stability followed only recently by significant erosion. The soil test pits excavated on the upper portions of slopes (i.e. summit, shoulder, backslope) exposed plowed deposits over decomposing bedrock and *in situ* soil strata that exhibited evidence for moderate to strong pedogenic alteration. Because of recent erosion, the original A horizon materials have been removed from the highest topographic positions on all of the tested slopes, and the exhumed soil B horizons and decomposing bedrock currently are cultivated there. In each case, soil properties suggest that the ABp and B horizons are genetically related, with the former incorporating high proportions of the latter due to mechanical mixing.

The repeated pattern reflects recent erosion of intact soils that formed on a stable landscape during the course of multiple millennia. Variability in the expression of time dependent pedogenic characteristics in the basal strata likely reflects variable depths of burial prior to the recent erosion as well as differences in topographic position, infiltration rates, and slope processes such as creep that have affected the deposits at geologic time scales. Unlike in the 1992 survey area, no artifacts were encountered

below the upper part of the plow zone in any location. This almost certainly cannot be due to a general lack of artifacts in the 2004 – 05 survey area. Although less common than they were in the 1992 survey area, sites and artifacts were recorded in numerous locations. In addition, artifacts were present in the plow zone in each of the test pits excavated on slope 4 and they were present at the surface on slope 3 and near slope 1. The vertical position of artifacts suggests that erosion was minimal during and after the Islamic period and prior to the 20th Century.

The surficial deposits at lower slope positions across the 2004 – 05 survey area include sediments that originated higher on the slope and that were redeposited by erosion following recent plowing. Boundary morphologies indicate that deposition was recent and the pedogenic characteristics exhibited by the upper strata must be inherited. The plowed deposits in each case overlie argillic horizons that are the intact lower portions of well-developed soils. In no case are there preserved strata that reflect geologically recent (i.e. Roman or Islamic period) deposition due to soil erosion at higher positions prior to the 20th Century, and artifacts again were never present below the plow zone. Unlike the fluvial studies in the 2004 – 05 survey area, the catenary studies uncovered evidence for significant landscape change prior to the appearance of agrarian populations in the area. The basal deposits in the toe slope positions on slopes 4, 5, and 6 appear to have been emplaced by mass movements, and the degree of pedogenic alteration suggests that these were associated with major climatic shifts at the Pleistocene – Holocene transition.

Comparison of Surveyed Areas

Like the stratigraphic studies in fluvial contexts, catenary investigations produced strong evidence that histories of landscape change were different in the two surveyed areas. In the 1992 survey area, soils at the higher geomorphic positions (i.e. summit, shoulder, and backslope) were thin, weakly developed, and usually rested directly on bedrock. The weak expression of time dependent pedogenic characteristics is consistent with initial deposition and soil formation since the Islamic period. In addition to the pedological data, artifacts dating to the Islamic period were encountered at the base of the poorly developed soils and in contact with bedrock in many locations in the 1992 survey area. Although the artifacts could have been mixed downward by post-depositional

processes, the repeated pattern of artifacts at the base of the soil suggests that they likely were emplaced before the surficial sediments in which soils are forming. In a few cases, discontinuous remnants of older soils were preserved in the interstices in bedrock; pedogenic characteristics and the absence of artifacts in the lower units suggest that the soil horizons are not genetically related. The clear implication is that erosion completely or almost completely removed soils from upland locations in the geologically recent past throughout that area. Finally, lag deposits at the surface and magnetic susceptibility measurements indicate recent and ongoing erosion.

Test pits excavated at lower geomorphic positions in the 1992 survey area consistently revealed evidence for two episodes of geologically recent deposition caused by erosion on the adjacent hillslopes. Numerous artifacts present in strata reflecting past deposition at foot and toe slope locations in the 1992 survey area indicate that the older cycle of hillslope erosion occurred during or after the Islamic period. The degree of pedogenic alteration in surface deposits, and boundary morphologies in particular, indicate that the more recent erosion is related to the widespread plowing of hillslopes during the 20th Century.

In addition to the stratigraphic position of artifacts, OSL dates constrain the timing of the past episode of landscape change. Assays from test pits adjacent to Queimada and Alcaria Longa suggest relative landscape stability through the Roman era. Dated sediments at Queimada and Cerro da Loiça reflect channel formation, related to hillslope erosion, during the later Islamic period. Finally, sediments buried by the most recent hillslope erosion at Queimada last were exposed to light at the beginning of the 20th Century. Taken together, the data indicate widespread hillslope erosion during the Islamic period followed by several centuries of relative landscape stability during which sediments accumulated and soils started to form on hillslopes. Subsequently, during the 20th Century, mechanical cultivation triggered renewed erosion throughout the 1992 survey area. Generalized stratigraphic relationships and depositional units inferred from catenary studies in the 1992 survey area are shown in figure 9.17 and the depositional units and stratigraphic relationships inferred from catenary studies in the 2004 – 05 survey area are shown schematically in figure 9.18.

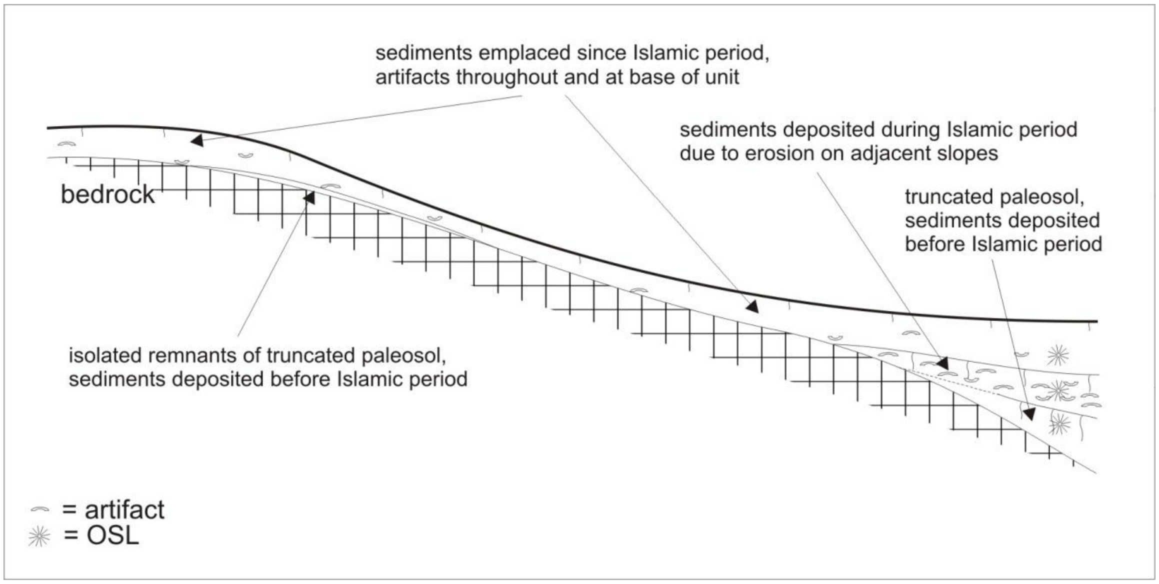

Figure 9.17: Depositional units on slopes in the 1992 survey area, inferred from catenary studies.

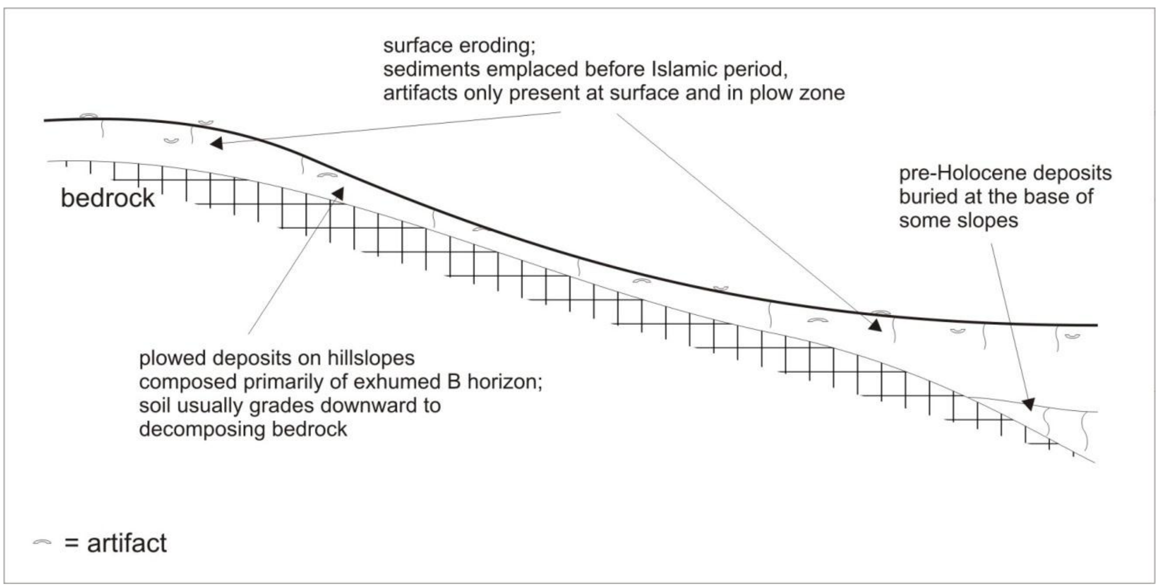

Figure 9.18: Depositional units on slopes in the 2004 - 05 survey area, inferred from catenary studies.

Catenary studies in the 2004 – 05 survey area revealed repeated soil-stratigraphic patterns that are significantly different from those observed in the 1992 survey area. Pedogenic characteristics of sediments at higher geomorphic positions reflect recent and ongoing erosion of well-developed soils. In particular, clay film morphology and ped structure indicate that hillslope soils in the 2004 – 05 survey area are older than those in the 1992 survey area. Although conclusions drawn from comparisons of magnetic susceptibility between areas must remain somewhat tentative because additional

laboratory work to characterize the magnetic mineralogy of the sediments has not been done, the uniformly higher magnetic susceptibility of sediments in the 2004 – 05 survey area is consistent with stronger soil development there.

Across the 2004 – 05 survey area, no strata that indicate hillslope erosion during the Holocene before the 20th Century were encountered in any test pits at the base of slopes. Plowed surficial deposits generally were soil A horizons removed from adjacent slopes, mixed with exhumed argillic B horizons. The plow zone was present above the argillic horizons of very well developed, ancient, truncated soils. In addition to soil characteristics, the stratigraphic position of artifacts in the 2004 – 05 survey area shows that sediments were not removed from the upper portions of hillslopes in the geologically recent past. At all slope positions, artifacts were present only at the surface and in the upper parts of the plow zone. The total absence of artifacts at depths greater than 9 cm below the modern ground surface suggests that buried artifacts have been moved downward by post-depositional processes, particularly repeated plowing. Furthermore, the repeated pattern implies that the presence of artifacts in contact with bedrock in the 1992 survey area reflects the timing of deposition and not the post-depositional mixing that has occurred in both areas. There are no data for the 2004 – 05 survey area that indicate significant erosion during the Islamic period or at any time during recent millennia before the 20th century. As in the 1992 survey area, however, all of the examined locations exhibit evidence for significant recent and ongoing soil loss.

In sum, geological studies in the 1992 survey area show that there was a period of severe erosion during the Islamic period. Soils and loose sediments were stripped from the upper portions of hillslopes across the area and deposited at lower positions. Subsequently, stream systems cut downward throughout the study area, removing some of those sediments. OSL and radiocarbon dates show that channels incised in three different locations during the 12th Century C.E., suggesting that channel formation was approximately contemporaneous throughout the surveyed area. By contrast, analogous investigations in the 2004 – 05 survey area did not produce any evidence for a cycle of erosion during the Islamic period; there was no indication of significant erosion during the Holocene prior to the 20th Century. The different histories of erosion in the two surveyed areas that otherwise are similar, along with evidence for different histories of

settlement density and land use, suggest that human activities caused erosion during the Islamic period in the 1992 survey area. The reasons for that erosion are explored more fully in the next chapter.

Chapter 10:

Discussion

The data presented in the preceding chapters provide answers to many of the research questions posed at the outset: Was there significant ecological change in the study area during the post-Roman era? Does it qualify as degradation? and Did humans cause the degradation? Data from the author's soil-geomorphic studies in the 1992 survey area show that there was severe and widespread soil erosion during the Islamic period, culminating in the 12th century with the formation of a network of continuously incised arroyos. Macrobotanical data also suggest changes in plant communities including a reduction in tree cover, increased prevalence of shrubby species, and some degree of rangeland degradation during the later Islamic period. Together these data sets indicate significant ecological change.

The documented changes meet the conditions that Butzer (2005) proposes for classifying ecological change as degradation in a Mediterranean environment. The macrobotanical data indicate at least some conversion of woodland or savannah to degraded scrubland, his first criterion. He also suggests that the formation of dense, deep gully networks signals degradation. Although increased sediment loads were not sufficient to convert the Guadiana to a braided stream, erosion clearly pushed the hillslope and fluvial geomorphic systems in the 1992 survey area beyond a threshold and they entered a phase of "soil, slope and stream disequilibrium" (*ibid.*: 1786), satisfying his second major criterion. Finally, the abandonment of rural settlements suggests that soil erosion was severe enough to reduce the productive potential of the landscape for several centuries, evidence of what he categorizes as an ecological "crash" (*ibid.*: 1795).

Determining whether people caused the observed degradation is somewhat more complicated. The dramatic increase in the number and total area of settlements in the study area during the Islamic period provides circumstantial evidence that human activity very likely impacted plant communities and caused soil erosion. Several lines of evidence, however, suggest relatively dry and warm conditions in the study area during the earlier Islamic period, with drought conditions perhaps reaching a peak during the 11th century. The 12th century then saw a shift to wetter conditions and perhaps an

increase in the frequency of large storms. These climate changes also would have favored erosion in the study area, particularly if the onset of wetter conditions was rapid.

Whatever role it may have played – and it could have been an important one – there are two reasons to believe that climate change cannot be viewed as *the* cause of degradation in the study area. First, the changes in the 11th and 12th centuries were small compared to other climate shifts. The climate models presented in chapter five suggest that the Pleistocene – Holocene transition, which caused widespread geomorphic change throughout Iberia, saw a reduction of more than 25 percent in mean annual precipitation (from more than 800 to less than 600 mm/yr) coupled with an increase in annual potential evapotranspiration from less than 500 to approximately 600 mm in the study area. The changes in the 8th through the 14th centuries are an order of magnitude smaller. Similarly, the total change from the Medieval Warm Period to the Little Ice Age probably was more significant than any changes that occurred during the 11th and 12th centuries. There are only hints of geomorphic change at a regional scale during the Islamic period and no evidence for such change during the Christian medieval period.

Comparatively small changes in storm patterns and effective moisture can, however, be important drivers of geomorphic change at smaller spatial and temporal scales. The second reason to suggest that climate change does not, in and of itself, explain degradation in the study area during the later Islamic period is that the geoarchaeological research reported here produced no evidence of channel formation or significant soil erosion in the 2004 – 05 survey area. It is appropriate here to echo Butzer's assertion that "without 'disturbance', forested hillsides in the subhumid Mediterranean lands are characteristically quite stable… in this particular Mediterranean and Holocene context, excessive precipitation events are unlikely to implement rapid and significant geomorophological change *without prior impairment* of the land cover by direct or indirect human activity." (2005:1785, emphasis in the original) At the very least, human activity was *a* cause of degradation in the study area during the later Islamic period.

Degradation in the study area probably cannot narrowly be ascribed with certainty to either climate change or human activity, and it may have resulted from some combination of the two. The more significant questions then become how and why

people caused degradation in the context of minor fluctuations in climate. In particular, how did people and the environment interact, and what were the processes involved in ecological change? And why did people act in ways that caused the widespread erosion and channel formation that severely reduced the productive potential of the landscape? The linked questions of how and why people caused degradation can be answered at several levels, from the proximate and simplistic assertion that human activities enhanced erosive forces and/ or reduced the forces keeping sediments on hillslopes, to the vague approximation of an ultimate cause in the statement that the high population density was unsustainable. The goal of this chapter is to find an answer at a satisfactory level of abstraction, one that addresses the historically specific context and at the same time generates some insights into human – environment interactions in general.

Theory Revisited

Because building and evaluating arguments is one of the primary functions of theory in archaeology, the salient points discussed in chapter two are revisited here. Among others, Butzer (2005) provides a cogent discussion of the problem of determining causation in complex socio-natural systems. He concludes that natural science following an inductive, data-driven approach is necessary to determine how and when the environment changed. Proper explanation of that change, however, also incorporates a humanistic aspect focused on historical context, belief systems, and cultural values that help to illuminate why people did what they did.

In a more general discussion of explanation in archaeology, Fogelin (2007) suggests that inference to the best explanation, a form of contrastive explanation, is typically the most successful when dealing with complex phenomena. This largely is because it allows a researcher to focus at an appropriate point along the continuum from proximate to ultimate causation. Combined with Butzer's work, his research implies that a satisfactory explanation of anthropogenic ecological degradation in the study area in the past will indicate why the degradation occurred when it did, as opposed to at another time, and will emphasize the ways in which long-term regional processes played out over shorter periods of time and at a local scale. Similarly, following Ghiselin (1997), explanation in the historical sciences in general should include a historical narrative and identify how general principles relate to the specific sequence of events.

Within this general theoretical framework, the literature concerning human-environment interactions provides several additional guidelines for building an explanation of why people caused degradation in the study area during the Islamic period. Current approaches emphasize the recursive, diachronic nature of those interactions, focusing on the ways humans have modified the world around them and adjusted to changes resulting from the intended and unintended consequences of their actions. Many scholars studying the problem suggest that research must focus on empirical measures of environmental change at specified temporal and spatial scales, often with the goal of building a better understanding of how to manage modern landscapes.

Similarly, a body of theory concerning various aspects of the relationships between elites, producers, and the environment is relevant to the central problem considered here. While few scholars have explicitly considered the interactions of all three entities, examinations of interactions between each of the different possible pairs help to identify the important variables and some of the ways in which they may be connected. Specifically, researchers in several fields have noted that the emergence and growth of complex social systems entails increasing alteration of the environment, while others have noted the parallel rising social and economic costs for primary producers. Both of these increases result from the necessity of increasing production to meet the demands of an elite class.

Allocation of those social and ecological costs is determined by negotiations between producers and the elites, and the social, economic, technological, and environmental contexts determine costs and benefits for the different actors. Political economy is a critical variable in that the different means of funding the state apparatus entail different degrees of extraction of wealth from primary producers. Finally, political ecology studies in innumerable contexts suggest that primary producers are cognizant of the ecological consequences of different means of increasing production. Butzer's (1994) historical research focused on the agronomic writings of the Classical and medieval Islamic worlds suggests that agrarian populations in the study area during the Islamic period probably shared that knowledge (see also Redman 1999: 20); a concern with maintaining long-term productivity can be assumed to be part of the cost-benefit calculus for producers.

Following from this, an adequate answer to why people caused ecological degradation in the study area during the later Islamic period will have several characteristics. It must begin with a historical narrative of ecological change derived from inductive, natural science research that uses empirical measures to show that changes of a particular type occurred at specified spatial and temporal scales. It should include a consideration of why people acted in the ways that they did, informed by social science approaches and sensitive to variables such as perceptions of degradation, social and economic structure, historical and environmental context, and the technologies of production. It ought to demonstrate how long-term, large-scale processes played out in the study area and at the scale of human lifetimes, and it should address how people's actions changed through time in the context of ecological changes driven at least in part by the intended and unintended consequences of their own actions. Bringing all of these together, a satisfying answer should explain the historical narrative by reference to the ways general principles played out in this specific context.

Building arguments to answer complex "why?" questions clearly is not a trivial task; a successful answer to a complex question is likely to be complex itself[51]. Building on ideas presented by Fogelin (2007), the approach that is most likely to be fruitful will be a comparison of different possible explanations to evaluate which best explicate the greatest breadth of observations. In this case, a good beginning point is an evaluation of different general models that have been proposed for explaining the causes and processes of anthropogenic environmental degradation.

Models of Anthropogenic Environmental Degradation

Scholars working in many fields have proposed general models that purport to clarify the causes and processes of ecological degradation. Among them three are considered here because it is plausible that they are applicable to the study area and because, to some extent, each provides valuable insights. The first suggests that the Mediterranean region is a ruined landscape, that it was severely degraded in ancient times and never recovered. A second focuses on the transfer of productive technologies to new

[51] On the surface, this would appear to violate Occam 's razor, the principle often stated as "The simplest explanation is the most likely to be correct." However, the principle actually states that the simplest explanation *that explains all of the available data* is the most likely to be correct.

environments as the cause of environmental degradation. The third, called fragilization with delayed response, describes a process of degradation whereby human impacts accumulate until a landscape becomes particularly fragile and a relatively small environmental shift causes rapid, dramatic, and destructive change.

The Ruined Landscape

Also called the Lost Eden theory, the characterization of the Mediterranean region as having been ruined by people in ancient times is widespread and familiar. It can be traced back at least to early Modern writings (Grove and Rackham 2001: 8 – 12). It appears in various guises in many environmental history texts (e.g., Chew 2001, 2007; Ponting 2007) and influential general histories (e.g., Braudel 1976), it was the central focus of pioneering research into anthropogenic soil erosion in the region (e.g., Judson 1963; Lowdermilk 1953; Vita-Finzi 1969), and to some degree it informs much recent research into desertification in southern Europe (e.g., the European Union's MEDALUS [MEditerranean Desertification And Land USe] Programs and resulting publications; Castro *et al.* 2000; van der Leeuw 2000). In essence, the Lost Eden theory is parallel to carrying capacity and overshoot models that are common in archaeology but it assumes that ecological rebound is extremely slow or perhaps impossible.

In the most popular iterations the eco-friendly Greeks avoided environmental disaster because they maintained sacred groves of trees that moderated the climate and minimized erosion. The more economically-minded Romans, however, cut down every tree in sight for lumber and destroyed forests to expand their slave-worked estates, and they generally managed the land poorly. Rain decreased and intensive farming caused such severe erosion that the landscape never fully recovered. All human activity since has only compounded the environmental problems. The implication is that the Mediterranean landscape is inherently fragile and that it cannot support intensive production. Tellingly, several recent popular accounts of archaeological investigations at the site of Göbekli Tepe in Turkey apply this people-destroyed-Mediterranean-environments meme, suggesting that the 12,000 year old ritual site in southeastern Anatolia marks something like a Garden of Eden that subsequently was destroyed by farming to feed a growing population (e.g., Knox 2009).

The first and most obvious critique of the ruined landscape model is that it functions poorly as a model. In order to be useful, a model should identify important variables, clarify how they are connected, be based on proven or at least plausible premises, and generate testable predictions[52]. The ruined landscape model fails on all counts. It simply claims that someone in the past, usually the Romans, mistreated the environment in poorly specified ways that probably included intensive farming and cutting down trees, causing equally poorly specified problems. Among the problems attributed to past mis-managers in various works are soil loss, deforestation, drought, flooding, and desertification. It is established historical fact that the Romans cut down trees and farmed intensively, and that each of the ecological problems listed above occurred during the Roman era at several or even many places in the empire. But the ruined landscape model does little to identify clearly the important variables (presumably soil types and thickness, topography, plant communities, population growth, and something about land tenure systems and agricultural practices) and does even less to specify how they are connected. Therefore it fails to predict where, when, or how Roman actions caused any of the observed environmental problems.

Grove and Rackham (2001) provide an extended critique of the ruined landscape model focusing on its premises. They note that it presumes that dense forests of large trees were "naturally" present across the Mediterranean region, "the sort of forests that modern foresters are trained to approve of" (Grove and Rachkam 2001: 9). They trace this assumption to several sources including Classical literature and Baroque paintings. They note that "forest" to an ancient Athenian – or, for that matter, to an early modern Spaniard – probably meant the presence of trees, but it almost certainly was not a word that specified the types of forests familiar to northern Europeans. Moreover, almost none of the Baroque painters who commonly depicted scenes from the Bible or Classical literature had actually traveled to the eastern Mediterranean or Greece and few had been to Italy, so they simply set their paintings on a familiar landscape, be it that of Normandy, Holland, or the Papal States. Wealthy Northern Europeans who traveled to the Mediterranean during the Age of Enlightenment were familiar with these writings and

[52] Of course models often work backward from the outcomes or "predictions" in the historical sciences. This doesn't alter the fact that they are predictions, as is clear when attempting to determine whether a given model is applicable in any particular time or place.

paintings and were surprised to find a dry, open landscape; they assumed it must have been wrecked since the time of the Bible or the ancient Greeks.

Grove and Rackham then present an impressive range of evidence to show that the distribution of dense forests of tall trees has actually been quite restricted in the Mediterranean region for at least the past two to three millennia and probably far longer. Instead, they argue that extant Mediterranean plant communities developed throughout the terminal Pleistocene and Holocene in the context of constant human occupation and alteration of the landscape. Human modifications of the environment have varied widely, from Upper Paleolithic anthropogenic fire regimes to modern intensive plow agriculture, but they have been important at least since the Mediterranean climate regime became established after the last glacial maximum. The complex mosaic of biotic communities present today is the result of climatic changes since the late Pleistocene as well as those anthropogenic impacts. Perhaps more than anywhere else in the world, there is no "natural" state without the influence of humans to which the region could be "restored" regardless of whether return to such a state would be practical or desirable.

Importantly in the context of this research, the oak savannah that frequently is viewed as a degraded forest has been present in parts of the Mediterranean for millennia, including the study area (Grove and Rackham 2001: Chapter 12). Although its range can be extended by active management, the only preconditions for its existence are a suitable summer-dry climate, thin, nutrient poor soils, a fire regime with a return interval of a few years to a few decades, and herds of grazing animals. It is unimportant whether the fires are started by people or whether the animals are domesticated.

Other premises of the ruined landscape model are that removal or degradation of the (imaginary) Mediterranean forests caused a regional shift to more arid conditions and that when rain did fall it caused severe flooding. The idea that deforestation increases regional aridity appears to be at least somewhat valid in the humid tropics where vast rainforests retain and cycle enormous quantities of water back into the atmosphere through evapotranspiration. On the other hand, it appears to be nothing more than speculation to assert that the same process causes appreciable differences in rainfall in the

Mediterranean, which supports far less dense forests, where the air is far less humid, and where forests cover far smaller contiguous areas of land[53].

Paleoclimate models suggest a long-term drying trend in the Mediterranean region beginning approximately 10,000 to 12,000 years ago, with conditions stabilizing within the range of modern observations by roughly 4,000 years ago; this cannot reasonably be attributed to the Romans or to deforestation which, if anything, has been more widespread in the past four millennia than it was before. Looking at modern data, different government policies have created a situation in which large areas of coastal Turkey are relatively densely forested while few forests remain on the adjacent islands controlled by Greece since World War I, or on most coastal portions of the Greek mainland. Precipitation maps of the area (SWAI 2010), however, show no differences in rainfall beyond those attributable to prevailing winds, elevation, and distance from the coast. Put simply, there is no reliable evidence that deforestation has significantly reduced precipitation in the Mediterranean region, and if it did the majority of the climate changes occurred well before rise of the Greek and Roman polities.

Similarly, the assertion that deforestation causes flooding is at best somewhat simplistic. It is true that during rainfall events forest cover reduces the rate at which water enters stream systems draining an area, when compared to bare ground. This is particularly important in the humid tropics where removal of vegetation can cause laterization of the soil. However, Mediterranean soils are not susceptible to laterization. Moreover, vegetation of various kinds tends to return relatively quickly after trees are removed and it has a similar effect of reducing runoff rates and minimizing soil loss (e.g., Grove and Rackham 2001: 233). More importantly, the largest and most destructive floods are caused by rare, extreme weather events (e.g., Klemes 1989). With sufficient rainfall any slope eventually will become saturated, infiltration rates will fall essentially to zero, and all additional precipitation will run off. Depending on the slope angle, thickness of soils and loose sediments, and other variables, those slopes may fail in landslides or mudslides regardless of the presence or absence of vegetation. Deforestation probably increases the frequency and severity of small to moderate floods

[53] The Amazon basin by itself covers slightly more than 5.5 times as much area as the total combined land area of the six Mediterraneanoid climate regions on six continents.

and localized slope failures, particularly if there is significant rainfall shortly after large areas are cleared, but truly catastrophic floods are caused by the same extreme climate events that are responsible for the majority of significant landscape change in the Mediterranean region (e.g., Grove and Rackham 2001: 247 – 251; Thornes and Gilman 1983).

As with flooding, the assertion that the Romans (or somebody else) caused severe soil erosion and ruined the Mediterranean landscape is overly simplistic. It begins with the premise that deep, fertile soils are "naturally" present in region. Due to geological and climatic factors the Mediterranean basin lacks the thick loess deposits and deep Mollisols (grassland soils) found at the mid-latitudes in North America, South America, Asia, and parts of Europe. Most of the Mediterranean basin has probably had relatively thin soils at least throughout the Holocene (e.g., Butzer 2005; Gilman and Thornes 1983).

Undoubtedly there was significant soil loss in many areas during the Roman era, and in some cases it was catastrophic for local farmers. However, if nothing else, the preceding chapters should make it clear that erosion and landscape change are complex processes. The history of soil erosion on any given landscape can only be understood through empirical study of that landscape. In addition, not all erosion equates to degradation in the sense of a loss of productive potential. Moreover, the argument that the Mediterranean landscape was ruined in antiquity ignores a central tenet of resilience theory (e.g., Fisher and Feinman 2005), namely that landscapes rebound over time and that human impacts can only be properly understood in the context of that potential rebound. With measured dust influx rates in parts of the Mediterranean as high as a metric ton per hectare per year (Grove and Rackham 2001: 29), it certainly is plausible that soil fertility and depth have been restored at least to some degree in the centuries since the dissolution of the western Roman Empire.

The ruined landscape model, then, appears to be little more than a just-so story based on questionable or demonstrably false premises. It purports to explain how something that never existed changed to become what we observe today through a vaguely specified series of events and processes that remain poorly demonstrated at

best[54]. Its predictions for the study area are similarly vague, amounting to little more than the suggestion that there should be evidence of severe degradation in the past – most likely during the Roman era – and that the modern, degraded landscape owes its origins to that past ecological disaster. In fact, the data presented in the preceding chapters show that there is no evidence of severe degradation in the study area during the Roman era. Even adjacent to the relatively large Roman site of Cerro da Loiça the evidence indicates erosion and channel formation during the later Islamic period. Similarly, although oak savannah currently is more widespread in the 2004 – 05 survey area, it is not absent from the 1993 survey area and it is at least plausible that those differences are due to recent land use and not the persistent effects of anthropogenic degradation that occurred centuries ago. Finally, although there are measurable differences in soils in the two surveyed areas that can be attributed to human actions during the Islamic period, they do not appear today to cause appreciable differences in productive potential.

While the ruined landscape model fails to explain much, if anything about the development of the landscape in the study area, this critique implies that a more successful model will incorporate certain ideas. Specifically, it suggests that the Mediterranean landscape is deeply anthropogenic; it cannot be understood except in relation to human impacts, it is simplistic to view those impacts as automatically causing degeneration from an idealized natural state, and the state of any specific Mediterranean landscape cannot be presumed without detailed study to be the result of past degradation caused by the Romans or anyone else. Finally, the oak savannah and tall scrub of the study area are not the remnants of a primeval forest degraded by human action; they are as natural as any Mediterranean landscape and are in many ways desirable. Finally, a more successful model will specify which human impacts caused what kinds of changes in the past, and how, and it will relate to the unique attributes of the particular landscape in question.

[54] Tainter (2006) suggests that virtually all proposed examples of overshoot and collapse in the archaeological literature are similarly flawed. While his assertion is overly enthusiastic, he alludes to an important point: each case should be evaluated empirically. Without relevant data, claims of overshoot and collapse remain hypotheses to be tested, not explanations.

The Transfer of Technologies

Beginning from a wide range of theoretical backgrounds and working in several different disciplines and many different settings, numerous researchers have suggested that traditional agriculturalists and agro-pastoralists are aware of the problems of soil erosion and exhaustion and will, in most circumstances, take steps to avoid or minimize them (e.g., Blaikie 1985; Butzer 2005; Lansing 2006; Lansing and Kremer 1993; Netting 1986, 1993; Robbins 2004; Scott 1998; Walker 2005; Zimmerer 1993a, 1993b, 2000). Similar observations led Karl Butzer (1996) to propose that a frequent cause of landscape degradation was the transfer of productive technologies developed in one environment, where they were sustainable, to new landscapes to which they were poorly suited (see also "false analogy," McGovern 1994: 149). Historical and archaeological data suggest that this may be a possibility for the study area. During the century following the Islamic invasion in A.D. 711, large numbers of Berbers from North Africa settled in many of the less productive hilly or mountainous regions of Iberia (Guichard 1976, 1998). This appears to be the case in the study area, where the immigrant Berbers probably merged with indigenous Hispano-Roman populations (Boone 2002). The population influx was at least partially responsible for the increased settlement densities visible in the archaeological record, and it is reasonable to assume that the immigrants continued to practice their own techniques of agrarian production.

This model predicts that degradation would have begun rapidly around each newly settled site following the initial arrival of Berbers and Arabs in the study area because their technologies of production were ill suited to the new environment. The model implies a high degree of settlement mobility, as degradation around each site eventually caused the inhabitants to move to more productive areas. Widespread landscape change would have to be the result of the cumulative effects of degradation in the vicinity of many individual sites.

Archaeological data from the surveyed areas show, however, that the village sites founded in the 10th century were continuously occupied until the 12th century, and radiocarbon dates from the smaller settlements founded in the Late Roman or Transitional periods show that some (e.g., Queimada) were occupied continuously occupied or episodically reoccupied over the course of several centuries (Boone and

Worman 2007). Similarly, within the limits of available dating technologies the widespread arroyo formation that marks degradation in the 1992 survey area appears to have occurred rapidly during the mid-12th century, roughly four centuries (or 16 to 20 generations) after the arrival of the Berbers. Finally, the lack of evidence for erosion during the Islamic period in the 2004 – 05 survey area suggests that this at best an incomplete explanation. The model offers no reason for the observed abandonment of rural areas in the 12th century when the inhabitants could have founded farms in lightly settled locales still unaffected by erosion.

Geographic and historical evidence also imply that Butzer's model, although it is doubtlessly useful elsewhere[55], is an unlikely explanation in this case. The environments of North Africa and southern Portugal are remarkably similar in terms of climate, topography, and biotic communities. In addition, historical sources suggest that agrarian production throughout the circum-Mediterranean world during the early medieval period was based on a shared set of crops, animals, and technologies exploited since classical antiquity (Butzer's "Mediterranean agrosystem" 1996; see also Redman 1999, compare to Luyun 1988 [1348]). Although Arab Muslims introduced significant new irrigation techniques to the riverine and karst regions of Andalucía (e.g., Glick 1995), these were impractical in the study area and in similar dry, hilly landscapes where surface water is absent for much of the year. The only change in production techniques apparent in the archaeological record in the study area is an avoidance of pork during the Islamic period. The environmental significance of this change is questionable, particularly as goats and pigs exploit similar environmental niches in a Mediterranean savannah (Grove and Rackahm 2001: 197). Put simply, the Arabs and Berbers did not bring new productive technologies to the study area and they were not transferring them to an environment that was substantially different or new to them[56].

[55] He initially applied it to the import of Old World productive technologies to the Americas after 1492.

[56] Lewis (2008: 205 – 206) correctly notes that many economically important domesticates were introduced to Iberia during the Islamic period, including citrus trees, apricots, saffron, mulberry, henna, sugar cane, date palm, rice, and the merino sheep – the last probably introduced by Berbers (Glick 1979: 66). The newly introduced crop plants, however, were grown almost exclusively in irrigated locations and were not particularly significant in the study area. The merino variety only added to flocks of other sheep and goats already present. Lewis' assertion that Muslims introduced the olive to Iberia is incorrect, although olive production increased during the Islamic period.

As with the ruined landscape model, the suggestion that the transfer of new productive technologies caused degradation does not explain much about landscape change in the study area during the post-Roman era; it does not fit with the available archaeological, geological, or historical data. It does, however, imply that a successful explanation will consider the relationship between population growth and degradation. Moreover, it suggests that the timing, extent, processes, and nature of the past soil erosion and eventual degradation are crucial variables that must be considered in any proposed explanation of its causes. Finally, the research that inspired the model suggests that rural populations in the study area during the Islamic period almost certainly were aware of the ongoing soil loss and changes in plant communities that ultimately culminated in significant environmental degradation.

Fragilization with Delayed Response

A third general model that plausibly might apply in this instance is called "fragilization with delayed response" (van der Leeuw 2000). According to this model, called the fragilization model here for the sake of brevity, human impacts accumulate through time and slowly increase a landscape's susceptibility to degradation. Eventually the synergistic effects of landscape modification and a minor climate change push the landscape beyond a threshold of resistance and catastrophic degradation occurs. This appears to fit the patterns observed in the study area where relatively high population densities were followed, after a significant time lag, by degradation and abandonment.

One of the most important contributions of this model is that applying it facilitates a focus on the processes of erosion and the spatial and temporal scales at which it impacts landscapes. Similarly, it also implies that the characteristics of a specific landscape, such as climate and topography, are important factors determining how human actions affect the environment in any given location. It is clear that in some cases erosion can cause significant landscape changes on a timescale of years to decades (for example, arroyo formation in the American Southwest – see e.g., Bahre 1991; Cook and Reeves 1976). The processes of geomorphic change, however, are complex. Frequently, as van der Leeuw suggests for socio-natural systems, dramatic landscape changes are the result of small, incremental changes building up to the point where they cross a threshold of resistance and the system rapidly changes to a new state (e.g., Bull 1991; Ritter *et al.*

1995; Selby 1993; analogous to a shift in domains of attraction, discussed by Winterhalder 1994: 38). The time required to build up to a threshold value varies depending on environmental parameters and the nature of the anthropogenic impacts and/or other environmental changes. Theoretically, the early phase of incremental change could last decades, centuries, or even millennia.

In addition to varying through time, the effects of soil erosion depend on its spatial extent, distribution, severity, and environmental context. Geomorphic research has shown that different attempts to quantify soil erosion produce widely different results depending on the scale of observation. For example, sediment yields from small test plots cannot be extrapolated to calculate erosion rates for hillslopes or drainage basins: "There is no simple relationship between the flux of sediment measured at a particular location and the area that contributes to that flux." (Parsons *et al.* 2004: 1295; see also Wilcox *et al.* 2003). The disparity, called the sediment delivery ratio, is due to sediment storage at various points along hillslopes and within catchments, and it dramatically affects how erosion impacts productivity at the landscape scale.

Sediment storage is particularly important in water-limited environments like the study area, where one likely result of moderate erosion is the concentration of sediments and available moisture in distinct "sink areas" (Wilcox *et al.* 2003). Vegetation patches thrive in these areas, and the vegetation in turn increases the efficiency of sediment and runoff capture after precipitation events. This capturing provides some resistance to channel formation by decreasing overland flow. Vegetation further increases resistance to erosion by increasing surface roughness and through the efficacy of roots in stabilizing and binding sediments. Over time, the formation of sink areas creates a resource-conserving dryland with higher aboveground net primary productivity (ANPP) than one with a homogeneous distribution of water, plants, and soil (*ibid.*, see also Yair 1994). Although it is somewhat counterintuitive, soil erosion is not always deleterious either to the environment (as measured through ANPP or indices of species diversity, for example) or to agrarian productivity (*contra* Balée 2006: 84).

While these patchy ecosystems are productive, they are also fragile in that disturbance of the sink areas can initiate a positive feedback loop where loss of vegetation enhances loss of soil and moisture and vice versa, resulting in rapid, persistent

degradation (Wilcox *et al*. 2003: 224). Arroyo formation can be particularly detrimental in this context. Ephemeral stream systems often are discontinuously incised and quasi-stable, with sediments eroded from one area and deposited on alluvial or channel fans some distance downstream (Bull 1997). When the forces favoring erosion persistently outweigh resisting forces, however, stream channels form a continuous, integrated system (*ibid.*, see also Selby 1993: 238).

Runoff concentrated within rills and arroyos is orders of magnitude more effective than sheetflow in removing sediments and water from hillslopes and, moreover, in transporting those sediments far greater distances (e.g., Parsons *et al.* 2004; Wilcox *et al.* 2003). In what amounts to the crossing of a threshold of resistance, an arroyo system that becomes continuously incised captures and transports runoff and mobilized sediments to trunk streams far more effectively than a discontinuous system, causing net soil loss over large areas, reducing infiltration, and often removing moisture from the root zones of crop plants (e.g., Bahre 1991; Bryan 1940, 1942; Love 1983). Significantly, these arroyo systems are likely to cut through and effectively bypass sink areas, destroying them. At a landscape scale, resource conserving drylands rapidly become nonconserving; ANPP falls dramatically and species diversity decreases.

Humans can mimic, enhance, or retard the processes that create and destroy sediment sinks in various ways. At the simplest level, pastoralism and farming are likely to increase erosion rates by removing vegetation. Initially this may increase delivery of sediments and moisture to sink areas, and traditional farmers in dry environments sometimes intentionally remove vegetation from slopes or otherwise alter them to enhance these processes (e.g., Bocco 1991; Doolittle 2000; Evenari *et al.* 1982). Similarly, even small, ephemeral check dams and terraces can create artificial sink areas (e.g., Homburg *et al.* 2005; Sandor *et al.* 2007) and more substantial irrigation systems that capture and channel runoff enhance edaphic conditions in the larger sink areas they feed (e.g., Vivian 1974; Vivian *et al.* 2006; Worman 2008; Worman and Matson 2010). Alternatively, depending on the scale, severity, and duration of the perturbation, human activities like cultivation of hillslopes can favor arroyo formation that degrades sink areas (e.g., McAuliffe *et al.* 2001). Terraced and otherwise altered landscapes may become susceptible to degradation if the erosion control systems are not maintained, such that

decreases in population and human inaction can cause significant degradation (e.g., Bocco 1991; Van Andel *et al.* 1990).

This understanding of the processes and likely results of moderate erosion in semiarid environments suggests that some version of the fragilization model accurately describes the trajectory of landscape change in the study area during the post-Roman era. During the centuries following the dissolution of the Western Roman Empire, and particularly after the Islamic conquest, farming and herding most likely caused some erosion as population densities increased. Continued population growth in the study area shows that this early phase of erosion was not immediately disastrous for the inhabitants. In fact, it probably created or enlarged sink areas and increased the ANPP of the landscape, and agriculture and pastoralism certainly increased the abundance of resources useful to people. Given the observed trajectory of population growth over the course of more than four centuries, the agrarian system appears to have been sustainable at the scale of human lifetimes.

Changes in settlement patterns also suggest that people responded to these changes in the landscape. The relocation of rural populations from dispersed hamlets to larger, nucleated villages during the 10th century may reflect movement to locations where erosional processes had created or enlarged areas of deep, well-watered soil. For example, next to Alcaria Longa the shallow gradient of the base of a valley surrounded by steep hills creates a large, localized sink area with deep cumulic soils and a spring. In a sense this relocation is analogous to population growth where the productivity of the landscape is increased by terracing; terrace complexes and rural communities dating to the Islamic period are widespread in many mountainous parts of Iberia, including the Serra do Monchique in the Algarve and especially the Sierra Nevada in Granada. The inhabitants of the study area did not, however, construct architectural features to enlarge or create additional sink areas. Instead of the labor investment required to do so, they moved to locations where natural processes had created similar edaphic conditions[57].

[57] With the single exception of slope 6 in the 2004 – 05 survey area, no ancient or modern terraces were encountered during the surveys conducted in the study area. A few check dams were recorded, but they appear to have been constructed in the past few decades in an attempt to forestall the ongoing erosion associated with mechanized agriculture.

Despite the apparent adjustment of the population to landscape change, the geological studies reported here show that there was widespread arroyo formation throughout densely populated portions of the study area during the later Islamic period. Hillslope erosion had decreased the thickness of soils, eventually reaching a point where large areas of bedrock were exposed or only thinly mantled. The loss of soil increased the rate and magnitude of runoff following precipitation, consistently favoring channel incision. In addition, production in sink areas may have reduced resistance to channel formation at those key points on the landscape. At the same time, paleoclimate data suggest a moderate increase in precipitation and perhaps in the frequency of large storms. These changes forced the landscape across a geomorphic threshold and widespread degradation probably occurred rapidly, within a few years to decades; within the limits of current dating technologies, arroyo formation appears to have taken place during the mid-12th century. The consequences were dire. Once stripped of soil, hillslopes had virtually no productive potential, and the previously productive sink areas deteriorated rapidly as through-flowing channels removed water and sediments to trunk streams. An ecological and economic crisis then led to the observed depopulation of the countryside.

The fragilization model fits the geological and archaeological evidence from the study area well in its central prediction that population growth was followed after a time lag by severe erosion and environmental degradation. It prompts a consideration of the processes of erosion and landscape change that leads to a more nuanced and complete understanding of the trajectory of degradation. In addition, it provides a plausible narrative that is well supported by data derived from geological investigations of the extent and timing of soil erosion and channel incision. By many measures, it is a successful explanation of past ecological degradation in the study area.

On the other hand, emphasizing the processes of landscape change also creates some weaknesses in the fragilization model. At an abstract level, it is presented as a predictive model but it functions poorly in prediction; it can only partially answer the question of why the landscape in the study area deteriorated during the 12th century. The fragilization model requires a climatic shift to trigger geomorphic change and various paleoclimate proxies suggest that there may have been a change from drier than average to wetter conditions in the study area at that time. The key problem, however, is that the

model does not specify that there must be a climate change of any particular kind or magnitude. While this is appropriate given a sound understanding of landscape change and thresholds of resistance, it creates a logical problem in terms of explanation. Because there are always minor fluctuations in climate at many scales, the fragilization model essentially predicts that there will be degradation following population increase whenever and wherever one might find evidence of that degradation. In this case, it does not indicate why there was severe erosion in the study area during the 12th century and not during the relatively arid 11th century or later during the Little Ice Age. Because the proposition that a minor climate fluctuation may have triggered degradation at any particular time cannot be refuted (i.e., it is not falsifiable), the fragilization model remains a plausible narrative of processes but by some measures it is not a wholly satisfactory explanation of cause.

A second problem is that the fragilization model assumes a mechanistic connection between humans and degradation. While this seems plausible at the broadest scales, it is an overgeneralization that obscures important variables in human-environment interactions; it amounts to an assumption that humans cannot produce food sustainably and it therefore discourages investigation of which forms of production might be most resilient on particular landscapes. It cannot explain the observation that farmers in the Zuni area of New Mexico have been farming the same fields for as long as two millennia without causing measurable degradation of the soils (Homburg *et al.* 2005; Sandor *et al.* 2007). Presumably one might suggest that traditional Zuni agriculture represents a minimal alteration of the landscape and therefore is not a form of fragilization. On the other hand, it would be very difficult to argue that the extensive Balinese terracing and rice paddy farming systems that have been constructed and extended over the course of many centuries are minimal alterations of the landscape. They have survived numerous changes in climate, extreme weather events, and expansion and contraction in the context of population growth and decline, and they continue to be highly productive when traditional techniques are used (Lansing 2006; Lansing and Kremer 1993). Clearly not all forms of production create fragilization in all environments and not all anthropogenic landscapes are particularly fragile.

Finally, the fragilization model leaves little room for intentional human action as part of an explanation of ecological change. It assumes that people generally do not notice soil loss or other changes or are powerless to alter their own behavior until after a threshold of resistance has been crossed; degradation becomes an accident that can be neither perceived nor prevented. While likely true in some cases, this assumption runs counter to common sense, is clearly false in the context of modern ecological problems (at least in terms of perception; e.g., global climate change, widespread soil erosion, loss of biodiversity, destruction of fisheries, coral reefs, and tropical rainforests), and is contrary to a wealth of evidence that primary producers in many contexts are aware of – and concerned about – the potential for their actions to cause various kinds of degradation (e.g., Blaikie 1985; Bocco 1991; Butzer 2005; Lansing 2006; Lansing and Kremer 1993; Netting 1986, 1993; Robbins 2004; Scott 1998; Walker 2005; Zimmerer 1993a, 1993b, 2000). Moreover, the fragilization model cannot explain why people abandoned rural areas in the aftermath of degradation. Some could have moved to areas that had not been affected by erosion, such as the 2004 – 05 survey area, while others could have modified their production strategies and remained in smaller communities where they were. In short, the fragilization model does little to illuminate human responses to environmental changes and it does not offer any hope that it might be possible to learn from cases of degradation and begin to manage production systems to improve resilience.

Admittedly portraying these characteristics as weaknesses is at least partially a matter of semantics and aesthetics. Only a very narrow definition of explanation assumes that it necessarily involves prediction. In this instance, the fragilization model functions well as a framework for describing some of the processes involved in human-environment interactions and it illuminates details of the historical trajectory of change and eventual degradation. This is a valid form of explanation if it is viewed as a historical model. On the other hand, accepting fragilization and minor climate change as *the* ultimate and proximate causes, respectively, of degradation in the study area in the 12th century may be incomplete, largely because it de-emphasizes the human aspect of the socio-natural system. The fragilization model is not incorrect. In fact, it is useful. But it does not ask why people acted and reacted in the ways that they did. As an alternative, it could be productive to consider why people might continue to act in the

ways that they do in the context of ecological degradation, or why people may even consciously choose a course of action that they know or suspect will exacerbate ecological problems.

Historical Context Revisited

Each of the general models considered above is useful in directing attention to a different aspect of human-environment interactions in the study area. By its evident failure to explain the timing or trajectory of environmental change, the ruined landscape model suggests empirical study of past degradation and the temporal scales of rebound (i.e., resilience) as a beginning point for understanding a deeply anthropogenic landscape. Similarly, the transfer of technologies model does not accurately describe any significant aspects of the past in the study area, but it implies that a successful explanation will include examination of the processes of degradation and a consideration of the inhabitants' perceptions of that degradation. The fragilization model provides a great deal of insight into the processes of environmental degradation in the study area, but fails to account for the agency and knowledge of the past inhabitants who both caused and witnessed the landscape change. Building on these contributions, a closer examination of historical context is necessary in order to explain more fully the causes of erosion and degradation in the study area.

From the perspective of rural populations, probably the most important aspect of regional political developments during the Islamic period was that they caused significant changes in the political economy of *al-Andalus*, i.e., the mechanisms by which the state was funded (see D'Altroy and Earle 1985 on wealth vs. staple finance). Both the Roman Empire and the feudal states of medieval Europe were staple-financed, although the Roman system was highly centralized (Hopkins 1980) while the feudal states were less so, being built on a series of patron – client relationships (Crone 1989; Wickham 1984). Boone *et al.* (1990) argue that *al-Andalus* and the Islamic empires of the medieval period were closer to the wealth-financed end of the spectrum of variability in political economy (see also Boone 2009: 79 – 83, 159 – 160; Boone and Benco 1999). The different means of funding the state imply different relationships between primary producers and elites.

During the so-called Dark Ages after the dissolution of the Western Roman Empire, rural populations enjoyed a considerable degree of autonomy across much of the

area formerly controlled by the empire (e.g., Bintliff 1999; Wickham 1984). Outside of locations that saw a high degree of conflict and raiding, there were few costs directly imposed on primary producers in the forms of tax, tribute, or theft and they were able to retain most of the surplus they produced. The relative lack of institutionalized inequality during the early Middle Ages followed by its growth with the appearance of feudal systems and then early modern states has been posited as one cause of the observed pattern of consistently declining average adult height (as estimated from skeletal remains) across much of northern Europe from the early Middle Ages through the 17th and 18th centuries; primary producers fed themselves adequately during the Dark Ages before feudal and then national elites emerged and began claiming a large proportion of the available food as rent or taxes (Steckel 2004). In most places average heights did not return to levels attained during the early Middle Ages before the 20th century.

Boone (1994, 2002; see also Glick 1995) suggests that parallel developments occurred in the study area during the Late Roman period. A form of autonomous tribal organization appeared during the centuries of reduced state power, and it persisted and eventually incorporated both Berbers and Hispano-Romans during the Islamic period. Taxation during the Late Roman period was carried out primarily by local leaders, usually Visigoth nobles with some kind of kinship ties to the king who was paramount among a contentious group of equals. Tribal organization gave primary producers a position of some power in negotiations with relatively weak local elites, contributing to inefficient taxation (from the perspective of the state) and fostering conditions in which rural populations were able to retain much of what they produced.

Taxation remained comparatively ineffective during the Emiral period after the Islamic conquest, marking Iberia's departure from the path taken by Christian and pagan Europe where feudal states were appearing. Many local leaders based in the cities of Iberia had capitulated as the Muslim armies advanced in 711 and subsequent years. Following the precedent set by the Prophet Muhammad, they were allowed to retain power and their religion provided that they paid taxes to the relatively weak central state and could organize a military force to support the state in times of need. Similarly, tribal leaders in many rural areas collected taxes according to agreements they had made with representatives of the state, in a pattern paralleling that seen in the Idrisid Empire of

North Africa (Boone *et al.* 1990; see also Dinsmore 1995). The important contrast with the feudal states emerging across the rest of Europe is that the local leaders drew their power and legitimacy from – and primarily had allegiance to – the local population, not the state. Although the state eventually became far more powerful and centralized and built its own military, this pattern of taxation in rural areas continued into the Califal period. The fabulous wealth of the Córdoban Caliphate was founded primarily on control of trade, manufacturing activities, and intensive irrigation agriculture in the Guadalquivir valley, and supplemented greatly during the early years of its existence by wealth wrested from the Christian kingdoms to the north and east during successive *jihads*; the state was essentially a successful private enterprise (Boone 2009: 160; Lewis 2008: 332).

Rural communities in the *Baixo Alentejo* appear to have benefited economically from this form of interaction with the wealth-financed state because it did not involve appropriation of the majority of agrarian surplus (Boone 2009: 115 – 119). Dinsmore (1995) implies that rural independence was particularly pronounced in regions like the study area where there were few resources of economic importance to the urban-based Arab state (see also Guichard 1998). The Caliph exerted little control over production or taxation in the rural hinterlands largely because the costs of doing so outweighed the potential benefits, particularly where production was highly variable. In return for accepting autonomy in the rural hinterlands, the Islamic state received guarantees of non-interference with trade and military aid against invaders. Rural populations guarded their independence jealously and negotiations with the urban-based Arab state often played out in rebellions, one of the only forms of urban-rural interaction consistently recorded in written documents (Borges 2003; Collins 1983; Fierro 1998; Glick 1995; Guichard 1998; Hernández 1998).

A civil war between different claimants to the title of Caliph decimated Cordoba in 1009 – 1010 C.E. Despite efforts to rebuild centralized power, the Caliphate disintegrated rapidly during the 11th century into smaller, semi-independent *taifal* states and Christian armies began to make inroads into *al-Andalus*. The waning of Califal power may have been due in part to an economic crisis precipitated by changes in the types of revenue available to the state. Using a model based on the concept of innovation diffusion, Richard Bulliet (1979) estimates that conversions of Hispano-Romans to Islam

increased rapidly after the late 9th century. Given the scriptural proscriptions against taxing fellow Muslims, the state must have faced declining funds. At the same time successful military campaigns against the Christians decreased markedly during the Califal period as the urban populace turned its attentions to more predictably lucrative commercial endeavors. It can hardly be coincidence that the *taifal* states that emerged as the caliphate disintegrated were led by individuals and families who had grown wealthy through their control of trade, intensive irrigation agriculture, and/ or various semi-industrial manufacturing activities. Essentially, they were able to compete with the Caliph, to buy their own armies and thereby guarantee their freedom to continue profitable commercial ventures unimpeded by state meddling.

However, in comparison to the Caliphate, the smaller *taifal* successor states could not control large volumes of long distance trade as effectively and they lacked the extent and diversity of resources necessary for controlling diverse craft manufacturing and intensive irrigation agriculture over large areas in the river valleys of southern Iberia. It is likely that during the 11th and 12th Centuries *taifal* leaders started to place increasing demands on rural communities, including tax payments (Barceló 1997:195-204). The timing of many historically recorded rural revolts supports this interpretation (Collis 1983; Fierro 1998; Glick 1995; Guichard 1998; Hernández 1998). As conflict within the Islamic system increased, the Christians rallied and advanced southward, often with the aid of disaffected Muslim leaders. North African Almoravid armies were invited to Iberia to fight the Christians after the fall of Toledo in 1085, and by the end of the 11th century the Almoravid dynasty had seized control of much of *al-Andalus*.

As with the Caliphate, the rise and fall of the Almoravids (and later the Almohads) in Iberia also seems to follow a trajectory determined, at least in part, by the economy. The Almoravids came to power in the Maghreb and Iberia advocating strict adherence to scriptural proscriptions against taxing fellow Muslims. As before, their state was largely a private enterprise funded by control of long-distance trade and the wealth generated by military campaigns. Powerful local families appear to have tolerated the deposing of *taifal* princes as long as the state imposed no significant taxes on commerce. As their military successes against the Christians slowed, however, the Almoravids lost a significant source of wealth. Their most reliable revenues came from

control of trade routes across the Maghreb, while local families retained control of most trade in Iberia. In order to fund continued military campaigns, the Almoravids began to impose taxes on the *Andalusis* and their power in Iberia declined rapidly, particularly after the death of their leader Yusuf ibn Tashfin in 1106. By the 1130s and 1140s Christian armies were once again advancing southward and *taifal* states began to re-emerge in Iberia. At the same time, the Almohads were advancing against the Almoravids in Africa, taking the capital at Marrakech in 1147 and, with it, control of important trans-Saharan trade routes.

These changing circumstances affected rural populations in several ways. The *taifal* leaders' demands for taxes would have prompted attempts to increase production. With the arrival of armies from North Africa, beholden to a government centered there, the tribally organized rural population's bargaining position became somewhat weaker in that they no longer negotiated with local leaders and the Islamic state no longer relied on them to the same extent for military assistance. It is at least plausible that tax demands increased further, particularly as the Almoravids cast about for ways to pay the army. In addition, the influx of thousands of soldiers from North Africa no doubt raised the demand for subsistence goods and drove up the price of wheat and other staples. Moreover, growing conflicts with Christians and within the Islamic state inevitably led to uncertainty about long-term prospects. Regional markets offered farmers the opportunity to transform agricultural surplus into durable, transportable wealth such as the silver jewelry and coins recovered from the later Islamic period village of Alcaria Longa (Boone 1994). Within this social and economic context, farmers probably chose to increase production rapidly despite signs of ecological degradation that must have become increasingly apparent.

Rural population densities already were high. The prevalence of grinding stones on rural sites and the general avoidance of the heavy clayey soils in the northern part of the 2004-05 survey area show that wheat was a mainstay of the rural economy at least from the Roman era on. Strategies for increasing production would have included both intensification of farming in productive sink areas and expansion of production on hillslope fields (see Morrison 1996 on different strategies to increase production). In particular, farmers probably devoted more area to wheat cultivation while flocks of sheep

and goats were moved farther from settlements (see Hassan 1994: 160 – 161 for a discussion of the spatial efficiencies of grain crops vs. animals). The land tenure system, which de-emphasized individual ownership, also would have provided flexibility that facilitated rapid increases in the area of land under cultivation.

Plowing dramatically increases soil erosion, surpassing the rates of soil loss associated with intensive grazing (Ballais 2000). Long-term experimental studies conducted near Mértola showed that plots cultivated in wheat experienced rates of soil loss almost as high as plots of bare soil, more than double those measured on short-fallow plots (covered with "stubble"), and an order of magnitude higher than on uncultivated land (Roxo and Casimiro 1998). The same study showed that erosion on all plots increased roughly tenfold in exceptionally wet years, while the relative erodibility of different plots remained the same. This implies that the rate of erosion on cultivated fields in wet years would be roughly twenty times the rate on a short-fallow plot in a normal year, and could be as much as two orders of magnitude higher than on uncultivated land in a normal year. Increased plowing on hillslopes during the later Islamic period would have thinned soils rapidly, increasing runoff, while wheat cultivation in sink areas also would have decreased resistance to erosion and channel formation in those particularly important locations. Moreover, increasing in the area under cultivation dramatically magnified the effects of a shift to wetter conditions during the 12th century.

By increasing production and particularly by plowing larger areas, people pushed the geomorphic and soil-hydrological systems towards the formation of a continuously incised channel network; overproduction led to widespread environmental degradation and the collapse of the rural economy within the span of a lifetime. The processes of landscape change are well described by the fragilization model as applied above. However, human actions likely were as important as minor climate change in triggering degradation. Instead of a slow, incremental, and imperceptible decrease in resistance to erosion, the choice to expand the area under cultivation quickly primed the landscape for dramatic change during a few relatively wet years. The eventual agrarian collapse promoted open conflict between rural populations and the state. In the study area, Ibn Qasi led a rural revolt. He captured Mértola, the regional center, and ruled an

independent kingdom there from 1144 to 1147 (Borges 2003). Archaeological survey data show that, outside of Mértola, the study area was largely abandoned after the mid-12th century. As rural populations declined or disappeared, the Islamic state was deprived of both agricultural resources and potential military personnel.

Data from the Campo Arqueológico's excavations in Mértola indicate that the city took on the character of a garrisoned outpost during the subsequent Almohad period. There was a major urban rebuilding and reorganization effort that included construction of the *bairro islâmico* in the most easily-defended area of the walled town as well as remodeling of and major additions to the castle, clearly a structure designed with defensive military considerations paramount. Artifacts recovered during the excavations suggest growth of a textile industry and possibly increased production of glass and ceramics. Although they are not conclusive, the data imply a shift in the focus of the local economy to activities that could be moved into the walled town as needed. Unlike a wheat field, a flock of sheep can be moved inside city walls at least temporarily, and the materials needed to produce glass and ceramics can be gathered fairly rapidly during times of relative calm and stored for later use.

This historical narrative adds to an explanation of degradation based on fragilization in important ways. It does not rely entirely on a climate shift to trigger erosion and it is consistent with the available geological, archaeological, and historical evidence. Unlike the fragilization model it focuses attention on human actions and it incorporates historicity by examining responses to changing conditions. It further illuminates interactions between the social and natural aspects that ultimately determined the historical trajectory of change in the socio-natural system (see e.g., Morrison 1996; Balée 1998; Butzer 2005 on the importance of agency and historical context).

The combination of the fragilization model with a broader historical narrative provides a historical model that is, in most ways, a satisfying explanation of anthropogenic ecological degradation in the study area during the later Islamic period. It might, however, be possible to augment that explanation by incorporating a more detailed examination of the motivations of the producers. In addition, the historical explanation as presented above does not include explicit reference to general principles. While many archaeologists (the author included) would not consider this a fatal flaw, it presents a

dilemma: if explanation is presented entirely in terms of unique historical circumstances it becomes difficult to generalize in any meaningful way about human interactions with the environment. A simple heuristic model based on microeconomic principles may clarify why people made the decisions they did in this particular case while at the same time providing some insight into human-environment interactions in general.

A Producer-Focused Model

Because land in the study area was controlled by the rural community as a group during the Islamic period, one way to account for degradation would be as a case of the tragedy of the commons (i.e., Hardin 1968), which suggests that because nobody in particular owned the land some individuals overused it for short term gain. However, the tragedy of the commons model has been criticized from several angles and is almost certainly not universally generalizable to cases where resources are shared. Probably the most cogent critique has been that of Elinor Ostrom (1990) who focuses on identifying conditions that affect whether or not sharing access to resources causes degradation.

The tribally organized land tenure system in the study area appears to meet the criteria identified by Ostrom (1990) for successful management of common pool resources, in this case arable land. Specifically, characteristics of tribal societies suggest that the social boundaries of the group controlling the land probably were well defined, and the separation of densely occupied areas from areas with few Islamic period settlements suggests that the physical boundaries of the shared land were similarly clear. Successful production through the early Islamic period indicates that the rules governing access to resources were flexible and well suited to local conditions, and similarities between sites and individual residences suggest a high level of parity between the participants who made land use decisions. The users clearly recognized their right to organize their own institutions, and they had mechanisms in place to mediate conflict and hold each other accountable. Finally, the system of taxation in place, in which tribal leaders negotiated with and delivered wealth to representatives of the state, facilitated interactions between the producers, their shared resource of productive land, and larger scale political and economic systems. In other words, it is unlikely that the eventual degradation in the study area can be understood as a tragedy of the commons in the traditional sense.

Beyond the conditions identified by Ostrom, the extent and severity of erosion suggest that it was probably not caused by even a relatively large and ambitious subset of the population. It very likely resulted from the decision of virtually everybody in the study area to increase production. Instead of focusing on competition between members of the group and the problem of cheaters, ultimately the center of the tragedy of the commons model, an alternative would be to show that every member of the group was motivated to increase production in similar ways.

For primary producers in an agrarian society, the major determinant of survival is the ability to raise, store, and maintain control of enough food to feed the family or analogous group through the year and through years of below average production. Moreover, long-term survival is directly linked to the capacity to access productive resources (i.e., cropland or pasture for herd animals) through subsequent years. It is the latter that explains why political ecology scholars and others consistently have shown that traditional producers are aware of and work to avoid causing ecological degradation. Similarly, it may partially explain why traditional agrarian systems in some cases self-organize, based on the self-interested decisions of each participant, into optimal configurations that remain resilient and productive over long periods of time in the face of climate variation, pest infestations, and other challenges (e.g., Lansing 2006; Lansing and Kremer 1993; see also Ostrom 1990).

At the annual time scale, agriculturalists weigh a wide range of variables when making production decisions. These include the necessities of subsistence, available and affordable technologies, expected productivity, the market economy, and costs imposed by political leaders (e.g., Netting 1986). Based on the preceding, they also consider the potential for their actions to cause degradation that would reduce future productivity. There is no reason to think that basic subsistence requirements of the family or village changed dramatically in the study area during the 11th and 12th centuries. Available technologies for dryland farming and herding remained more or less constant from late antiquity through the Islamic period and did not change significantly before the introduction of chemical fertilizers, hybrid crop varieties, and mechanization in the 20th century. Similarly, the expected productivity of a given plot devoted to a particular form of production remained more or less constant in the absence of severe degradation. As

described above, however, regional events changed the political and economic landscape in ways that would have motivated farmers to increase production through the 11th and 12th centuries. On the other hand, the problem of potential degradation was a counterbalance to the motivation to increase production significantly.

Producers had several choices when faced with increased demands. They could maintain a constant level of production while ceding more to the political elites or revolt in an attempt to establish and maintain political and economic independence. Alternatively, they could leave the area and try to acquire productive land elsewhere. Finally they could increase production to meet the increased costs. Examining the risks and benefits of each potential course of action helps to illuminate why they chose the last.

Maintaining a constant level of production while ceding more surplus to elites might not immediately be disastrous, particularly as the archaeological evidence shows that rural populations in the study area enjoyed a fair amount of material wealth. That wealth could be viewed as a reserve – something like disposable income – that could be tapped to pay taxes and tribute. On the other hand, it almost certainly is more accurate to characterize the material wealth as a means of storing surplus to provide for the family through years of poor productivity, something that is particularly important in settings like the study area where production is highly variable. Using modern climate data as a proxy (see Figure 1.2, above), the probability that precipitation in a given year would be more than 100 mm (roughly 20%) below average in a given year is 30 percent. It seems reasonable to assume that yields would be significantly reduced at that level, requiring people to use at least some of their stored wealth to survive roughly every third year. Once stored wealth was gone, the probability of hunger or starvation in a given year would be the same as the probability of a failed crop, roughly one in three; ceding surplus to elites without increasing production would be a risky course of action.

Revolting in an attempt to establish and maintain independence would be an even riskier alternative. The *taifal* leaders had enough military power to establish independence from the Caliphate and to challenge the Christians and, for a time, the Almoravids. They taxed rural populations precisely because they had limited options for raising revenue, so it is unlikely that they would acquiesce and allow economic independence without conflict. Moreover, the Almoravids took control of *al-Andalus*

with armies that bested the troops mustered by recalcitrant *taifal* leaders and also inflicted severe losses on the Christians. Although they were armed, the rural population would be at a severe disadvantage in a direct military contest against the soldiers of either the *taifal* leaders or the Almoravids. Therefore the probability that a rural revolt would be quashed quickly and violently was high and one could expect that the costs imposed, particularly on the leaders of any revolt, also would be high.

Leaving the area and hoping to secure productive land elsewhere would be similarly risky. It is unlikely that there was desirable land available for the taking anywhere in Iberia after several centuries of sustained population growth, and the situation probably was little different in the nearby portions of North Africa. After the expense of moving, then, any remaining stored wealth likely would be used to secure access to productive land. In addition, individuals or families migrating on their own would lose the social power of the larger group, and in the study area membership in that group was the basis of the family's access to productive resources. The cost of failure would be high, including poverty and possibly dispersal of the family and/ or death of some members. Moreover, the benefit associated with using stored wealth or rebelling was maintaining the status quo, while the benefit of migration would be uncertain. Given the high risk and uncertain benefit, migration probably would be a choice of last resort.

Finally, people could choose to increase production to meet increased demand. Assuming the producers knew that increased production could cause erosion or other degradation, it also is reasonable to assume that they understood the landscape and their productive systems well enough to estimate with some certainty that it would take some time for that erosion to become so severe and extensive that it would significantly reduce yields across the total area available for farming and herding. Given the likelihood that the other courses of action would lead to starvation, violent death, or impoverishment in the relatively near future, producers chose to increase production to meet tax demands.

Conditions did not remain static after the initial decision to increase production to meet the demands made by *taifal* leaders in the 11^{th} century. The study area is at the southern margin of the western marches, a contested territory between the Christian kingdoms to the north and the center of *al-Andalus* to the south and east. The first independent *taifa* centered on Mértola, established during the dissolution of the

Caliphate, struggled against and eventually was conquered and absorbed by the larger kingdom of Seville in 1044. Meanwhile, the Christians advanced from the north. After the early successes of the Almoravid armies, Christian armies again were again pushing southward by the 1130s. In 1139 Afonso Henriques led a Christian army to victory over the Almoravid leader Ali ibn Yusuf at Ourique, less than 50 km west of Mértola.

People in and around Mértola could not have remained ignorant of these conflicts, and the rural producers no doubt began to question whether they could expect to maintain access to their land and the food they produced as different armies moved through the area. In addition, the geological studies presented above show that erosion caused by increased production was removing soil from hillslopes in densely populated portions of the study area by the early 12th century. Signs of erosion and degradation must have become increasingly obvious to the people living there. The productive potential of the landscape was declining while at the same time it was becoming more likely that access to that land might be lost through warfare, particularly as the Christians became increasingly intolerant of Islam in the 12th century. These changing conditions must have affected the decisions made by producers in the study area.

The initial decision to increase production might have been viewed as a temporary solution, with producers hoping that tax demands eventually would decline. The demands continued, however, as political instability increased. In that context attempting to forestall erosion by reducing production while at the same time ceding surplus to the Almoravids remained an untenable option. The risks associated with that course of action remained constant or increased as erosion impaired the productive potential of the landscape. At the same time, the benefit of supporting the Almoravids declined as it became increasingly uncertain that they could guarantee continued access to land and the monetized markets of the Islamic world. Similarly, the risks associated with migration remained basically the same and the potential benefits only became more unpredictable as others were displaced by the Christian advance and sought to secure resources for themselves. Migration probably remained an option of last resort.

On the other hand, the calculus of risk and benefits changed in different ways for rebellion and for increasing production. By the 1130s and 1140s the Almoravids were retreating from the Christians to the north and from the Almohads who were sweeping

across the Maghreb to the south. The probability declined that they would (or could) devote significant resources to quelling a revolt in the Alentejo. Particularly after the emergence of Ibn Qasi as a potential leader and after his initial successes, joining a rebellion against the Almoravids became an attractive option because the probability declined that a revolt would be put down violently and quickly. Meanwhile, the potential benefits of rebellion included participation in a system that appeared to offer defense against Christian advances and the likelihood that the rural populace could negotiate lower levels of taxation in return for their support of the new *taifa*. Given the declining productivity of the landscape, the latter may have been particularly important; the lowered benefit of continued access to land in the study area would be offset at least partially by the lowered cost of maintaining that access.

At the same time, the option of increasing production would have remained attractive in the short term. There is no benefit to maintaining access to unproductive land. Therefore, and somewhat counterintuitively, as degradation became increasingly widespread the value of the land declined such that little gain could be realized by restricting production to minimize erosion. On the other hand, another potential benefit of increasing production increased dramatically in value in the context of warfare and the attendant uncertainty: surplus could be converted into storable and portable forms like silver. That wealth might then be used to diminish the risks associated with alternative courses of action, particularly migration. People changed their strategies as degradation proceeded; they increasingly favored short-term gain through overproduction as the prospects for long-term productivity evaporated.

In this context, revolt became the favored option alongside continued overproduction. Faced with political uncertainty and increasing degradation, these were the best choices among a set of poor options. The rural populace supported Ibn Qasi's *taifa* until it failed after just a few years, and the final phase of degradation set in with the formation of through-flowing incised channels in the mid-12th century. People abandoned virtually all settlements outside of Mértola rapidly and at about the same time. Each family gathered the portable wealth they had accumulated and sought another livelihood, fleeing uncertainty, the threat of violence, and a landscape with severely impaired productive potential. Many very likely left the area. The growth of a textile

industry and the reorganization of the urban core of Mértola suggest that others moved within the city walls and shifted their focus to pastoralism. Whatever the fate of the individual families, the semi-independent rural communities did not survive the combined effects of ecological degradation and political uncertainty.

The eventual failure of the system appears to be due to the breakdown of one of the criteria identified by Ostrom (1990) for long-term use of common pool resources to be successful: there must be mechanisms in place to negotiate the interactions between the community of users, their shared resource(s), and larger scale political and economic systems. In this case, large-scale political and economic conditions caused the *taifal* leaders and the Almoravids to demand an increased share of the surplus generated by primary producers, and tribal leaders were not in a position to resist successfully. A simple heuristic model based on microeconomic principles shows that increasing production would have been the preferred choice for producers in that context. There is no reason to suppose that degradation was caused by a small group of “free riders” who violated the norms of production because every household faced the same pressures. The eventual destruction of the productive potential of the landscape was caused by a series of individual decisions that fundamentally amounted to prioritizing feeding the family today or this year over threats to future productivity.

Evaluation

To be clear, perhaps to the point of redundancy, the reconstruction of ecological change inspired by the fragilization model and based on empirical data generated in the field is a historical model that successfully explains the processes of erosion and degradation. It is not incorrect, but it remains a partial explanation even with evidence for a minor climate shift in the 12th century. The addition of contextual information from documentary and archaeological sources clarifies the roles of social, political, and economic structure, and shows in greater detail how human activity combined with climate change to cause rapid and extensive degradation when and where it occurred. To a great extent, it also clarifies how large scale processes played out locally and at the scale of human lifetimes. The central remaining question was why people in the study area might have caused degradation despite being aware that their actions could or would do so.

Questioning why producers in the study area chose one particular course of action among several options adds to the other explanations by moving the focus to the producers. It shows that, given the options determined by the context, increasing production to meet the increased tax burden was the least risky choice. It also provides a framework for examining how the changing political and ecological context created ever-increasing pressure to increase production. Where the fragilization model reduces degradation to an unavoidable consequence of any relatively intense human presence on the landscape, the microeconomic model suggests that it was the unintended but not unexpected consequence of the choice to focus on short term overproduction at the expense of long term productivity, a choice made by rational actors in a particular situation. Where the historical narrative relies on inexplicit assumptions about how people respond to changes in external conditions, the microeconomic model builds an argument concerning choice among multiple alternatives based on the simple assumptions that people are aware of their environment and interested in survival.

At the same time, the microeconomic model facilitates comparison to other cases. For example, it mirrors the suggestion of Castro and colleagues (2000: 159) that the Islamic period was characterized by "'environmentally friendly' cultivation systems" as long as "Production was in the hands of more or less self-sufficient, autonomous farmers, rather than directed by external political and economic forces." Similarly, it is possible that events broadly similar to those in the study area caused the pulse of erosion that Butzer (2005) documents in the Sierra de Espadán during the 12th century, and the parallels are unmistakable to his conclusion that severe erosion during the 15th and 16th century was due to increased taxation and political instability which prompted farmers to favor short term maximization.

At a more general level, the model highlights the relevance of political stability, conflict, and economic realities for understanding human-environment interactions. The ecological impacts – either positive or negative – of virtually any human activity are likely to be realized on a time scale of multiple years to decades or longer. The economic impacts of agrarian production decisions, on the other hand, are realized at an annual scale, and the effects of conflict can be nearly instantaneous. This creates what Cumming and colleagues (2006) identify as a temporal scale mismatch likely to result in

mismanagement of resources unless stability allows producers to plan years into the future.

At a more abstract level, the combination of the microeconomic model with the insights of the fragilization model and a detailed understanding of historical context satisfies several theoretical criteria used to evaluate explanations. The combined model is internally consistent and it is consistent with the available archaeological, historical, and geological data. In other words, it meets the criteria of coherence and correspondence that can be used to evaluate all forms of archaeological interpretation and explanation (McGuire 2008: 7).

Finally, the microeconomic model introduces a specifically contrastive form of explanation that suggests why people chose a particular course of action over others. Using simple generalizations, it shows how peoples' choices changed through time as external conditions changed, and in concert with the other models it identifies why degradation occurred when and where it did. In that respect, combining the insights from the three models allows for explanation that is both agent based and process oriented, bridging the false dichotomy between history and science. It provides a plausible connection between large scale, long term processes and the short term decisions that drove the trajectories of social, political, and ecological change in the study area during the later Islamic period. As such, it explains a historical narrative by reference to the ways general principles played out in a specific context.

Summary and Broader Implications

This research has several implications, from the more narrowly historical to the more general. Specifically, the geoarchaeological study suggests that anthropogenic degradation may have contributed to the eventual failure of *al-Andalus*. It provides an example of the ways that geological techniques can be combined with archaeological and historical research to investigate the trajectory of change in a socio-natural system. Understanding the past of that system is relevant for managing the landscape in the present and future. Finally, the research illuminates several aspects of human-environment interactions in general.

The possibility that anthropogenic environmental degradation contributed to the eventual failure of the Islamic state is an aspect of the history of *al-Andalus* that has not

been examined thoroughly. The results of this investigation indicate that anthropogenic degradation caused an ecological and economic crisis in the study area in the mid-12th century that added to political unrest and eventually led to rapid depopulation of the countryside. The loss of productive potential and an armed populace that could be recruited to fight against incursions no doubt increased the vulnerability of the Mértola area to Christian attacks. It remains an open question, however, whether and to what extent these results can be generalized to other parts of Iberia.

The Islamic state in Iberia persisted for a century after the agrarian crisis in the study area, and for much longer in Granada where markedly different environmental and agricultural conditions prevailed. Events in the study area almost certainly did not immediately affect the urban centers along the Guadalquivir River, the heart of *al-Andalus.* On the other hand, similar social and environmental conditions pertained throughout much of a broad arc of Berber-dominated uplands that had formed a buffer between southern Iberia and the Christian kingdoms to the north (i.e., the marches). In addition, it is possible that widespread erosion in upland areas had some impact on the highly productive irrigation agriculture systems in the major river valleys of southern Iberia by increasing sediment loads and, possibly, the frequency and magnitude of floods. Investigating those possible impacts is beyond the scope of this study. It is instructive, however, to note that major episodes of alluviation dating to the Islamic period and ascribed to human activity have been recorded in the river valleys of southern Portugal (Chester and James 1991, 1999), there was major geomorphic change along the Guadalquivir at Córdoba during the later Islamic period (Uribelarrea and Benito 2008), and data suggest increased sedimentation at the mouth of the Tagus River beginning in the late 11th to early 12th century (Abrantes *et al.* 2005).

If the trajectories of ecological degradation and population decline parallel to those observed in the study area occurred throughout large parts of the marches, it probably had an important and previously unrecognized impact on the fate of *al-Andalus*. A depopulated and degraded buffer zone, diminished agricultural potential, and increasing internal conflict would have weakened the Islamic state. It survived for a time, but it did so mostly because of external support. After the fall of the Almoravids, the Islamic system was propped up by a second major influx of soldiers from North

Africa that occurred when the Almohad dynasty seized control of most of *al-Andalus* in the late 1140s. Ultimately, however, the Christian armies advanced south and successfully laid siege on the remaining urban centers. Seville, the Almohad center of power, fell to the Christians in 1246 and the Islamic presence in Iberia was reduced to the kingdom of Granada.

No new geological or archaeological techniques were developed for this study, but it involved applying a suite of methods that have not previously been used together to investigate human-landscape interactions in Iberia. The geoarchaeological research began with investigation of the sediments deposited by small stream systems as one line of evidence concerning the type and extent of landscape change in the past. More importantly, the geological investigations extended beyond the fluvial systems to include detailed study of soils and sediments on hillslopes to determine the severity of erosion in the past and to illuminate further its timing and extent. Artifacts in different strata provided one means of chronological control, but most attempts to use radiocarbon dating proved unsuccessful due to significant bioturbation and the shallow depths of burial of strata deposited during the time period of interest. Optically stimulated luminescence (OSL) assays, however, generated direct measurements of the time elapsed since sediments in different strata were exposed to daylight, effectively measuring the timing of past episodes of erosion. Although gaining in popularity, this dating technique remains under-utilized in archaeological research and it clearly is useful for studying past landscape change. This integrated approach demonstrated how and when the landscape changed in the past.

Several lines of evidence indicate that humans caused the erosion reflected in the geological data. Analyses of macrobotanical remains recovered from archaeological sites suggested changes in plant communities during the Islamic period. In addition, two areas with similar climate, biota, topography, bedrock geology, and soils were surveyed and the results showed significant differences in past occupation histories. Soil geomorphic studies in each area indicated that the 1992 survey area, which was densely occupied during the Islamic period, saw severe soil erosion at that time. There was no evidence of significant past erosion during the Holocene in the 2004 – 05 survey area, which had few Islamic period sites. While it is likely that the 12th century saw a shift to wetter

conditions after a prolonged period of below average rainfall, the climate change had no discernible impact in the 2004 – 05 survey area; human actions must be considered in any attempt to identify the cause of past erosion in the study area.

Finally, the hillslope studies demonstrated that erosion in the 1992 survey area was severe and widespread, stripping virtually all soils and loose sediments from the upper portions of each slope that was investigated. The studies of fluvial strata indicated that the erosion culminated in the formation of a system of through-flowing incised channels during the 12th century. The extent and severity of erosion, changes in plant communities, arroyo formation, and evidence of what Butzer (2005) calls "slope stream disequilibrium" show that the anthropogenic environmental changes can be characterized as degradation. In sum, the research reported here combined geological methods with archaeological investigations to demonstrate the timing, nature, and extent of landscape change in the past, to show that the changes were caused by human actions, and to determine that the changes can be characterized as significant ecological degradation.

The results of this research have practical consequences for current and future use of the landscape in the study area. At one level they could be seen as evidence that high population densities and intensive production are unsustainable on Mediterranean landscapes. This formulation is overly simplistic and obscures several important aspects of human-environment interactions. A closer examination of the data shows that agro-pastoralism supported growing populations for centuries during the transitional and Islamic periods. This culminated in at least two centuries during which Alcaria Longa and other large villages were occupied. Survey data suggest that the population, as estimated from total number of sites and total site area, was higher during those centuries than at any time before or since. The persistence of intensive occupation of rural areas for at least two centuries implies that people living in the study area were capable of producing a great deal of food there in ways that could be sustained for generations without causing significant degradation. High population density and relatively intensive production were not, in and of themselves, the cause of degradation.

This study showed that significant erosion and ecological degradation occurred rapidly during the mid-12th century. Archaeological and historical evidence suggest that changes in social and economic conditions in *al-Andalus* during the 11th and 12th

centuries prompted producers to increase production in order to meet short-term goals. Several observations, including the identification of a buried plowed zone in cumulic soils at the base of the slope below Alcaria Longa, the importance of wheat production throughout the post-Roman period, the spatial efficiencies of cereal production vs. herding, and analogy to modern processes, suggest that people triggered rapid and severe erosion by expanding the area cultivated for wheat. That the expansion of cultivation probably coincided with a shift to somewhat wetter conditions dramatically magnified the impacts of both changes on the landscape.

This clearly implies that widespread cereal cultivation, particularly on hillslopes, is not an optimal use of the landscape in the sense that it is likely to cause erosion that significantly impairs productive potential; it is not sustainable at the scale of human lifetimes. Although the relevant data are sparse, two radiocarbon dates on burned plant material recovered from strata exposed by arroyo formation near the sites of Cerro da Loiça and Alcaria Longa suggest widespread burning in the study area during the mid-17th century. The dates fall during the historically recorded period of resettlement of the study area, implying that the charcoal might be the result of fires used to clear large areas of land. The Portuguese government actively encouraged resettlement at that time, but it is at least plausible that peoples' return also coincided with the eventual rebound of the landscape to the point where it could again support agro-pastoral production. If correct, this is an indication that the degradation caused by widespread cereal cultivation is likely to persist for periods of time on the order of half a millennium.

By contrast, extensive herding and wheat production on a more limited scale supported relatively dense populations in rural areas for centuries during the Islamic period. Assuming that some form of production and a functioning rural economy are desirable, these probably are among the best potential uses of the landscape in the study area. At present they are economically viable[58], at least at some scales, and they are a means of managing the landscape to increase resilience. With periods of fallowing, cultivation of cereals in limited areas where soils are relatively deep and slope angles are shallow is unlikely to cause significant erosion. Contour plowing also could reduce

[58] As in many parts of the EU, their viability is probably tied to niche markets and various subsidies.

erosion at minimal cost and construction of terraces on steeper slopes clearly helps to retain soils, although the cost of doing so is probably prohibitive.

Herding in particular is one way to utilize a Mediterranean oak savannah that takes advantage of the particular properties of that biome and, if the size and movements of herds are managed well, it can be sustained for long periods of time without causing degradation. Because each of the widely spaced trees in a savannah is able to monopolize scarce nutrients and moisture in its area, and grasses, annuals, and shrubs fill the areas between, savannah typically has a higher aboveground net primary productivity (ANPP) than dense stands of the same trees in the same environment. Moreover, the widely spaced trees promote the presence of grasses adapted both to full sun and to partial shade such that the savannah also has higher biodiversity than either dense forest or treeless grassland (Grove and Rackham 2001: chapter 12). The presence of the different varieties extends the season during which high quality grass is available to grazing animals, and the oak trees also produce acorns that are an important source of food for pigs or goats and a supplementary food for sheep. Far from being a degraded forest (as it often is viewed), where the conditions are appropriate savannah is a healthy plant community by the most commonly used biological measures (ANPP and biodiversity), it provides benefits to grazing animals and any humans that depend on them, and in the absence of plowing or severe overgrazing it is resistant to soil erosion.

At present, there are three ways in which significant portions of the study area are used. Most of the area is devoted to extensive wheat cultivation combined with herding, some has been planted in pine or, less frequently, oak trees, and some portions are used as hunting preserves. The studies of hillslope soils presented above show that the areas devoted to cereal cultivation currently are experiencing severe soil loss. In most locations, hillslope soils have been severely degraded and without chemical fertilizers they would not support a viable crop. In the most eroded areas people use mechanical farm equipment to break up the friable bedrock and plant cereals in the resulting gravelly sediment on the upper portions of slopes. This clearly is not a sustainable use of the landscape that will provide economic benefit in the future, and without subsidies it is unlikely that it would do so in most years today.

Supported by the European Union, attempts to establish dense monoculture forests in the study area are misguided. They are based on the mistaken assumption that dense forests should "naturally" be present there and that they are therefore desirable. In addition, planting requires significant mechanical recontouring of slopes which temporarily removes vegetation, disturbs any remaining intact soils, and temporarily increases their susceptibility to rapid erosion thereby removing most naturally occurring nutrients from the root zones of any trees planted there. As an aside, the recontouring also destroys archaeological sites in locations selected for forestation. Once established, the nascent forests are highly susceptible to fire. Finally, as it currently is structured the forestation projects require that the land be removed from economically productive use. Assuming once again that some form of production, a functioning rural economy, and opportunities for the extant local population are desirable, this is counterproductive.

Finally, there are the areas set aside for hunting by tourists. Many currently are covered by a tall-grass Mediterranean savannah or tall *Esteva* scrub. As long as the savannah can be maintained by the game animals' grazing, this is a desirable outcome from an ecological perspective. However, the widespread presence of shrubby species (*Esteva* spp. and others) suggests that some additional management practices such as controlled burning or rotational grazing of domestic animals may be necessary to maintain the savannah and reduce the chances of catastrophic fires in those areas. From an economic perspective, the relative merits of hunting preserves depend on whether they provide more benefit – i.e. more jobs and income – than herding and limited cereal production.

Finally, this research also contributes to the body of theory relevant to understanding human-environment interactions. It attempts to meet the significant challenges of demonstrating the causes of change in a complex socio-natural system and of identifying when anthropogenic environmental change can be characterized accurately as degradation. It does so by beginning with empirical geomorphic, pedological, and archaeological research conducted to show how and when the landscape changed, the extent of those changes, and the degree to which they impacted the productive potential of the landscape. Beyond demonstrating that people caused degradation, the research is an attempt to answer why they did so while assuming that the individual actors were

aware of their surroundings and the potential for their actions to alter the environment. It is the last that illuminates important aspects of the ways in which social structure can mediate human impacts on the environment, and it at that level that the findings might contribute in some way to building resilient agrarian production systems in the modern world.

The different land tenure systems that were in place in the study area at different times in the past – *latifundia* and tribally organized local control –have different implications for human-landscape interactions. The details of the timing of population growth and landscape change illuminate the crucial importance of scale issues in research focused on complex socio-natural systems. At the broadest scale, it appears as though the *latifundia* system was sustainable while the tribally organized system in place during the Islamic period was not. This characterization is misleading, as becomes apparent upon closer examination of the characteristics of each system that affect resilience. The apparent sustainability of the *latifundia* system was the result of low population densities and limited production. In the past, the labor required to plant and harvest cereals made it uneconomical to cultivate large areas where the vagaries of rainfall made the investment risky. People focused farming on smaller areas with relatively deep soils that more reliably produced a yield, and left larger areas and particularly hillslopes fallow for long periods between plantings or used them solely for grazing and wood.

Changing technologies have altered the situation dramatically. With the introduction of chemical fertilizers and modern farming equipment, particularly small bulldozer-like tractors, it now is possible for a small population to cultivate large areas far more intensively and for the landowners to realize an economic return in most years. Widespread mechanized cultivation currently is causing severe soil erosion, continuously incised stream systems have formed throughout the study area, and gravel bars forming in the Guadiana in the past few years suggest a dramatic increase in sediment delivery to the trunk stream. At the same time, because so much land is controlled by absentee landlords, the people performing the work on which they depend for an income have little stake in trying to farm in ways that reduce erosion. The *latifundia* system no longer is sustainable.

In the past, the *latifundia* system moderated human impacts on the landscape, but many of its aspects were and remain undesirable from a human perspective. It benefits a few wealthy families but it fosters a weak rural economy and the majority of the population remains, for the most part, underemployed and impoverished. By contrast, the alternative system in place during the Islamic period appears in many ways beneficial from a human perspective. The retention of the majority of surplus by the primary producers fostered a better developed rural economy and decreased poverty. The more intensive production also entailed more economic opportunity in rural communities and supported higher population densities. However, these characteristics created conditions where people eventually caused significant ecological degradation relatively rapidly.

Because of its benefits in human terms, it is worth considering whether a system similar to the tribally based one could provide the economic benefits of relatively intensive production and a well-developed rural economy without inevitably causing degradation. While higher population densities in any given area might not be considered beneficial, global population growth suggests that there are few alternatives and finding ways to support an increased population without degrading the environment is desirable. Understanding the aspects of the land use system in place during the Islamic period that are related to resilience and degradation highlights some ways intensive production systems might be made more resilient.

By contrast to the *latifundia* system, one obvious advantage of a system of local control is that the decision makers are present and aware of the consequences of their actions. Unlike absentee landowners, they are capable of monitoring local conditions on a regular basis and adjusting their production strategies accordingly; the scale of management is matched to the scale of ecological processes (Cumming *et al.* 2006). It is relatively easy to understand how absentee landlords, motivated by different concerns and at least partially insulated from the consequences of land use decisions, might cause degradation. It is more difficult to explain degradation caused by knowledgeable primary producers as long as they are invested in maintaining production. The simple microeconomic model developed above suggests that producers knowingly caused degradation because increasing production was the least risky option available when faced with the combination of subsistence needs, increased external demand, and political

instability. It implies that, although agrarian producers in general have a strong incentive to avoid degrading the resources on which they depend, political stability, continued expectations of access to land, and the ability to meet subsistence needs are necessary preconditions for maintaining resilient production systems.

One problem that confronts systems similar to the tribally based one is that they rely on a shared resource, making them susceptible to free riders or the problem outlined as the tragedy of the commons (Hardin 1968). At a general level, there are three solutions that usually are proposed to meet the challenges of managing a shared resource. One is control by a larger-scale entity, usually the state, but the failures of the *latifundia* system suggest that such an approach has significant drawbacks in this case. Those failures also suggest that the second, privatization, is untenable for large holdings. Spatial and temporal variability in production in the study area suggest that privatizing small to medium-sized parcels of land would be highly risky for the individual owners. Assuming that resistance from current landowners could be overcome in some way, it might be possible in the study area and in many other settings to replicate the characteristics of the Islamic period land tenure system that contributed to resilience by building cooperatives or worker-owned enterprises that manage access to large tracts of land. Such institutions would have to be designed such that each individual realized the benefits of contributing to the long-term resilience of agrarian production, and they would require political stability and a basic expectation of continued access to the land.

One of the greatest challenges of building such a system would be moderating its interactions with larger political and economic systems. Interestingly, parallel situations have been the focus of a great deal of political ecology research where modern global markets have come into contact with traditional agrarian production systems (e.g., Blakie 1985; Robbins 2004; Scott 1998; Zimmerer 1993b). Some possible approaches to solving these problems include developing local markets, diversifying production to include multiple commodities subject to different market pressures, and reserving a proportion of surplus to help all participants through market downturns. If the challenges could be overcome, the landscape could support relatively intensive production indefinitely while providing economic opportunities for the populace.

References:

Abrahams, A. D., A. J. Parsons and K. S. Luk

1988 Hydrologic and sediment responses to simulated rainfall on desert hillslopes in southern Arizona. *Catena* 15: 105 – 117.

Abrantes, F., S. Lebreiro, T. Rodrigues, I. Gil, H. Bartels-Jónsdóttir, P. Oliveira, C. Kissel, and J. O. Grimalt

2005 Shallow-marine sediment cores record climate variability and earthquake activity off Lisbon (Portugal) for the last 2000 years. *Quaternary Science Reviews* 24 (2005): 2477 – 2494.

Acién Almansa, M.

1998 Settlement and Fortification in Southern Al-Andalus: the formation of a land of *husun*. In *The Formation of Al-Andalus. Part 1:History and Society*, edited by M. Marín, pages 347 – 376. Ashgate Variorum, Aldershot.

Adams, Robert McC.

1965 *Land Behind Baghdad, a History of Settlement on the Diyala Plains.* University of Chicago Press, Chicago.

Aitken, Martin

1990 *Science-based Dating in Archaeology*. Longman Press, London.

1998 *An Introduction to Optical Dating: the Dating of Quaternary Sediments by the Use of Photon-stimulated Luminescence.* Oxford University Press, Oxford.

Alcock, Susan E. and John F. Cherry (editors)

2004 *Side-by-Side Survey: Comparative Regional Studies in the Mediterranean World.* Oxbow Books, Oxford.

Angelucci, Diego E.

2006 Micromorphological observations on some samples from the prehistoric site of Barca do Xerez de Baixo (Reguengos de Monsaraz, Portugal). *Revista Portuguesa de Arqueologia* (9) 1: 2006.

Angelucci, D. E., A. M. Soares, L. Almeida, R. Brito and V. Laitão

2007 Neolithic occupation and mid-Holocene soil formation at Encosta de Sant'Ana (Lisbon, Portugal): a geoarchaeological approach. *Journal of Archaeological Science* 34 (10): 1641 – 1648.

Arnold, Jeanne.

1992 Complex Hunter – Gatherer – Fishers of Prehistoric California: Chiefs, Specialists, and Maritime Adaptations of the Channel Islands. *American Antiquity* 57(1): 60 – 84.

1995 Transportation Innovation and Social Complexity among Maritime Hunter – Gatherer Societies. *American Anthropologist* 97(4): 733 – 747.

Athanassopoulos, Effie and LuAnn Wandsneider (editors)
2004 *Mediterranean Archaeological Landscapes: Current Issues.* University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.

Bahre, C.J.
1991 *A Legacy of Change: Historical Human Impact on Vegetation in the Arizona Borderlands.* University of Arizona Press, Tucson.

Baker, Victor R.
1988 Geological fluvial geomorphology. *Geological Society of America Bulletin* 100 (8): 1157 – 1167.

Balée, William
2006 The Research Program of Historical Ecology. *Annual Reviews in Anthropology* 35: 75 – 98.

Balek, Cynthia A.
2002 Buried Artifacts in Stable Upland Sites and the Role of Bioturbation: A Review. *Geoarchaeology: An International Journal* 17 (1): 41 – 51.

Ballais, J.
2000 Conquest and Land Degradation in the Eastern Maghreb During Classical Antiquity and the Middle Ages. In *The Archaeology of Drylands: Living at the Margin.* ed. G. Barker and D. Gilbertson. Routledge, London. 125 – 136.

Banning, E.B., A. L. Hawkins and S. T. Stewart
2006 Detection Functions for Archaeological Survey. *American Antiquity* 71 (4): 723 – 742.

Barker, G.
1989 The Italian Landscape in the First Millennium AD: Some Archaeological Approaches. in *The Birth of Europe* ed. K. Randsborg, Analecta Romana Instituti Danici, Roma.

Barton, C. Michael, Joan Bernabeu, J. Emili Aura and Oreto Garcia
1999 Land-Use Dynamics and Socioeconomic Change: An Example from the Polop Alto Valley. *American Antiquity* 64 (4): 609 – 634.

Barton, C. Michael, Joan Bernabeu, J. Emili Aura, Oreto Garcia and Neus La Roca
2002 Dynamic Landscapes, Artifact Taphonomy, and Landuse Modeling in the Western Mediterranean. *Geoarchaeology* 17 (2): 155 – 190.

Barton, C. Michael, Joan Bernabeu, J. Emili Aura, Oreto Garcia, Steven Schmich, and Lluis Molina
2004 Long-Term Socioecology and Contingent Landscapes. *Journal of Archaeological Method and Theory* 11 (3): 253 – 295.

Bawden, Garth
1995 The Structural Paradox: Moche Culture as Political Ideology. *Latin American Antiquity* 6 (3): 255 – 273.

Bayham, Frank E.
1979 Factors Influencing the Archaic Pattern of Animal Exploitation. *The Kiva* 44 (2-3): 219 – 235.

Bazzana, A., P Cressier, and P. Guichard.
1988 *Les châteaux ruraux d'al-Andalus: histoire et archéologie des husun du sud-est de l'Espagne.* Casa de Velázquez, Madrid.

Bazzana, A., P. Guichard, and J. M. Segura Marti
1982 Du hisn musulman au castrum chrétien: le château de Perpunchet (Lorcha, Prov. de Alicante). *Melanges de la Casa de Velázquez* 17: 449 – 465.

Benedict, James B. and Byron L. Olson
1978 *The Mount Albion Complex: A Study of Prehistoric Man and the Altithermal.* Research Report No. 1, Center for Mountain Archaeology, Ward, Colorado.

Benito, Gerardo, Andrés Díez-Herrero and María Fernández de Villalta
2003 Magnitude and Frequency of Flooding in the Tagus Basin (Central Spain) Over the Last Millennium. *Climatic Change* 58: 171 – 192.

Benito, Rafael Gómez, Maria Dolores Blanca López, Julia Ramos Molina and Lourdes Blanca López
2003 Restauración de tres lámparas de bronce de la Mezquita de Medina Elvira. In *Las lámparas de Medina Elvira,* C. Vílchez Vílchez (coordinador), pages 62 – 71. Mueso Arqueológico y Etnológico de Granada, Granada, Spain.

Bentley, R. Alexander and Stephen J. Shennan
2003 Cultural Transmission and Stochastic Network Growth. *American Antiquity* 68 (3): 459 – 485.

Berdan, Frances, Richard Blanton, Elizabeth Boone, Mary Hodge, Michael Smith and Emily Umberger
1996 *Aztec Imperial Strategies*. Dumbarton Oaks, Washington D.C.

Bergesen, Albert and Tim Bartley

2000 World-System and Ecosystem. In *A World-Systems Reader: New Perspectives on Gender, Urbanism, Cultures, Indigenous Peoples and Ecology*, edited by Thomas Hall, pages 307 – 322. Rowman and Littlefield, Lanham, Maryland.

Bicho, Nuno Ferreira, Jonathan Haws, Bryan Hockett, Anastasia Markova and Willam Belcher

2003 Paleoecologia e ocupação humana da Lapa do Picareiro: resultados preliminaries. *Revista Portuguesa de Arqueología* 6 (2): 49 – 81.

Binford, Lewis

1962 Archaeology as Anthropology. *American Antiquity* 28 (2): 217 – 225

1964 A Consideration of Archaeological Research Design. *American Antiquity* 29 (4): 425 – 441

Bintliff, John

1977 *Natural environment and human settlement in Greece.* British Archaeological Reports 28. Oxford.

1992 Erosion in the Mediterranean Lands: A Reconsideration of Pattern, Process and Methodology. In *Past and Present Soil Erosion: Archaeological and Geographical Perspectives*, Edited by M. Bell and J. Boardman. Pages 125-132. Oxbow Monograph 22. Oxbow Books, Oxford.

1999 Structure, contingency, narrative and timelessness. In *Structure and Contingency: Evolutionary Processes in Life and Human Society*. Edited by John Bintliff, pages 132 – 148. Leicester University Press, London.

2002 Time, Process and Catastrophism in the Study of Mediterranean Alluvial History: A Review. *World Archaeology* 33 (3): 417 – 435.

Bintliff, John (ed)

1999 *Structure and Contingency: Evolutionary Processes in Life and Human Society*. Leicester University Press, London.

Bintliff, J.L. and W. Zeist

1982 *Paleoclimates, paleoenvironments, and human communities in the eastern Mediterranean region in later prehistory.* British Archaeological Reports S133. Oxford

Bird, Robert M.

1988 Preceramic Archaeobotany of Huaca Prieta: Investigations from 1946 – 1986. In *Economic Prehistory of the Central Andes*. Edited by Elizabeth Wing and Jane Wheeler, pp. 3 – 17, Oxford.

Birkeland, P.

1999 *Soils and Geomorphology*. Oxford University Press, New York.

Birkeland, Peter and Ran Gerson

1991 Soil-catena development with time in a hot desert, southern Israel – field data and salt distribution. *Journal of Arid Environments* 21: 267 – 281.

Blaikie, Piers

1985 *The Political Economy of Soil Erosion in Developing Countries.* Longman Development Studies, Singapur, London.

Bocco, G.

1991 Traditional knowledge for soil conservation in central Mexico. *Journal of Soil and Water Conservation* 46: 346 – 348.

Bocek, B.

1986 Rodent Ecology and Burrowing Behavior: Predicted effects on archaeological site formation. *American Antiquity* 51: 589 – 603.

1992 The Jasper Ridge Reexcavation Experiment: Rates of artifact mixing by rodents. *American Antiquity* 57: 261 – 269.

Boone, James

1986 Parental Investment and Elite Family Structure in Preindustrial States: A Case Study of Late Medieval-Early Modern Portuguese Genealogies. *American Anthropologist* 88: 859 – 878.

1992a The First Two Seasons of Excavations at Alcaria Longa: A Califal – Taifal Settlement in the Lower Alentejo of Portugal. *Arqueologia Medieval* 1: 51 – 64.

1992b Competition, Conflict and the Development of Social Hierarchies. In *Evolutionary Ecology and Human Behavior*. Edited by E. A. Smith and B. Winterhalder, pp. 301 – 338, Aldine de Gruyter, New York.

1993 The Third Season of Excavations at Alcaría Longa. *Arqueologia Medieval* 2: 111 – 125.

1994 Rural Settlement and Islamization: The evidence from Alcaria Longa. In *Arqueologia en el Etorno del Bajo Guadiana: Actas del Encuentro de Arqueologia del Suroeste*, ed. J.M. Campos, J. A. Perez, F. Gomez, pp. 527 – 544. Huelva: Universidad de Huelva.

1996 Uma Sociedade Tribal no Baixo Alentejo Medieval? *Arqueologia Medieval* 4: 25 – 35.

2002 Tribalism, Ethnicity, and Islamization in the Baixo Alentejo of Portugal: Preliminary results of investigation into transitional period (AD 550 – 850) rural settlements. *Era Arqueologia* 4: 104 – 121.

2009 *Lost Civilization: The Contested Islamic Past in Spain and Portugal.* Duckworth, London.

Boone, James and Nancy Benco

1999 Islamic Settlement in North Africa and the Iberian Peninsula. *Annual Reviews in Anthropology* 28: 51 – 71.

Boone, J., J. Meyers and C. Redman
1990 Archaeological and Historical Approaches to Complex Societies: The Islamic States of Medieval Morocco. *American Anthropologist* 92: 630 – 646.

Boone, James L. and Eric A. Smith
1998 Is It Evolution Yet? A Critique of Evolutionary Archaeology. *Current Anthropology* 39 (supplement): S141 – S170.

Boone, James and F. Scott Worman
2007 Rural Settlement and Soil Erosion from the Late Roman Period through the Medieval Islamic Period in the Lower Alentejo of Portugal. *Journal of Field Archaeology* 32 (2): 115 - 132.

Boserup, Ester
1965 *The Conditions of Agricultural Growth: the economics of agrarian change under population pressure.* Aldine Publishing Company, Chicago.

Bourdieu, Pierre
1977 *Outline of a theory of practice.* Cambridge University Press, New York.

Bowler, J.M., H. Johnson, J.M. Olley, J.R. Prescott, R. G. Roberts, W. Shawcross and N.A. Spooner
2003 New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421: 837 – 840.

Box, George E. P., and Norman R. Draper
1987 *Empirical Model-Building and Response Surfaces.* Wiley, New York.

Bradley, Raymond S.
1999 *Paleoclimatology: Reconstructing Climates of the Quaternary, Second Edition.* Academic Press (Elsevier), San Diego, California.

Braidwood, Robert J. and Linda S. Braidwood
1953 The Earliest Village Communities of Southwestern Asia. *Journal of World History* 1: 278 – 310.

Braudel, Fernand
1976 *The Mediterranean and the Mediterranean World in the Age of Philip II.* Translated by Sian Reynolds, original publication 1949. Harper and Row, New York.

Briggs, John, Katherine Spielmann, Hoski Schaafsma, Keith Kintigh, Melissa Kruse, Kari Morehouse and Karen Schollmeyer

2006 Why ecology needs archaeologists and archaeology needs ecologists. *Frontiers in Ecology and the Environment* 4 (4): 180 – 188.

Brown, A. G.

1992 Slope Erosion and Colluviation at the Floodplain Edge. In *Past and Present Soil Erosion: Archaeological and Geophysical Perspectives.* Edited by M. Bell and J. Boardman. Oxbow Monograph 22. Oxbow Books, Oxford. pp. 77 – 87.

Brumfiel, Elizabeth

1983 Aztec State Making: Ecology, Structure, and the Origin of the State. *American Anthropologist* 85(2): 261 – 284.

Brumfiel, Elizabeth and John Fox (editors)

1994 *Factional Competition and Political Development in the New World*. Cambridge University Press, Cambridge.

Bryan, Kirk

1925 Date of channel trenching (arroyo cutting) in the arid Southwest. *Science* 62 (1307): 338 – 344.

1940 Erosion of the valleys of the Southwest. *New Mexico Quarterly Review* 10: 227-232.

1942 Pre-Columbian Agriculture in the Southwest as Conditioned by Periods of Alluviation. In *Proceedings of the Eighth American Scientific Congress Held in Washington May 10 – 18, 1940*, pp. 57 – 74. Department of State, Washington.

Bryant, Vaughn, Jr. and Stephen Hall

1993 Archaeological Palynology in the United States: A Critique. *American Antiquity* 58 (2): 277 – 286.

Bryson, R.A.

2005 Archaeoclimatology. *The Encyclopedia of World Climatology*. Edited by J.E. Oliver. Dordrecht (Springer), New York. p. 58 – 63.

Bulliet, Richard

1979 *Conversion to Islam in the Medieval Period: an Essay in Quantitative History*. Harvard University Press, Cambridge, Massachusetts.

Bull, William

1991 *Geomorphic Responses to Climate Change*. Oxford University Press, New York.

1997 Discontinuous Ephemeral Streams. *Geomorphology* 19: 227 – 276.

Buol, S., F. Hole, R. McKracken, R. Southard
1997 *Soil Genesis and Classification.* Iowa State University Press, Ames.

Burger, O., L. Todd, and P. Burnett
2008 The Behavior of Surface Artifacts: Building a Landscape Taphonomy on the High Plains, in *Archaeological Landscapes on the High Plains*, edited by L. L. Scheiber and B. Clark. University Press of Colorado, Boulder.

Burger, Oskar and Lawrence C. Todd
2006 Grain, Extent, and Intensity: The Components of Scale in Archaeological Survey. In *Confronting Scale in Archaeology: Issues of Theory and Practice,* edited by Gary Lock and Brian Molyneaux, pp. 235 256. Springer, New York

Burger, O., L. Todd, T. Stohlgren, P. Burnett and D. Stevens
2004 Multi-Scale and Nested-Intensity Sampling Techniques for Archaeological Survey. *Journal of Field Archaeology* 29 (3-4): 409 – 423.

Burnett, B. N., G. A. Meyer, and L. D. McFadden
2008 Aspect-related microclimatic influences on slope forms and processes, northeastern Arizona. *Journal of Geophysical Research* 113: F03002, doi: 10.1029/2007JF000789. Electronic document, accessed August 28, 2008.

Butzer, Karl
2005 Environmental history in the Mediterranean world: cross-disciplinary investigation of cause-and-effect for degradation and soil erosion. *Journal of Archaeological Science* 32: 1773 – 1800.
1996 Ecology in the Long View: Settlement, Agrosystem Strategies, and Ecological Performance. *Journal of Field Archaeology* 23 (2): 141 – 150.
1994 The Islamic Traditions of Agroecology: Crosscultural Experience, Ideas and Innovations. *Ecumene: a journal of environment, culture, meaning* 1: 7 – 50.
1982 *Archaeology as human ecology*. Cambridge University Press, Cambridge.

Butzer, K., J. F. Mateu, E. K. Butzer, and P. Kraus
1985 Irrigation Agrosystems in Eastern Spain: Roman or Islamic Origins? *Annals of the Association of American Geographers* 75: 479 – 504.

Canti, M. G.
2003 Earthworm Activity and Archaeological Stratigraphy: A Review of Products and Processes. *Journal of Archaeological Science* 30: 135 – 148.

Carneiro, Robert
1970 A Theory on the Origin of the State. *Science* 169: 733 – 738.

Carrión Marco, Yolanda

2006 *Reconstructing Environment and Wood Uses from Charcoal Analysis in Four Historical Sites in Portugal*. Unpublished manuscript, on file at the University of New Mexico.

Cartmill, M.

1980 John Jones' Pregnancy: Some Comments on the Statistical Relevance Model of Scientific Explanation. *American Anthropologist* 82: 382 – 385.

Castro, P., S. Gili, V. Lull, R. Micó, C. Rihuete, R. Rish, M.E. Sanahuja Yll and R. Chapman

2000 Archaeology and desertification in the Vera basin (Almería, south-east Spain). *European Journal of Archaeology* 3 (2): 147 – 166.

Catarino, Helena

2003 De novo sobre a Batalha de Aljubarrota: os resultados da intervenção arqueológica de 1999. *Arqueologia Medieval* 8: 253 – 266. Campo Arqueológico de Mértola, Mértola, Portugal.

Chamberlin, T. C.

1965 The Method of Multiple Working Hypotheses. *Science* 148: 754 – 759. Originally published 1890, *Science* (old series), 15, 92.

Chester, David and Peter James

1991 Holocene alluviation in the Algarve: the case for an anthropological cause. *Journal of Archaeological Science* 18: 73 – 87.

1999 Late Pleistocene and Holocene Landscape Development in the Algarve Region, Southern Portugal. *Journal of Mediterranean Archaeology* 12 (2) 169 – 196.

Chew, Sing C.

2001 *World Ecological Degradation: Accumulation, Urbanization, and Deforestation 3000 B.C. – A.D. 2000*. Alta Mira Press, Walnut Creek, California.

2007 *The Recurring Dark Ages: Ecological Stress, Climate Changes, and System Transformation.* Alta Mira Press, Walnut Creek, California.

Childe, V. Gordon

1957 The Evolution of Society. Reprinted 2004 in *Foundations of Social Archaeology: Selected Writings of V. Gordon Childe.* Edited by T. Patterson and C. Orser. Alta Mira Press, Walnut Creek, California. Pages 171 – 176. Originally published in *Antiquity* 31 (124): 210 – 214.

1950 The Urban Revolution. *The Town Planning Review* 21: 3 – 17.

Chrisholm, M.

1968 *Rural Settlement and Land Use.* Hutchison, London.

Clark, J.G.D.
1954 *Excavations at Starr Carr*. Cambridge University Press, Cambridge.

Clarke, M., H. Rendell and A. Wintle
1999 Quality assurance in luminescence dating. *Geomorphology* 29: 173 – 185.

Codding, Brian F. and Terry L. Jones
2007 Man the showoff? or the ascendance of a just-so-story: a comment on recent applications of costly signaling theory in American archaeology. *American Antiquity* 72 (2): 349 – 357.

Collins, Roger
1983 *Early Medieval Spain: Unity in Diversity*. Macmillan Press, London.
1989 *The Arab Conquest of Spain, 710 – 797*. Basil Blackwell, Oxford

Cooke, Ronald U. and Richard W. Reeves
1976 *Arroyos and Environmental Change in the American Southwest.* Clarendon Press, Oxford.

Cressier, P.
1992 *Estudios de arqueología medieval en Almería.* Ediciónes Instituto de Estudios Almerienses, Granada.
1991 Agua, fortificaciones, y poblamiento: el aportede la arqueología a los estudios sobre el sureste penínsular. *Aragon en la edade media* 9: 403 – 427.

Crumley, Carole L. (editor)
1994 *Historical Ecology: Cultural Knowledge and Changing Landscapes.* School of American Research Press, Santa Fe, New Mexico.

Crumley, Carole L.
1994b The Ecology of Conquest: Contrasting Agropastoral and Agricultural Societies' Adaptation to Climate Change. In *Historical Ecology: Cultural Knowledge and Changing Landscapes,* edited by Carol Crunley. School of American Research Press, Santa Fe, New Mexico.
1998 Forward. In *Advances in Historical Ecology*, edited by W. Balée. Columbia University Press, New York, pp. ix – xiv.
2007 Historical Ecology: Integrated Thinking at Multiple Temporal and Spatial Scales. In *The World System and the Earth System: Global Socioenvironmental Change and Sustainability Since the Neolithic*, edited by Alf Hornborg and Carole Crumley. Left Coast Press, Walnut Creek, California.

Crumley, C. and W. Marquardt
1987 *Regional Dynamics: Burgundian Landscapes in Historical Perspective.* Academic Press, San Diego.

Cumming, Graeme S., David H. M. Cumming, and Charles R. Redman
2006 Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. *Ecology and Society* 11(1): 14. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art14/

Curtis, Wayne
1915 *The North American Indian, Vol. 10*. Johnson Reprint Corp., New York. (1978)

Dalan, Rinita and Subir Banerjee
1996 Soil Magnetism, an Approach for Examining Archaeological Landscapes. *Geophysical Research Letters* 23: 185 – 188.
1998 Solving Archaeological Problems Using Techniques of Soil Magnetism. *Geoarchaeology* 13 (1): 3 – 36

D'Altroy, T. and T. Earle
1985 Staple Finance, Wealth Finance and Storage in the Inka Political Economy. *Current Anthropology* 26: 187 – 206.

Daniel, Glyn
1967 *The Origins and Growth of Archaeology*. Galahad Books, New York City.

Daniels, F. C. Boyd and D. Saunders
1953 Thermoluminescence as a Research Tool. *Science* 117 (3040): 343 – 349.

Darwin, Charles
1837 On the formation of mould. *Proceedings, Geological Society of London* 2: 574 – 575.
1881 *The Formation of Vegetable Mould, Through the Action of Worms, With Observations on Their Habits.* John Murray, London.

Davidson, D.A.
1980 Erosion in Greece during the first and second millennia BC. In *Timescales in Geomorphology*, R. Cullingford, edited by D. Davidson, & J. Lewin. Wiley, Chichester.

Dean, J.S.
1978 Independent Dating in Archaeological Analysis. In *Advances in Archaeological Method and Theory, Volume 1*. Edited by M. B. Schiffer, pages 223 – 255. Academic Press, New York.

Deckers, Katleen
2005 Post-Roman History of River Systems in Western Cyprus: Causes and Archaeological Implications. *Journal of Mediterranean Archaeology* 18 (2): 155 – 181.

Delano Smith, Catherine
1979 *Western Mediterranean Europe*. Academic Press, London.

DeMarrais, Elizabeth, Luis Jaime Castillo and Timothy Earle
1996 Ideology, materialization, and power strategies. *Current Anthropology* 37: 15 – 31.

Diamond, Jared
2005 *Collapse: How Societies Choose to Fail or Succeed*. Viking, New York.

Dincauze, Dena
2000 *Environmental Archaeology: principles and practice*. Cambridge University Press, Cambridge.

Dinsmore, Elizabeth
1994 *Rural Settlement and Political Change: An Intersite Analysis of Roman- and Islamic-Period Settlement Organization in the Baixo Alenejo, Portugal*. Unpublished M.A. Thesis, Arizona State University.
1995 Marginal Tribes in Al-Andalus: Two Models for an Historical Archaeology of the "Berberization" of Iberia, 8^{th} – 10^{th} Centuries. *Arqueologia Medieval* 3: 17 – 26. Campo Arqueológico de Mértola, Mértola, Portugal.

Doolittle, W. E.
2000 *Cultivated Landscapes of Native North America.* Oxford University Press, New York.

Dornan, Jennifer L.
2002 Agency and Archaeology: Past, Present and Future Directions. *Journal of Archaeological Method and Theory* 9(4): 303 – 330.

Drake, Brandon L., James L. Boone, and David Hanson
n.d. The Use of Radiocarbon-Derived $\Delta^{13}C$ Values as a Paleoclimate Indicator: Applications in the Lower Alentejo of Portugal. Manuscript submitted to the *Journal of Archaeological Science*, 2011.

Dunlop, David
1995 Magnetism in rocks. *Journal of Geophysical Research* 100 (B2): 2161 - 2174

Dunnell, R. C.
1982 Science, Social Science, and Common Sense: The Agonizing Dilemma of Modern Archaeology. *Journal of Anthropological Research* 38: 1 – 25.
1989a Aspects of the Application of Evolutionary Theory in Archaeology. In *Archaeological Thought in America*, ed. C.C. Lamberg-Karlovsky, 35 – 49. Cambridge University Press, Cambridge.
1989b The Philosophy of Science and Archaeology. In *Critical Traditions in Contemporary Archaeology: Essays in Philosophy, History and Socio-Politics*, edited by V. Pinsky and A. Wylie, pp. 5 – 9. University of New Mexico Press, Albuquerque.

Dunnell, R. C. and W. S. Dancey
1983 The Siteless Survey: A Regional Scale Data Collection Strategy. *Advances in Archaeological Method and Theory 6*, edited by M. B. Schiffer, pp. 267 – 288. Academic Press, New York.

Ebert, James I.
1992 *Distributional Archaeology*. University of New Mexico Press, Albuquerque.

Edward, J., J. M. Fossey and L. Yaffe
1984 Analysis by neutron activation of human bone from the Hellenistic cemetery at Asine, Greece. *Journal of Field Archaeology* 11: 37 – 46.

Edward, J. and R. Benfer
1993 The Effects of Diagenesis on the Paloma Skeletal Material. In *Investigations of Ancient Human Tissue: Chemical Analyses in Anthropology.* Food and Nutrition in History and Anthropology, Volume 10. Edited by M. K. Sandford. Gordon and Breach Science Publishers. Langhorne, Pennsylvania. Pages 183 – 268.

Ellwein, Amy L., Shannon A. Mahan, and Leslie D. McFadden
2011 New optically stimulated luminescence ages provide evidence of MIS3 and MIS2 eolian activity on Black Mesa, northeastern Arizona, USA. *Quaternary Research* doi:10.1016/j.yqres.2010.12.002

Ely, Lisa
1997 Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. *Geomorphology* 19: 175 – 201.

Eppes, M., L. McFadden, J. Matti, and R. Powell
2002 Influence of soil development on the geomorphic evolution of landscapes: an example from the Transverse Ranges of California. *Geology* 30 (3): 195 – 198.

Eppes, M., E. McDonald, and L. McFadden
2003 Soil geomorphological studies in the Mojave Desert: Impacts of Quaternary tectonics, climate, and rock type on soils, landscapes, and plant community ecology. In *Quaternary Geology of the United States, INQUA 2003 Field Guide Volume* edited by D. Easterbrook, pages 105 – 122.

Eriksson, M., J. Olley and R. Payton
2000 Soil erosion history in central Tanzania based on OSL dating of colluvial and alluvial hillslope deposits. *Geomorphology* 36: 107 – 128.

Erenstein, Olaf
2006 Intensification or extensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. *Agricultural Systems* 90 (1-3): 132 – 158.

Erlandson, J. M.
1984 A Case Study in Faunalturbation: Delineating the effects of the burrowing pocket gopher on the distribution of archaeological materials. *American Antiquity* 49: 785 – 790.

Escobar, Arturo
1999 After Nature: Steps to an Antiessentialist Political Ecology. *Current Anthropology* 40 (1): 1 – 16.

EuroWeather
2008 http://www.eurometeo.com/english/home, Electronic document, accessed September 2008.

Evans, John G.
2003 *Environmental Archaeology and the Social Order*. Routledge, London.

Evenari, M., L. Shanan, and N. Tadmor
1982 *The Negev: The challenge of a desert* (2nd Edition). Harvard University Press, Cambridge, Massachusetts.

Feathers, James K.
2003 Use of luminescence dating in archaeology. *Measurement Science and Technology* 14: 1493 – 1509.

Feldman, Robert A.
1985 Preceramic Corporate Architecture: Evidence for the Development of Non – Egalitarian Social Systems in Peru. In *Early Ceremonial Architecture in the Andes*. Edited by C. Donnan, pp. 71 – 92, Dumbarton Oaks.

1987 Architectural Evidence for the Development of Nonegalitarian Social Systems in Coastal Peru. In *The Origins and Development of the Andean State*. Edited by Jonathan Haas, Shelia Pozorski and Thomas Pozorski, pp. 9 – 14, Cambridge University Press, Cambridge.

Feinman, Gary and Joyce Marcus (editors)
1998 *Archaic States*. School of American Research Press, Santa Fe, New Mexico.

Feinman, Gary and Jill Neitzel
1984 Too Many Types: An Overview of Sedentary Pre-state Societies in the Americas. In *Advances in Archaeological Method and Theory,* Volume 7, edited by M. B. Schiffer, pages 39 – 102. Academic Press, New York.

Fennegan, Franklin and Fred Wendorf
1956 Excavations at the Ignacio, Colorado Field Camp Site – LA2605. In *Pipeline Archaeology: Reports of Salvage Operations in the Southwest in El Paso Natural Gas Company Projects*. Laboratory of Anthropology and the Museum of Northern Arizona. Santa Fe and Flagstaff.

Fierro, Maribel
1998 Four Questions in Connection With Ibn Hafsun. In *The Formation of al-Andalus, Part1: History and Society*. Edited by Manuela Marín. Ashgate, Brookfield, Vermont. pages 291 – 312.

Fisher, Christopher and Gary Feinman
2005 Introduction to "Landscapes over Time". *American Anthropologist* 107 (1): 62 – 69.

Flannery, Kent V.
1973 Archaeology with a Capital S. In *Research and Theory in Current Archaeology,* edited by C. L. Redman, pages 47 – 58. Wiley, New York.
1972 The Cultural Evolution of Civilizations. *Annual Review of Ecology and Systematics* 3: 399 – 426. Annual Reviews, Palo Alto, California.

Fogelin, Lars
2007 Inference to the Best Explanation: A Common and Effective Form of Archaeological Reasoning. *American Antiquity* 72 (4): 603 – 625.

Force, Eric
2004 Late Holocene Behavior of Chaco and McElmo Canyon Drainages (Southwest U.S.): A Comparison Based on Archaeologic Age Controls. *Geoarchaeology* 19(6): 583 – 609.

Force, E. and W. Howell
1997 *Holocene Depositional History and Anasazi Occupation in McElmo Canyon, Southwestern Colorado.* Arizona State Museum Archaeological Series 188, Arizona State Museum, The University of Arizona, Tucson.

Force, E., R. Vivian, T. Windes, and J. Dean
2002 *Relation of "Bonito" Paleo-channels and Base-level Variations to Anasazi Occupation, Chaco Canyon, New Mexico.* Arizona State Museum Archaeological Series 194, Arizona State Museum, The University of Arizona, Tucson.

Forman, S., R. Smith, W. Hackett, J. Tullis and P. McDaniel
1993 Timing of Late Quaternary Glaciations in the Western United States Based on the Age of Loess on the Eastern Snake River Plain, Idaho. *Quaternary Research* 40: 30 – 37.

Forman, S., R. Oglesby, V. Markgraf and T. Stafford
1995 Paleoclimatic significance of Late Quaternary eolian deposition on the Piedmont and High Plains, Central United States. *Global and Planetary Change* 11: 35 – 55.

Forrest, B., W. Rink, N. Bicho and C. Ferring
2003 OSL ages and possible bioturbation signals at the Upper Paleolithic site of Lagoa do Bordoal, Algarve, Portugal. *Quaternary Science Reviews* 22: 1279 – 1285.

French, C., D. Passmore, and L. Schulte
1998 Geomorphological erosion and edaphic processes. In *Aguas Project. Palaeoclimatic Reconstruction and the Dynamics of Human Settlement and Land Use in the Area of the Middle Aguas (Almería) in the South-East of the Iberian Peninsula* edited by P.V. Castro, R.W. Chapman, S. Gili, V. Lull, R. Micó, C. Rihuete, R. Risch and Ma.E. Sanahuja. European Commission, Luxembourg, p. 45 – 52.

Fried, M.H.
1967 *The Evolution of Political Society.* Random House, New York.

Friedman, Jonathan
1975 Tribes, States, and Transformations. In *Marxist Analyses and Social Anthropology*, Edited by Maurice Bloch, pp. 161 – 203. John Wiley & Sons, New York.

Fritz, J. and F. Plog
1970 The Nature of Archaeological Explanation. *American Antiquity* 35: 405 – 412.

Frodeman, Robert
1995 Geological Reasoning: Geology as an interpretive and historical science. *Geological Society of America Bulletin* 107 (8): 960 – 968.

Frolking, Tod, and Bradley Lepper
2001 Geomorphic and Pedogenic Evidence for Bioturbation of Artifacts at a Multicomponent Site in Licking County, Ohio, U.S.A. *Geoarchaeology: An International Journal* 16 (3): 243 – 262.

Gamble, Lynn, Phillip Walker, and Glenn Russell
2001 An Integrative Approach to Mortuary Analysis: Social and Symbolic Dimensions of Chumash Burial Practices. *American Antiquity* 66 (2): 185 – 212.

Geertz, Clifford M.
1973 *The Interpretation of Cultures.* Basic Books, New York.

Gellis, A., M. Pavich, P. Bierman, E. Clapp, A. Ellwien, and S. Aby
2004 Modern Sediment Yield Compared to Geologic Rates of Sediment Production in a Semi-Arid Basin, New Mexico: Assessing the Human Impact. *Earth Surface Processes and Landforms* 29: 1359 – 1372.

Ghiselin, M. T.
1997 *Metaphysics and the Origin of Species*. State University of New York Press, Albany.

Giddens, Anthony
1984 *The Constitution of Society: Outline of the Theory of Structuration.* Polity Press, Cambridge.

Gifford-Gonzalez, Diane P., David B. Damrosch, Debra R. Damrosch, John Pryor, and Robert L. Thunen
1985 The Third Dimension in Site Structure: An Experiment in Trampling and Vertical Dispersal. *American Antiquity* 50 (4): 803 – 818.

Gilbert, G.K.
1917 Hydraulic-mining debris in the Sierra Nevada. *U.S. Geological Survey Professional Paper 105.* U.S. Government Printing Office.

Gile, L.H. and R. B. Grossman
1979 *The Desert Project Soil Monograph: Soils and Landscapes of a Desert Region Astride the Rio Grande Valley Near Las Cruces, New Mexico*. United States Department of Agriculture, Soil Conservation Services, Washington, D.C.

Gile, L. H., F. F. Peterson and R. B. Grossman
1966 Morphological and Genetic Sequences of Carbonate Accumulation in Desert Soils. *Soil Science* 101: 347 – 360.

Gilman, Antonio
1981 The Development of Social Stratification in Bronze Age Europe. *Current Anthropology* 22 (1): 1 – 23.
1989 Marxism in American Archaeology. In *Archaeological Thought in America*, edited by C. C. Lamberg-Karlovsky, 63 – 73. Cambridge University Press, Cambridge

Gilman, A. and J. B. Thornes
1985 *Land-use and Prehistory in South-East Spain*. Allen and Unwin, London.

Glick, Thomas F.
1995 *From Muslim Fortress to Christian Castle: Social and Cultural Change in Medieval Spain*. Manchester University Press, Manchester.
1979 *Islamic and Christian Spain in the Early Middle Ages.* Princeton University Press, Princeton, New Jersey.

Godelier, Maurice
1986 *The Mental and the Material*. M. Thom, translator. Verso, London.

Gómez Martínez, Susana
2005 Cerámica a molde de época islámica. *Arqueologia Medieval* 9:221 – 232. Campo Arqueológico de Mértola, Mértola, Portugal.
2003a Mértola, Vila Museu. Un Proyecto Cultural de Desarrollo Local. In *Cultura y Turismo*, pages 173 – 189, Antonio Miguel Nogués Pedregal, coordinador. Signatura Ediciones de Andalucía, Sevilla, Spain.
2003b Producciones Cerámicas en la Mértola Islámica. *Proceedings of the Seventh International Congress on the Medieval Ceramics of the Mediterranean, held in Thessalonica, Greece, October 11 – 16, 1999.* Ministry of Culture, Treasury of Archaeological Resources and Expropriations, Athens, Greece.[59]
2002 Objectos del Garb Al-Andalus. In *O Mediterrâneo Ocidental: Identidades e frontera*, coordinated by Maria da Graça A. Mateus Ventura, pages 241 – 264. Edições Colibri, Lisbon.
1998 A cerâmica no Gharb al-Ândalus. In *Portugal Islâmico: Os últimos sinais do Mediterrâneo*, annotated and illustrated exhibit catalogue coordinated by Santiago Macias and Cláudio Torres, pages 121 – 131. Printer Portuguesa, Lisbon.

[59] Thanks to Connie Constan for translating the cover of the offprint (a copy of the title page of the volume) from the original Greek.

Gómez Martínez, Susana and Virgílio Lopes
2007 Trabalhos Arqueológicos de Estácio da Veiga em Mértola. *Revista XELB 7: Actas do 4º Encontro de Arqueologia do Algarve.*
2003 Intervenção Arqueológica de Emergência Realizada Realizada em Mértola. *Al-Madan*, second series, number 12. Centro de Arqueología de Almada, Almada, Portugal.

Goody, J.
2004 *Islam in Europe.* Polity Press, Malden, Massachusetts.
1984 *The Development of the Family and Marriage in Europe.* Cambridge: Cambridge University Press.

Goodland, Robert
1995 The Concept of Environmental Sustainability. *Annual Review of Ecology and Systematics* 26: 1 – 24.

Gosden, Chris
2001 Postcolonial Archaeology: Issues of Culture, Identity, and Knowledge. In *Archaeological Theory Today*, edited by I. Hodder, pages 241 – 261. Polity Press, Cambridge.

Goulart, Artur
1992 Ibn Qasi, Rei de Mértola e Mahdi Luso-Muçulmano. *Arqueología Medieval* 1: 209 – 216. Campo Arqueológico de Mértola, Mértola, Portugal. (Also reprinted as a separate booklet, 2003.)

Gould, Stephen Jay
1984 Balzan Prize to Ernst Mayr. *Science* 223: 255 – 257.

Graf, W. L., R. Hereford, J. Laity and R. Young
1987 Colorado Plateau. In *Geomorphic systems of North America.* Edited by W. L. Graf. pp. 259 – 301. Geological Society of America, Centennial Special Volume 2. Boulder, Colorado.

Grave, Peter and Lisa Kealhofer
1999 Assessing Bioturbation in Archaeological Sediments using Soil Morphology and Phytolith Analysis. *Journal of Archaeological Science* 26: 1239 – 1248.

Graybill, Donald
1989 The Reconstruction of Prehistoric Salt River Streamflow. In *The 1982 – 1984 Excavations at Las Colinas: Environment and Subsistence*, edited by D. Graybill, D. Gregory, F. Nials, S. Fish, C. Miksicek, R. Gasser and C. Szuter, pp. 25 – 38. Archaeological Series 162, Volume 5, Arizona State Museum, University of Arizona, Tucson.

Greene, Kevin
1986 *The Archaeology of the Roman Economy.* University of California Press, Berkeley.

Grogler, N., F. G. Houtermans, and H. Stauffer
1968 *Proceedings of the Second Geneva Conference*, 226. Pergamon.

Grove, A. T., and Oliver Rackham
2001 *The Nature of Mediterranean Europe, An Ecological History*. Yale University Press, New Haven, Connecticut.

Guichard, Pierre
1976 *Al-Andalus: Estructura Antropologica de una Sociedade Islamica en Occidente*. Barral Editories, Barcelona.
1998 The Population of the Region of Valencia During the First Two Centuries of Muslim Domination. In *The Formation of al-Andalus, Part1: History and Society*. Edited by Manuela Marín. Ashgate, Brookfield, Vermont. pages 129 – 182.

Gutierrez-Lloret, S.
1988 *Ceramica Commun Paleoandalusi del Sur Alicante (siglos VII-X).* Publicaciones de la Caja de Ahorros Provincial, Alicante.
1989 Espacio y poblamiento paleoandalusí en el sur de Alicante: origen y distribución. *III Congreso de Arqueología Medieval Española*, pages 341 – 348. Ovideo.

Hack, J. T.
1942 *The changing physical environment of the Hopi Indians of Arizona*. Peabody Museum Papers Volume 25, Number 1. Peabody Museum, Cambridge, Massachusetts.

Hall, Seven A.
1980 Channel trenching and climatic change in the southern Great Plains. *Geology* 18: 342 – 345.

Hanson, P., J. Mason and R. Goble
2004 Episodic Late Quaternary slopewash deposition as recorded in colluvial aprons, Southeastern Wyoming. *Quaternary Science Reviews* 23: 1835 – 1846.

Harden, J.
1982 A quantitative index of soil development from field descriptions: Examples from a chronosequence in central California. *Geoderma* 28: 1-28.

Harden, J. and E. Taylor
1983 A quantitative comparison of soil development in four climatic regimes. *Quaternary Research* 20: 342 – 359.

Hardin, Garret
1968 The Tragedy of the Commons. *Science* 162: 1243 – 1248.
1998 Extensions of the Tragedy of the Commons. *Science* 280 (5364): 682 – 683.

Hassan, Fekri A.
1981 *Demographic Archaeology*. Studies in Archaeology, Academic Press, New York.

Hawkes, Kristen, Kim Hill, and James F. O'Connell
1982 Why Hunters Gather: Optimal Foraging and the Ache of Eastern Paraguay. *American Ethnologist* 9: 379 – 398.

Hayashida, Frances M.
2005 Archaeology, Ecological History, and Conservation. *Annual Review of Anthropology* 34: 43 – 65.

Hegmon, Michelle
2003 Setting Theoretical Egos Aside: issues and theory in North American archaeology. *American Antiquity* 68 (2): 213 – 243.

Helama, Samuli, Jouko Meriläinen, and Heikki Tuomenvirta
2009 Multicentennial megadrought in northern Europe coincided with a global El Niño-Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* 37: 175 – 178.

Hempel, C.
1965 *Aspects of Scientific Explanation.* Reprint of *The Function of Laws in History* originally published 1942. Free Press, New York.

Hereford, Richard
1984 Climate and ephemeral-stream processes: Twentieth century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. *Geological Society of America Bulletin* 95: 654 – 668.

Hernández, M.
1998 The Social Structure of Al-Andalus During the Muslim Occupation (711-55) and the Founding of the Umayyad Monarchy. In *The Formation of al-Andalus, Part1: History and Society*. Edited by Manuela Marín. Ashgate, Brookfield, Vermont. pages 51 – 83.

Higgs, Eric S., and Claudio Vita-Finzi
1970 Prehistoric Economies in the Mt. Carmel Area Palestine: Site Catchment Analysis. *Proceedings of the Prehistoric Society of London* 36: 1 – 37.

Hill, J. Brett
2004 Land Use and an Archaeological Perspective on Socio-Natural Studies in the Wadi Al-Hasa, West Central Jordan. *American Antiquity* 69 (3): 389 – 412.

Hodder, Ian
1982 The Identification and Interpretation of Ranking in Prehistory: A Contextual Perspective. In *Ranking, Resource and Exchange: Aspects of the Archaeology of Early European Society*. C. Renfrew and S.J. Shennan, eds. pp. 150 – 154. Cambridge University Press, Cambridge.
1984 Burials, Houses, Women and Men in the European Neolithic. In *Ideology, Power and Prehistory,* Edited by D. Miller and C. Tilley, pp. 51 – 68. Cambridge University Press, Cambridge.
1985 Postprocessual Archaeology. In *Advances in Archaeological Method and Theory, Vol. 8*. Edited by M. Schiffer, pp. 1 – 26. Academic Press, New York.
1990 *The Domestication of Europe: Structure and Contingency in Neolithic Societies.* Blackwell, Oxford.
1991 Interpretive Archaeology and Its Role. *American Antiquity* 56 (1): 7 – 18.
1992 *Theory and Practice in Archaeology*. Routledge, New York.
1992b Politics and Ideology in the World Archaeological Congress 1986. In *Theory and Practice in Archaeology*, ed. I. Hodder, 135 – 141. Routledge, New York.
2001 Introduction: A Review of Contemporary Theoretical Debates in Archaeology. In *Archaeological Theory Today*, edited by I. Hodder, pages 1 – 13. Polity Press, Malden Massachusetts.

Hodges, Richard
1989 Archaeology of the Class Struggle in the First Millennium AD. in *The Birth of Europe* edited by K. Randsborg, Analecta Romana Instituti Danici, Roma.
2003 *Villa to Village: The Transformation of the Roman Countryside in Italy, C. 400 – 1000.* Duckworth, London.

Hole, F. D.
1961 A classification of pedoturbations and some other processes and factors of soil formation in relation to isotropism and anisotropism. *Soil Science* 91: 375 – 377.

Holliday, Vance T.
2004 *Soils in Archaeological Research*. Oxford University Press, Oxford.

Holliday, Vance, Bruce Huckell, James Mayer, Steven Forman and Leslie McFadden
2006 Geoarchaeology of the Boca Negra Wash Area, Albuquerque Basin, New Mexico. *Geoarchaeology* 21 (8): 765 - 802.

Homburg, Jeffrey A., Jonathan A. Sandor, and Jay B. Norton
2005 Anthropogenic Influences on Zuni Agricultural Soils. *Geoarchaeology: An International Journal* 20 (7): 661 – 693.

Hopkins, Kieth
1980 Taxes and Trade in the Roman Empire (200 BC – AD 400). *Journal of Roman Studies* 70: 101 – 125.

Huckleberry, Gary
2001 Archaeological Sediments in Dryland Alluvial Environments. In *Sediments in Archaeological Context*, edited by J. Stein and W. Farrand, pages 67 – 92. The University of Utah Press, Salt Lake City.

Hull, D. L.
1988 *Science as a Process*. University of Chicago Press, Chicago.

Huntley, D.J., D. I. Godfrey-Smith, and M.L.W. Thewalt
1985 Optical dating of sediments. *Nature* 313: 105 – 107.

Instituto Português de Arqueologia
2009 www.ipa.min-cultura.pt Electronic document, accessed February 2009.

Janssen, Cornelius R.
1994 Palynological indications for the extent of the impact of man during Roman times in the western part of the Iberian peninsula. In *Evaluation of Land Surfaces Cleared from Forests in the Mediterranean Region During the Time of the Roman Empire,* edited by B. Frenzel. Gustav Fischer, Stuttgart. Pages 15 – 22.

Jenny, H.
1941 *Factors of Soil Formation.* McGraw-Hill, New York.

Joanitis, Aldona
1991 *Chiefly Feasts: The Enduring Kwakiutl Potlatch*. University of Washington Press, Seattle.

Johnson, C. David, Timothy Kohler and Jason Cowan
2005 Modeling Historical Ecology, Thinking about Contemporary Systems. *American Anthropologist* 107 (1): 96 – 108.

Johnson, Donald L.
1989 Subsurface Stone Lines, Stone Zones, Artifact-Manuport Layers, and Biomantles Produced by Bioturbation Via Pocket Gophers (*Thomomys Bottae*). *American Antiquity* 54 (2): 370 – 389.
1990 Biomantle Evolution and the Redistribution of Earth Materials and Artifacts. *Soil Science* 149 (2): 84 – 102.
2002 Darwin Would Be Proud: Bioturbation, Dynamic Denudation, and the Power of Theory in Science. *Geoarchaeology: An International Journal* 17 (1): 7 – 40.

Johnson, D. L., Daniel R. Muhs, and Michael L. Barnhardt
1977 The Effects of Frost Heaving on Objects in Soils, II: Laboratory Experiments. *Plains Anthropologist* 22:133-147.

Johnson, D. L. and D. Watson-Stegner
1987 Evolution model of pedogenesis. *Soil Science* 143: 349 – 366.

Johnson, D. L., D. Watson-Stegner, D. N. Johnson, and R. J. Schaetzl
1987 Proisotropic and Proanisotropic Processes of Pedoturbation. *Soil Science* 143: 278 – 292.

Jones, Sian
1997 *The Archaeology of Ethnicity: Constructing Identities in the Past and Present*. Routledge, London.

Judson, Sheldon
1963 Erosion and Deposition of Italian Stream Valleys During Historic Time. *Science* 140: 898 – 899.

Kantner, John
2003 Biological Evolutionary Theory and Individual Decision-Making. In *Essential Tensions in Archaeological Method and Theory*, edited by Todd VanPool and Christine VanPool, pp. 67 – 88. University of Utah Press, Salt Lake City.
2004 Geographical approaches for reconstructing past human behavior from prehistoric roadways. In *Spatially Integrated Social Science: Examples in Best Practice*, edited by M. F. Goodchild and D. G. Janelle, pp. 323 – 344. Oxford University Press, Oxford.
2008 The Archaeology of Regions: From Discrete Analytical Toolkit to Ubiquitous Spatial Perspective. *Journal of Archaeological Research* 16: 37 – 81.

Kelley, J.H. and M.P. Hanen
1987 *Archaeology and the Methodology of Science*. University of New Mexico Press, Albuquerque.

Kemper, W., A. Nicks, and A. Corey
1994 Accumulation of Water in Soils Under Gravel and Sand Mulches. *Soil Science Society of America Journal* 58: 56 - 63.

Killick, David and Paul Goldberg
2009 A Quiet Crisis in American Archaeology. *The SAA Archaeological Record* 9 (1): 6 – 10, 40.

Kirkby, M. J., K. Atkinson and J. Lockwood
1990 Aspect, Vegetation Cover and Erosion on Semi-arid Hillslopes. In *Vegetation and Erosion: Processes and Environments* edited by J. B. Thornes. John Wiley and Sons, Ltd., Chichester. Pages 25 – 39.

Klemes, V.
1989 The Improbable Probabilities of Extreme Floods and Droughts. In *Hydrology of Disasters: proceedings of the technical conference in Geneva organized by the World Meteorological Organization, November 1988.* Edited by O. Starosolszky and O. M. Melder, pages 43 – 51. Earthscan, London.

Knox, Tom
2009 Do these mysterious stones mark the site of the Garden of Eden? *Mail Online* [online version of the *Daily Mail*]. Electronic document, http://www.dailymail.co.uk/sciencetech/article-1157784/Do-mysterious-stones-mark-site-Garden-Eden.html accessed January 2011.

Kristiansen, Kristian
1998a The formation of tribal systems in northern Europe, 4000 – 500 BC. In *Social Transformations in Archaeology: Global and Local Perspectives,* edited by Kristian Kristiansen and Michael Rowlands, pages 70 – 105. Routledge, Oxford.
1998b From stone to bronze: the evolution of social complexity in northern Europe, 2300 – 1200 BC. In *Social Transformations in Archaeology: Global and Local Perspectives,* edited by Kristian Kristiansen and Michael Rowlands, pages 106 – 141. Routledge, Oxford.
1998c The consumption of wealth in Bronze Age Denmark: a study in the dynamics of economic processes in tribal societies. In *Social Transformations in Archaeology: Global and Local Perspectives*, edited by Kristian Kristiansen and Michael Rowlands, pages 183 – 216. Routledge, Oxford.
1998d Chiefdoms, states and systems of social evolution. In *Social Transformations in Archaeology: Global and Local Perspectives*, edited by Kristian Kristiansen and Michael Rowlands, pages 243 – 267. Routledge, Oxford.

Kuhn, Thomas S.
1996 *The Structure of Scientific Revolutions.* Third edition. The University of Chicago Press, Chicago. Originally published 1962.

Lamb, H. H.
1965 The Early Medieval Warm Epoch and its Sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1: 13 – 37.
1995 *Climate, History and the Modern World (Second Edition).* Routledge, London.

Lambert, G., C. Lavier, and Y. Trenard
2008 *Bourgogne 29 Master Series*. In National Oceanic and Atmospheric Administration, Paleoclimatology Branch, WDC for Paleoclimatology, Tree Ring Data Search, International Tree Ring Data Bank. http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering Electronic Document, accessed September 2008.

Lamothe, M., S. Balescu, and M. Auclair
1994 Natural IRSL intensities and apparent luminescence ages of single feldspar grains extracted from partially bleached sediments. *Radiation Measurements* 23: 555 – 561.

Lança, Maria João
2002 Acções de Salvaguarda do Património Arqueológico da Albufeira de Alqueva. *Al-Madan*, second series, number 11: 66 - 73. Centro de Arqueología de Almada, Almada, Portugal.

Lancaster, Jane B.
1997 The Evolutionary History of Human Parental Investment in Relation to Population Growth and Social Stratification. In *Feminism and Evolutionary Biology: Boundaries, Intersections, and Frontiers* edited by P. Gowaty, pages 466 – 488. Chapman and Hall, International Thompson Publishing, New York.

Lang, A.
1994 Infra-Red Stimulated Luminescence Dating of Holocene Reworked Silty Sediments. *Quaternary Geochronology (Quaternary Science Reviews)* 13: 525 – 528.
2003 Phases of soil erosion-derived colluviation in the loess hills of South Germany. *Catena* 51: 209 – 221.

Lang, A. and G. Wagner
1996 Infrared Stimulated Luminescence Dating of Archaeosediments. *Archaeometry* 38 (1): 129 – 141.

Lansing, J. Stephen
2006 *Perfect Order: Recognizing Complexity in Bali.* Princeton University Press, Princeton, New Jersey.

Lansing, J. Stephen and James Kremer
1993 Emergent Properties of Balinese Water Temple Networks: Coadaptation on a Rugged Fitness Landscape. *American Anthropologist* 95 (1): 97 – 114.

LeBorgne, E.
1965 Les Propriétes Magnétiques du Sol. Application à la Prospection des Sites Archéologiques. *Archaeo-Physika* 1: 1 – 20.

Leonard, Robert
2001 Evolutionary Archaeology. In *Archaeological Theory Today*, edited by Ian Hodder, pages 65 – 97. Polity Press, Cambridge.

Leone, M., P. Potter and P. Shackel
1987 Toward a Critical Archaeology. *Current Anthropology* 28 (3): 283 – 301

Leone, Mark and Parker Potter
1996 Archaeological Annapolis: A Guide to Seeing and Understanding Three Centuries of Change. In *Contemporary Archaeology in Theory: A Reader*, ed. R. Preucel and I. Hodder, 570 – 598. Blackwell Publishing, New York.

Leopold, Luna
1976 Reversal of erosion cycle and climate change. *Quaternary Research* 6: 557 – 562.

Levin, M.
1973 On Explanation in Archaeology: A Rebuttal to Fritz and Plog. *American Antiquity* 38: 387 – 395.

Lewis, David Levering
2008 *God's Crucible: Islam and the Making of Europe, 570 – 1215.* W.W. Norton, New York.

Lian, O., D. Huntley and S. Wolfe
2002 Optical Dating of Eolian Dune Sand from the Canadian Prairies. *Géographie physique et Quaternaire* 56 (2-3): 191 – 202.

Lian, Olav and Richard Roberts
2006 Dating the Quaternary: progress in luminescence dating of sediments. *Quaternary Science Reviews* 25: 2449 – 2468.

Lillios, Katina T.
1997 Amphibolite tools of the Portuguese Copper Age (3000 – 2000 B.C.): A geoarchaeological approach to prehistoric economics and symbolism. *Geoarchaeology: An International Journal* 12 (2): 137 – 163.

Lopes, Virgílio
2003 *Mértola na Antiguidade Tardia: a topografia histórica da cidade e do seu território nos alvores do cristianismo.* Campo Arqueológico de Mértola, Mértola, Portugal.

Love, David
1983 Summary of the Late Cenozoic Geomorphic and Depositional History of Chaco Canyon. In *Chaco Canyon Country*, edited by S. Wells, D. Love, and T. Love, D. Gardner, pp. 187 – 194. American Geomorphical Field Group, Adobe Press, Albuquerque, New Mexico.

Lowdermilk, W. C.
1953 *Conquest of the Land through 7,000 Years.* Agriculture Information Bulletin No. 99, United States Department of Agriculture, Washington, D.C.

Lucas, Gavin
2008 Time and the Archaeological Event. *Cambridge Archaeological Journal* 18 (1): 59 – 65.

Lundquist, Lance
2005 *McEuen Cave Lithic Artifacts and the Transition to Agriculture in Southeastern Arizona.* Paper presented at the 70th Annual Meeting of the Society for American Archaeology, Salt Lake City, Utah.

Machette, M.N.
1985 Calcic Soils of the Southwestern United States. *Geological Society of America, Special Paper 203*. pp. 1 – 21.

Macias, Santiago
2007 *Mértola, O Último Porto do Mediterrâneo*. Annotated museum exhibit at the Centro de Estudos Islâmicos e do Mediterrâneo, Mértola, Portugal.
1993 O Gharb al-Andalus: Resenha dos factos políticos. In *História de Portugal*, Vol. 1, *Antes de Portugal.* Edited by J. Mattoso. Editorial Estampa, Lisbon.

Marcus, Joyce and Gary Feinman
1998 Introduction. In *Archaic States*, edited by G. Feinman and J. Marcus, pages 3 – 13. School of American Research Press, Santa Fe, New Mexico.

Matthiesen, Diana G.

1988 Preceramic Animal Use at Huaca Prieta. In *Economic Prehistory of the Central Andes*. Edited by Elizabeth Wing and Jane Wheeler, pp. 18 – 31, Oxford.

Mattoso, José
2001 No 850º aniversário da conquista de Lisboa. *Arqueologia Medieval* 7: 11 – 14. Campo Arqueologico de Mértola, Mértola, Portugal

McAuliffe, J., P. Sundt, A. Valiente-Banuet, A. Casas and J. Viveros
2001 Pre-columbian soil erosion, persistent ecological changes, and collapse of a subsistence agricultural economy in the semi-arid Tehacán Valley, Mexico's 'Cradle of Maize'. *Journal of Arid Environments* 47: 47 – 75.

McClure, S., M.A. Jochim, and C. M. Barton
2006 Human behavioral ecology, domestic animals, and land use during the transition to agriculture in Valencia, eastern Spain. In *Behavioral Ecology and the Transition to Agriculture* edited by D. Kennett and B. Winterhalder, pages 358 - 390. University of California Press, Berkeley.

McDonald, E. and L. McFadden
1994 Quaternary Stratigraphy of the Providence Mountains Piedmont and Preliminary Age Estimates and Regional Stratigraphic Correlations of Quaternary Deposits in the Eastern Mojave Desert, California. *G.S.A. Cordilleran Section Guidebook: Geological Investigations of an Active Margin, Trip 8:* 205 – 210.

McFadden, Leslie, Stephen Wells and Jerry Schultz
1983 Soil Development on Late Quaternary Eolian Deposits, San Juan Basin, New Mexico. In *Chaco Canyon Country*, edited by S. Wells, D. Love, and T. Gardner, pp. 167 – 175. American Geomorphical Field Group, Adobe Press, Albuquerque, New Mexico.

McFadden, L. and J. McAuliffe
1997 Lithologically influenced geomorphic responses to Holocene climatic changes in the Southern Colorado Plateau, Arizona: A soil-geomorphic and ecologic perspective. *Geomorphology* 19: 303-332.

McGovern, Thomas H.
1994 Management for Extinction in Norse Greenland. In *Historical Ecology: Cultural Knowledge and Changing Landscapes*, edited by C. Crumley, pages 127 – 154. School of American Research Press, Santa Fe, New Mexico.

McGuire, Kelly and William R. Hildebrandt
2005 Re-thinking Great Basin foragers: prestige hunting and costly signaling during the Middle Archaic period. *American Antiquity* 70 (4): 695 – 712.
2007 Costly signaling and the ascendance of no-can-do archaeology: a reply to Codding and Jones. *American Antiquity* 72 (2): 358 – 365.

McGuire, Randall H.
1993 Archaeology and Marxism. In *Archaeological Method and Theory, Volume 5*, edited by M. B. Schiffer, pages 101 – 139. The University of Arizona Press, Tucson.
2008 *Archaeology as Political Action.* University of California Press, Berkeley.

McMillan, Garnett P.
1997 A preliminary analysis of the Paleo-Christian and Islamic cemeteries of Rossio do Carmo, Mértola, Portugal. *Arqueología Medieval* 5: 15 – 22.

McMillan, Garnett and James Boone
1999 Population History and the Islamization of the Iberian Peninsula: Skeletal Evidence from the Lower Alentejo, Portugal. *Current Anthropology* 40 (5): 719 – 726.

Montgomery, David R.
2007 *Dirt: The Erosion of Civilizations.* University of California Press, Berkeley.

Moran, Emilio
2004 The Challenge of Scalability. In *The Archaeology of Global Change*, edited by C. Redman, S. James, P. Fish and D. Rogers, pages 278 – 284. Smithsonian Institution, Washington, D.C.

Morris, Ian
2000 *Archaeology as Cultural History: Words and Things in Iron Age Greece*. Blackwell Publishers, Malden, Massachusetts.

Morrison, Kathleen
1994 Intensification of production: Archaeological approaches. *Journal of Archaeological Method and Theory* 1 (2): 111 – 159.
1996 Typological Schemes and Agricultural Change: Beyond Boserup in Precolonial South India. *Current Anthropology* 37 (4): 583 – 608.
2006 Failure and how to avoid it. *Nature* 440: 752 – 754.

Moseley, Michael
1992 *The Incas and Their Ancestors: The Archaeology of Peru*. Thames and Hudson, London.

Munsell
1994 *Munsell Soil Color Charts*. Munsell Color, Macbeth Division of Kollmorgen Instruments Corporation, New Windsor, New York.

Munson, H.
1989 On the Irrelevance of the Segmentary Lineage Model in the Moroccan Rif. *American Anthropologist* 91: 386 – 400.

Murray, A.S. and V. Mejdahl
1999 Comparison of regenerative-dose single aliquot and multi-aliquot (SARA) protocols using heated quartz from archaeological sites. *Quaternary Geochronology (Quaternary Science Reviews)* 18: 223 – 229.

Murray, A.S. and R.G. Roberts
1997 Determining the burial time of single grains of quartz using optically stimulated luminescence. *Earth and Planetary Science Letters* 152: 163 – 180.
1998 Measurements of the equivalent dose in quartz using a regenerative-dose single-aliquot protocol. *Radiation Measurements* 29: 503 – 515.

Murray A.S. and A.G. Wintle
2000 Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* 32: 57 – 73.

Netting, Robert
1986 *Cultural Ecology* (second edition). Waveland Press, Prospect Heights, Illinois.
1993 *Smallholders, Householders: Farm Families and the Ecology of Intensive, Sustainable Agriculture.* Stanford University Press, Stanford.

Nials, F., D. Gregory and D. Graybill
1989 Salt River Streamflow and Hohokam Irrigation Systems. In *The 1982 – 1984 Excavations at Las Colinas: Environment and Subsistence*, edited by D. Graybill, D. Gregory, F. Nials, S. Fish, C. Miksicek, R. Gasser and C. Szuter, pp. 59 – 76. Archaeological Series 162, Volume 5, Arizona State Museum, University of Arizona, Tucson.

NOAA
2008 National Oceanic and Atmospheric Administration, Paleoclimatology Branch, WDC for Paleoclimatology, Tree Ring Data Search, International Tree Ring Data Bank. http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering Electronic Document, accessed September 2008.

Oliveira, J. T.
1989 *Carta Geológica do Sul de Portugal*, Lisbon.

Olley. J., T. Pietsch and R. Roberts
2004 Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz. *Geomorphology* 60: 337 – 358.

Ostrom, Elinor
1990 *Governing the Commons: The Evolution of Institutions for Collective Action.* Cambridge University Press, Cambridge.

Paine, Richard R. (editor)
1997 *Integrating Archaeological Demography: Multidisciplinary Approaches to Prehistoric Population.* Occasional Paper No. 24, Center for Archaeological Investigations, Southern Illinois University, Carbondale.

Parker Pearson, Michael
1984 Economic and Ideological Change: Cyclical growth in the pre-state societies of Jutland. In *Ideology, Power and Prehistory* ed. D. Miller and C. Tilley, pages 69 – 92. Cambridge University Press, Cambridge.

Parsons, Anthony J, John Wainwright, D. Mark Powell, Jorg Kaduk and Richard E. Brazier
2004 A Conceptual Model for Determining Soil Erosion by Water. *Earth Surface Processes and Landforms* 29: 1293 – 1302.

Patton, P. and S. Schumm
1981 Ephemeral-stream processes: implications for studies of Quaternary valley fills. *Quaternary Research* 15: 24 – 43.

Pauketat, Timothy R.
2003 Resettled Farmers and the Making of a Mississippian Polity. *American Antiquity* 68 (1): 39 – 66.

Paulson, Susan, Lisa L. Gezon and Michael Watts
2003 Locating the Political in Political Ecology: An Introduction. *Human Organization* 62 (3): 205 – 217.

Peacock, Evan and David Fant
2002 Biomantle Formation and Artifact Translocation in Upland Sandy Soils: An Example from the Holly Springs national Forest, North-Central Mississippi, U.S.A. *Geoarchaeology: An International Journal* 17 (1): 91 – 114.

Pederson, J., G. Smith and F. Pazzaglia
2001 Comparing the modern, Quaternary, and Neogene records of climate-controlled hillslope sedimentation in southeast Nevada. *GSA Bulletin* 113 (3): 305 – 319.

Peregrine, Peter

2000 Archaeology and World-Systems Theory. In *A World-Systems Reader: New Perspectives on Gender, Urbanism, Cultures, Indigenous Peoples, and Ecology* edited by Thomas Hall, pages 59 - 68. Rowman and Littlefield, Lanham, Maryland.

Peters, Emrys

1990 *The Bedouin of Cyrenaica: studies in personal and corporate power.* Edited by Jack Goody and Emanuel Marx. Cambridge University Press, Cambridge.

Phillips, David A., Jr.

2009 Adoption and Intensification of Agriculture in the North American Southwest: Notes Toward a Quantitative Approach. *American Antiquity* 74 (4): 691 – 707.

Pires de Oliveira, Eduardo

1984 *Bibliografia Arqueológica Portuguesa (1935 – 1969).* Instituto Portugués do Património Cultural, Departamento de Arqueologia, Lisboa (Lisbon).

1985 *Bibliografia Arqueológica Portuguesa (1969 – 1979).* Instituto Portugués do Património Cultural, Departamento de Arqueologia, Lisboa (Lisbon).

Plog, F.

1973 Laws, Systems of Law, and the Explanation of Observed Variation. In *The Explanation of Culture Change: Models in Prehistory*, edited by C. Renfrew, pp. 649 – 661. University of Pittsburgh Press, Pittsburgh.

Poesen, J.

1986 Surface Sealing as Influenced by Slope Angle and Position of Simulated Stones in the Top Layer of Loose Sediments. *Earth Processes and Landforms* 11: 1 – 10.

Poesen, J., F. Ingelmo-Sanches, and H. Mucher

1990 The Hydrological Response of Soil Surfaces to Rainfall as Affected by Cover and Position of Rock Fragements in the Top Layer. *Earth Processes and Landforms* 15: 653 – 671.

Ponting, Clive

2007 *A New Green History of the World.* Penguin Books, New York.

Pope, K.O. and T.H. van Andel

1984 Late Quaternary alluviation and soil formation in the southern Argolid. *Journal of Archaeological Science* 11: 281-306.

Potter, T.W.
1976 Valleys and settlement: some new evidence. *World Archaeology* 8: 207-219.

Prescott, J.R. and J.T. Hutton
1994 Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation Measurements* 23: 497 – 500.

Pyne, Stephen J.
1998 Forged in Fire: History, Land and Anthropogenic Fire. In *Advances in Historical Ecology* edited by William Balée, pages 64 – 103. Columbia University Press, New York.

Quilter, Jeffry
1989 *Life and Death at Paloma*. University of Iowa Press, Iowa City.

Ramenofsky, Ann
1998 The Illusion of Time. In *Unit Issues in Archaeology: Measuring Time, Space, and Material* edited by A. Ramenofsky and A. Steffen, pages 74 – 84. Foundations of Archaeological Inquiry series, The University of Utah Press, Salt Lake City.

Rapp, George and Christopher Hill
1998 *Geoarchaeology: The Earth-Science Approach to Archaeological Interpretation*. Yale University Press, New Haven.

Redman, Charles
1999 *Human Impact on Ancient Environments*. University of Arizona Press, Tucson.
2005 Resilience Theory in Archaeology. *American Anthropologist* 107 (1): 70 – 77.

Redman, C., S. James, P. Fish and D. Rogers (editors)
2004 *The Archaeology of Global Change.* Smithsonian Institution, Washington, D.C.

Rees, William
1996 Revisiting Carrying Capacity: Area-Based Indicators of Sustainability. *Population and Environment* 17 (3): 195 – 215.

Rei, António
2003 A fronteira no Sudoeste Peninsular (1234 – 1242). Novas visões da "Reconquista" a partir do al-Mughrib... de Ibn Sa'îd de Granada. *Arqueologia Medieval* 8: 29 – 42. Campo Arqueológico de Mértola, Mértola, Portugal.

Reitz, Elizabeth J. and Elizabeth S. Wing
1999 *Zooarchaeology*. Cambridge Manuals in Archaeology, Cambridge University Press, Cambridge.

Renfrew, Colin and Paul Bahn
2000 *Archaeology: theories, methods, and practice.* 3rd Edition. Thames and Hudson, New York.

Retuerce Velasco, Manuel
1998 *La cerámica andalusí de la Meseta, Vol. 1 & 2.* Colección Cran Estudios. CRAN, Madrid.

Reynolds, Paul
1993 *Settlement and pottery in the Vinalopó valley (Alicante, Spain) A.D. 400 – 700.* Tempvs Reparatvm: Oxford.

Ritter, D.F., Kochel, R.C., and Miller, J.R.
1995 *Process Geomorphology* (third edition). Boston, Mass: WCB McGraw-Hill.

Robbins, Paul
2004 *Political Ecology: A Critical Introduction.* Wiley-Blackwell, Hoboken, New Jersey.

Roberts, Alexandra
1992 *An Archaeological and Ethnohistorical Investigation of Restricted Mobility Among Navajo Families in the Wupatki Basin, Arizona.* Unpublished Ph.D. dissertation, Department of Anthropology, University of New Mexico.

Roberts, Richard G.
1997 Luminescence dating in archaeology: from origins to optical. *Radiation Measurements* 27: 819 – 892.

Romero, Federico Hita
2003 En busca de nuestra Historia. In *Las lámparas de Medina Elvira*, C. Vílchez Vílchez (coordinador), page 9. Mueso Arqueológico y Etnológico de Granada, Granada, Spain.

Rosen, L.
1979 Social Identity and Points of Attachment: Approaches to Social Organization. In *Meaning and Order in Moroccan Society*. Edited by Clifford Geertz. Cambridge University Press, Cambridge.

Rosselló, Guillermo
1978 *Ensayo de sistematización de la cerámica árabe de Mallorca.* Palma de Mallorca, Mallorca, Spain.

Rowley-Conwy, Peter
1983 Sedentary Hunters: the Ertebolle Example. In *Hunter – Gatherer Economy in Prehistory*. Edited by G. Bailey, Cambridge University Press, Cambridge.

Roxo, M. J., and Cortisão Casimiro
1998 Human impact on land degradation in the inner Alentejo, Mértola, Portugal. In *Atlas of Mediterranean Environments in Europe: the desertification context.* Edited by P. Mariota, J. B. Thornes, and N. Geeson. Wiley, Chichester.

Sahlins, M. D. and E. R. Service
1960 *Evolution and Culture.* University of Michigan Press, Ann Arbor.

Salgueiro Navarro, José Antonio Pedroso
1987 Resenha Histórica da Estrutura Agrária Alentejana. In *II Congresso Sobre o Alentejano Semeando Novos Rumos*, pp. 65 – 69. Edição da Associação de Municípios do Distrito de Beja, Beja, Portugal.

Salmon, M.
1976 "Deductive" versus "Inductive" Archaeology. *American Antiquity* 41: 376 – 381.

Sanders, W., J. Parsons and R. Santley
1979 *The Basin of Mexico: Ecological Processes in the Evolution of a Civilization.* Academic Press, New York.

Sanders, W., and D. Webster
1978 Unilinealism, Multilinealism, and the Evolution of Complex Societies. In *Social Archeology: Beyond Subsistence and Dating*. Edited by C. Redman, M. Berman, E. Curtin, W. Langhorne, Jr., M. Versaggi and J. Wanser, pp. 249 – 301. Academic Press, New York.

Sandford, Mary K.
1993 Understanding the Biogenic – Diagenetic Continuum: Interpreting Elemental Concentrations of Archaeological Bone. In *Investigations of Ancient Human Tissue: Chemical Analyses in Anthropology.* Food and Nutrition in History and Anthropology, Volume 10. Edited by M. K. Sandford. Gordon and Breach Science Publisherrs. Langhorne, Pennsylvania. Pages 3 – 57.

Sandor, J., J. Norton, J. Homburg, D. Muenchrath, C. White, S. Williams, C. Havener, and P. Stahl

2007 Biogeochemical Studies of a Native American Runoff Agroecosystem. *Geoarchaeology: An International Journal.* 22 (3): 359 – 386.

Schiffer, Michael B.

1972 Archaeological Context and Systemic Context. *American Antiquity* 37: 156 – 165.

1975 Archaeology as Behavioral Science. *American Anthropologist* 77 (4): 836 – 848

1987 *Formation Processes of the Archaeological Record.* University of New Mexico Press, Albuquerque.

Schoeneberger, P. J., D. A. Wysocki, E. C. Benham, and W. D. Broderson (editors)

2002 *Field Book for Describing and Sampling Soils, Version 2.0.* Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.

Schumm, S. A., and R. S. Parker

1973 Implications of Complex Response of Drainage Systems for Quaternary Alluvial Stratigraphy. *Nature: Physical Science* 243 (128): 99 – 100.

Schumm, S. A.

1977 *The Fluvial System.* John Willey and Sons, New York.

Scott, James C.

1998 *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed.* Yale University Press, New Haven, Connecticut.

Selby, M.J.

1993 *Hillslope Materials and Processes* (second edition). Oxford University Press, Oxford.

Serre-Bachet, F.

2008 *Les Merveilles Mixed Source (Live and Dead) Series.* In National Oceanic and Atmospheric Administration, Paleoclimatology Branch, WDC for Paleoclimatology, Tree Ring Data Search, International Tree Ring Data Bank. http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering Electronic Document, accessed September 2008.

Service, E.R.

1962 *Primitive Social Organization: An Evolutionary Perspective.* Random House, New York.

Shanks, Michael and Chris Tilley
1987 *Re-Constructing Archaeology*. Cambridge University Press, Cambridge

Shennan, Stephen
1996 Cultural Transmission and Cultural Change. In *Contemporary Archaeology in Theory: A Reader,* ed. R. Preucel and I. Hodder, 282 – 296. Blackwell Publishing, New York.

Simonson, R. W.
1978 A multiple-process model of soil genesis. In *Quaternary Soils*, edited by W. C. Mahaney, pages 1 – 25. Geo Abstracts, University of East Anglia, Norwich, England.

Soil Survey Staff
1975 *Soil Taxonomy*. US Department of Agriculture Handbook 436. US Government Printing Office, Washington, D.C.
1993 *Soil Survey Manual*. U.S. Department of Agriculture Handbook No. 18. US Government Printing Office, Washington, D.C.
1999 *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys.* Second Edition. U.S. Department of Agriculture Handbook 436. U.S. Government Printing Office, Washington, D.C.

SRAO (Seviço de Reconhecimento e de Ordanamento Agrario, Ministero da Economia)
1959 *Carta dos Solos de Portugal*. Litografia Esperança, Lisboa, Portugal.

Steckel, Richard H.
2004 New Light on the Dark Ages: The Remarkably Tall Stature of Northern European Men during the Medieval Era. *Social Science History* 28 (2): 211 – 228.

Stein, Julie K.
1983 Earthworm Activity: A Source of Potential Disturbance of Archaeological Sediments. *American Antiquity* 48 (2): 277 – 289.

Stein, Julie and William Farrand
2001 *Sediments in Archaeological Context*. University of Utah Press, Salt Lake City.

Stevenson, A.C. and R.J. Harrison
1992 Ancient forest in Spain: a model for land-use and dry forest management in south-west Spain from 4000BC to 1900 AD. *Proceedings of the Prehistoric Society* 58: 227 – 247.

Stiner, Mary C., Natalie D. Munro, and Todd A. Surovell
2000 The Tortoise and the Hare: Small-Game Use, the Broad-Spectrum Revolution, and Paleolithic Demography. *Current Anthropology* 41 (1): 39 – 59.

Stockton, C. W.
1975 *Long term Streamflow Records Reconstructed from Tree Rings.* Paper 5, Laboratory for Tree Ring Research. University of Arizona Press, Tucson.

Stokes, S.
1999 Luminescence dating applications in geomorphological research. *Geomorphology* 29: 153 – 171.

Stokes, S. and C. Breed
1993 A chronostratigraphic re-evaluation of the Tusayan Dunes, Moenkopi Plateau and southern Ward Terrace, Northeastern Arizona. In *The Dynamics and Environmental Context of Aeolian Sedimentary Systems* edited by K. Pye, Geological Society Special Publication No. 72: 75 – 90.

Stokes, S. and D. Gaylord
1993 Optical Dating of Holocene Dune Sands in the Ferris Dune Field, Wyoming. *Quaternary Research* 39: 274 – 281.

Stone, Glenn
1996 *Settlement Ecology: The Social and Spatial Organization of Kofyar Agriculture*. University of Arizona Press, Tucson.

Stone, G. and C. Downum
1999 Non-Boserupian Ecology and Agricultural Risk: Ethnic Politics and Land Control in the Arid Southwest. *American Anthropologist* 101: 113 – 128.

Straus, Lawrence G.
1992 L'Abbé Henri Breuil: Archaeologist. *Bulletin of the History of Archaeology* 2 (1): 5 – 9.
1994 The Abbé Henri Breuil: Pope of Paleolithic Prehistory. *Monografías, Museo y Centro de Investigación de Altamira*, 17: 189 – 198. Santander, Spain.

Straussfogel, Debra
2000 World-Systems Theory in the Context of Systems Theory: An Overview. In *A World- Systems Reader: New Perspectives on Gender, Urbanism, Cultures, Indigenous Peoples and Ecology*, edited by Thomas Hall, pages 169 – 180. Rowman and Littlefield, Lanham, Maryland.

Stuiver, Minze, and Paula J. Reimer
1993 Extended 14C Database and Revised CALIB Radiocarbon Calibration Program. *Radiocarbon* 35: 215 – 230.

Sullivan III, Alan P., Philip B. Mink, II and Patrick M. Uphus
2007 Archaeological Survey Design, Units of Observation, and the Characterization of Regional Variability. *American Antiquity* 72 (2): 322 – 333.

Suttles, Wayne
1991 Streams of Property, Armor of Wealth: The Traditional Kwakiutl Potlatch. In *Chiefly Feasts: The Enduring Kwakiutl Potlatch*. Edited by Aldona Jonaitis. pp. 71 – 134, University of Washington Press, Seattle.

SWAI
2010 *Swiss World Atlas Interactive Version 1.0.1*. Electronic document, http://karswa.ethz.ch/java/atlas_version_1/SWA_en.jnlp, accessed February 2011.

Tainter, Joseph
2006 Archaeology of Overshoot and Collapse. *Annual Review of Anthropology* 35: 59 – 74.
1988 *The Collapse of Complex Societies*. Cambridge University Press, Cambridge.

Thomas, D. H., and R. Kelly
2006 *Archaeology*. *Fourth Edition.* Thompson Wadsworth, Belmont, California.

Thomas, David H.
1975 Nonsite Sampling in Archaeology: Up the Creek Without a Site? In *Sampling in Archaeology*, edited by James W. Mueller, pages 61 – 81. University of Arizona Press, Tucson.

Thompson, R., J. Bloemendal, J. Dearing, F. Oldfield, T. Rummery, J. Stober, G. Turner
1980 Environmental Applications of Magnetic Measurements. *Science* 207 (4430): 481 – 486.

Thompson, Roy and Frank Oldfield
1986 *Environmental Magnetism*. Allen and Unwin, London

Thorndycraft, V. R., and G. Benito
2006 Late Holocene fluvial chronology of Spain: The role of climatic variability and human impact. *Catena* 66: 34 – 41.

Thornes, J.B.
1987 The Palaeo-ecology of Erosion. In *Landscape and Culture: Geographical and Archaeological Perspectives.* Edited by J. M. Wagstaff. Basil Blackwell, New York. 37 – 55.

Thornes, J.B. (editor)
1990 *Vegetation and Erosion: Processes and Environments*. John Wiley and Sons, Chichester, England.

Thornes, J. and A. Gilman
1983 Potential and Actual Erosion Around Archaeological Sites in South East Spain. *Catena Supplement 4*: 91 – 113.

Tillery, Anne, P. Fawcett, L. McFadden, L. Scuderi and J. McAuliffe
2003 Late Holocene behavior of small drainage basins on the Colorado Plateau: Influences of lithology, basin form, and climate change. In *New Mexico Geological Society Guidebook, 54th Field Conference, Geology of the Zuni Plateau*. Edited by S. Lucas, S. Semken, W. Berglof, and D. Ulmer-Scholle. New Mexico Geological Society, Socorro. Pages 197-207

Tilley, Christopher
1996 *An Ethnography of the Neolithic.* Cambridge University Press, Cambridge.

Tite, M. S. and C. Mullins
1971 Enhancement of the Magnetic Susceptibility of Soils on Archaeological Sites. *Archaeometry* 13: 209 – 219.

Torres, Cláudio
1987 *Cerâmica islâmica Portuguesa, Exposição*. Fundação Calouste Gulbenkian, Lisbon. (rept. 1987, Campo Arqueológico de Mértola, Mértola, Portugal.)

Torres, Cláudio, Susana Gómez and Manuela Barros Ferreira
2003 Os nomes da cerâmica medieval. Inventário de termos. *Actas das Tercas Jornadas de Cerâmica Medieval e Pós-Medieval*, pages 125 – 134.

Torres, Cláudio and Santiago Macias
n.d. *Para Compreender o Islão: Edição Especial para livraria, que inclui O Legado Islâmico em Portugal.* Publicações e Conteúdos Multimédia, Lda., Lisboa. (*O Legado Islâmico em Portugal* originally published 1998, Círculo de Leitores, Lisbon.)

Toubert, Pierre
1990 *Castillos, Señores y Campesinos en la Italia Medieval.* Editorial Crítica, Barcelona.

Trigger, Bruce

1989 *A History of Archaeological Thought.* Cambridge University Press, Cambridge.

1990 Monumental Architecture: A Thermodynamic Explanation of Symbolic Behaviour. *World Archaeology* 22 (2): 119 – 132.

1995 Romanticism, Nationalism, and Archaeology. in *Nationalism, Politics, and the Practice of Archaeology,* edited by P. Kohl and C. Fawcett, pages 263 - 279. Cambridge University Press, Cambridge.

1996 Alternative Archaeologies: Nationalist, Colonialist, Imperialist. In *Contemporary Archaeology in Theory, A Reader*, edited by R. Preucel and I. Hodder, pages 615 – 631. Blackwell Publishing, Malden, Massachusetts.

2006 *A History of Archaeological Thought, Second Edition.* Cambridge University Press, New York.

Tuggle, H. D., A. Townsend, and T. Riley

1972 Laws, Systems, and Research Designs: A Discussion of Explanation in Archaeology. *American Antiquity* 37: 3 – 12.

Twining, A. C.

1833 On the growth of timber. *American Journal of Science and Arts* 24: 391 – 393.

Uribelarrea, David and Gerardo Benito

2008 Fluvial changes of the Guadalquivir river during the Holocene in Córdoba (Southern Spain). *Geomorphology* 100: 14 – 31.

Vakil, Abdoolkarim

2003 From the *Reconquista* to *Portugal Islâmico*: Islamic Heritage in the Shifting Discourses of Portuguese Historiography and National Identity. *Arqueologia Medieval* 8: 5 – 15. Campo Arqueologico de Mértola, Mértola, Portugal.

Valdés, Fernando and Susana Díaz

2002 El Castillo de Cuncos: una ciudad islámica desconocida en la raya hispano-portuguesa. *Al-Madan*, second series, number 11: 213 – 218. Centro de Arqueología de Almada, Almada, Portugal.

van Andel, Tjeerd

1986 Five thousand years of land use and abuse in the southern Argolid, Greece. *Hesperia* 55:103-128.

van Andel, T.H., E. Zangger and A. Demitrack

1990 Land Use and Soil Erosion in Prehistoric and Historical Greece. *Journal of Field Archaeology* 17: 379 – 396.

van den Brink, L. M. and C. R. Janssen
1985 The effect of human activities during cultural phases on the development of montane vegetation in the Serra da Estrela, Portugal. *Review of Palaeobotany and Palynology* 44: 193 – 215.

van der Knaap, W. O. and J. F. N. van Leeuwen
1995 Holocene vegetation succession and degradation as responses to climatic change and human activity in the Serra da Estrela, Portugal. *Review of Palaeobotany and Palynology* 89: 153 – 211.

van der Leeuw, Sander
2000 Desertification, Land Degradation and Land Abandonment in the Rhone Valley, France. in *The Archaeology of Drylands: Living at the Margin.* ed. G. Barker and D. Gilbertson. Routledge, London.

van der Leeuw, Sander and Charles Redman
2002 Placing Archaeology at the Center of Socio-Natural Studies. *American Antiquity* 67 (4): 597 – 605.

van der Schriek, T., D. Passmore, J. Rolão and A. Stevenson
2007 Estuarine-fluvial floodplain formation in the Holocene Lower Tagus valley (Central Portugal) and implications for Quaternary fluvial system evolution. *Quaternary Science Reviews* 26 (22 – 24): 2937 – 2957.

VanPool, Christine and Todd VanPool
1999 The Scientific Nature of Postprocessualism. *American Antiquity* 64 (1): 33 – 53.

Vayda, Andrew (editor)
1969 *Environment and Cultural Behavior: Ecological Studies in Cultural Anthropology.* University of Texas Press, Austin.

Veblen, Thorstein
2007 *The Theory of the Leisure Class.* Oxford University Press, Oxford. Reprint, originally published 1899.

Vega, Sebastião Phillipes Martins Estacio da
1983 *Memórias das Antiguidades de Mértola.* Reproduction by Câmara Municipal de Mértola, original published 1880, Imprensa Nacional – Casa da Moeda.

Verosub, Kenneth and Andrew Roberts
1995 Environmental Magnetism: Past, present, and future. *Journal of Geophysical Research* 100 (B2): 2175 - 2192

Vílchez Vílchez, Carlos (coordinador)
2003 *Las lámparas de Medina Elvira.* Mueso Arqueológico y Etnológico de Granada, Granada, Spain.

Vis, Geert-Jan, Cornelis Kasse, and Jef Vandenberghe
2008 Late Pleistocene and Holocene palaeogeography of the Lower Tagus Valley (Portugal): effects of relative sea level, valley morphology and sediment supply. Q*uaternary Science Reviews* 27: 1682 – 1709.

Vita-Finzi, Claudio
1969 *The Mediterranean Valleys: Geological Changes in Historical Times*. Cambridge University Press, London.
1976 Diachronism in Old World alluvial sequences. *Nature* 263:218-219.

Vivian, R. Gwynn
1974 Conservation and Diversion: Water-control systems in the Anasazi southwest. In *Irrigation's Impact on Society,* edited by T. E. Downing and M. Gibson, pp. 95-112. Anthropological Papers of the University of Arizona no. 25, Tucson.

Vivian, R. G., C. R. Van West, J. S. Dean, N. J. Akins, M. S. Toll, and T. C. Windes
2006 Ecology and Economy. In *The Archaeology of Chaco Canyon, An Eleventh-Century Pueblo Regional Center,* edited by S. Lekson, pp. 45 – 65. School of American Research Press, Santa Fe, New Mexico.

Wagner, Gunther
1998 *Age Determination of Young Rocks and Artifacts: Physical and Chemical Clocks in Quaternary Geology and Archaeology.* Springer, Berlin.

Wainwright, John
1994 Anthropogenic Factors in the Degradation of Semi-arid Regions: A Prehistoric Case Study in Southern France. in *Environmental Change in Drylands: biogeographical and geomorphological perspectives.* Ed. A. Millington and K. Pye, J. Willey and Sons, New York. 285 – 304.

Walker, Paul
2005 Political ecology: where is the ecology? *Progress in Human Geography* 29 (1): 73 – 82.

Walker, Theodore, Brian Waugh, and Anthony Grone
1978 Diagenesis in first-cycle desert alluvium of Cenozoic age, southwestern United States and northwestern Mexico. *Geological Society of America Bulletin* 89: 19 – 32.

Wallerstein, Immanuel
1979 *The Capitalist World Economy*. Cambridge University Press, Cambridge.

1980 *The Modern World-System II: Mercantilism and the Consolidation of the European World-Economy, 1600 – 1750.* Academic Press, New York.

Wallinga, J.
2002 Optically stimulated luminescence dating of fluvial deposits: a review. *Boreas* 31: 303 – 322.

Wandsneider, LuAnn
1998 Regional Scale Processes and Archaeological Landscape Units. In *Units in Archaeology: Measuring Time, Space, and Material*, edited by Ann F. Ramenofsky and Anastasia Steffen, pp. 87-102. University of Utah Press, Salt Lake City.

Waters, Michael R.
1992 *Principles of Geoarchaeology: A North American Perspective*. University of Arizona Press, Tucson.

Watkins, Joe
2005 Through Wary Eyes: Indigenous Perspectives on Archaeology. *Annual Review of Anthropology* 34: 429 – 449.

Watson, P. J., S. Le Blanc, and R. Redman
1971 *Explanation in Archaeology: An Explicitly Scientific Approach*. Columbia University Press, New York.
1974 The Covering Law Model in Archaeology: Practical Uses and Formal Interpretations. *World Archaeology* 6: 125 – 132.
1984 *Archaeological Explanation: The Scientific Method in Archaeology*. Columbia University Press, New York.

White, Leslie A.
1959 *The Evolution of Culture: The Development of Civilization to the Fall of Rome.* McGraw-Hill, New York.

Wickham, Chris
1984 The Other Transition: From the Ancient World to Feudalism. *Past and Present* 103: 3 – 36.
1989 Italy and the Early Middle Ages. In *The Birth of Europe: Archaeology and Social Development in the First Millennium A.D.* Edited by Klaus Reandsborg. Roma: Analecta Romana Institui Danici Supplementum XVI.

Wilcox, Bradford P., David D. Breshears and Craig D. Allen
2003 Ecohydrology of a Resource-Conserving Semiarid Woodland: Effects of Scale and Disturbance. *Ecological Monographs* 73 (2): 223 – 239.

Willey, Gordon R.
1953 *Prehistoric Settlement Patterns in the Virú Valley, Perú*. Bureau of American Ethnology Bulletin No. 155. Smithsonian Institution, Washington, D.C.

Winterhalder, Bruce and Eric A. Smith
1981 *Hunter-Gatherer Foraging Strategies: Ethnographic and Archaeological Analyses*. The University of Chicago Press, Chicago.
2000 Analyzing adaptive strategies: human behavioral ecology at twenty-five. *Evolutionary Anthropology* 9(2): 51 – 72.

Wolf, Eric R.
1982 *Europe and the People Without History*. University of California Press, Berkeley.

WorldClimate
2008 http://www.worldclimate.com, Electronic Document, accessed September 2008.

Worman, Frederick C. V.
1969 *Archaeological Investigations at the U.S. Atomic Energy Commission's Nevada Test Site and Nuclear Rocket Development Station.* Los Alamos Scientific Laboratory publication LA-4125, United States Atomic Energy Commission Contract W-7405-ENG. 36. Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia.

Worman, F. Scott
2004 Geoarchaeological Investigations of Agricultural Features at LA 131821. In *Across the Caja del Rio Plateau II: Hunters and Farmers in the Northern Rio Grande*, edited by P. Gerow and A. Kurota, pp. 215 – 251. Office of Contract Archaeology, University of New Mexico, Albuquerque.
2008 Soils, Stratigraphy and Geomorphology. In *LA 134645: Excavations at an Agricultural Production Site on Albuquerque's West Mesa, Bernalillo County, New Mexico* edited by Robin M. Cordero. Office of Contract Archeology, University of New Mexico.

Worman, F. Scott and James Boone
2004 *Conquests and Landscapes: The Geoarchaeology of Islamic Period Southern Portugal*. Paper presented at the 69th Annual Meeting of the Society for American Archaeology, Montreal, Canada
2005 *Culture or Climate? Identifying Anthropogenic Environmental Change in Islamic Period Southern Portugal*. Paper presented at the 70th Annual Meeting of the Society for American Archaeology, Salt Lake City, Utah.

2006 *Take a Closer Look: New Evidence for Variation in Settlement and Land Use during the Islamic Period in Southern Portugal.* Paper presented at the 71st Annual Meeting of the Society for American Archaeology, San Juan, Puerto Rico.

Worman, F. Scott and Hannah V. Mattson

2010 Arroyos and Agriculture: Geoarchaeological Investigations at Pueblo Pintado. *The Kiva* 75.4: 447 – 482.

Worman, F. Scott, Christopher A. Turnbow, Yuichi Nakazawa, and Richard C. Chapman

2009 *Archaeological Data Recovery Program at LA 26917: VC02 (Road B) Mitigation, Valles Caldera National Preserve, New Mexico.* Office of Contract Archeology, University of New Mexico.

Wylie, Alison

2002 Introduction: Philosophy from the Ground Up. In *Thinking From Things: Essays in the Philosophy of Archaeology*, by Alison Wylie, pages 1 – 22. University of California Press, Berkeley.

Yair, Aaron

1994 The Ambiguous Impact of Climate Change at a Desert Fringe: Northern Negev, Israel. In *Environmental Change in Drylands: Biogeographical and Geomorphological Perspectives*, edited by A. Millington and K. Pye, pp. 199 – 228. John Willey and Sons, New York.

Zimmerer, Karl

2000 Rescaling Irrigation in Latin America: The Cultural Images and Political Ecology of Water Resources. *Ecumene* 7 (2): 150 – 175.

1993a Soil Erosion and Social (Dis)Courses in Cochabamba, Bolivia: Perceiving the Nature of Environmental Degradation. *Economic Geography* 69 (3): 312 – 327.

1993b Soil Erosion and Labor Shortages in the Andes With Special Reference to Bolivia, 1953 – 91: Implications for "Conservation-With-Development". *World Development* 21 (10): 1659 – 1675.

Zinn, Howard

1980 *A People's History of the United States*. Harper and Row, New York.

APPENDIX 1: SOIL DESCRIPTIONS

This appendix includes a "Key to Soil Descriptions" that provides simple definitions of the notation and terminology used in formal in-field pedostratigraphic recording. Profile descriptions of each fluvial study unit and soil test pit are then presented along with a brief narrative interpretation of the data. For units where the analyses were undertaken, the results of OSL and radiocarbon assays also are given. Graphs summarizing the mass corrected and averaged results of magnetic susceptibility measurements are presented with the description of each sampled profile. The complete magnetic susceptibility data are presented separately in Appendix 2 and the full OSL data are provided in Appendix 3.

Key to Soil Descriptions:

Horizon:

Horizon designations consist of a master horizon, given as a capital letter, and subordinate distinguishing modifiers, given as lower-case letters. Numbers indicate observed changes within a soil horizon. *N.B.: unlike other information recorded in the field and presented in the tables below, these are* ***interpretations*** *based on those data.*

Master horizons encountered in the study area include O, A, B, and C. O denotes an organic horizon, such as a layer of moss or leaf litter that has not been significantly altered by pedogenic processes. For the purposes of this research, it was not necessary to provide formal modifiers for organic layers and, where present, they are described in the notes. The A horizon is the uppermost layer of the mineral soil, usually enriched in organic carbon, and in which biotic processes are most significant. It is also a zone of eluviation, i.e. weathering products are removed from this horizon and translocated downwards through the soil profile. The B horizon is the zone of illuviation in which weathering products such as pedogenic clays accumulate when they are translocated downward from higher in the solum. C denotes unaltered or minimally altered parent material, usually decomposing bedrock or fluvial strata in the study area. Bedrock that has not weathered to loose sediment often is identified as R; here, resistant bedrock is simply noted and described as the base of the superjacent B or C horizon.

Subordinate distinguishing modifiers used here include p, t and b. p signifies a horizon that has been plowed. t denotes an accumulation of pedogenic clays and, by definition, is used to describe a B horizon (i.e., Bt). b indicates burial.

Numbers placed before the horizon designations indicate a different source of deposition (different parent material) for sediments that are affected by the same pedogenic processes and that are parts of the same soil horizon. Numbers after the designation indicate a change in observed characteristics within a horizon not related to deposition.

Mixing of two horizons where pockets of sediment originating in each remain identifiable is indicated by listing both horizons separated by a virgule, e.g. A/B. Where thorough mixing precludes distinguishing sediments originating in either horizon, both are listed, e.g., AB. Where one horizon's characteristics are dominant, it generally is listed first.[60]

In the case of *soil welding*, where one horizon is being transformed into another due to a change in conditions such as burial, two horizon designations are given separated by a greater than sign, e.g., AB>Bt2. The first designation refers to the origin or past state of

[60] Reflecting the historically agricultural orientation of soil science, most pedologists will list any plowed deposit as an Ap horizon regardless of whether the A horizon has been removed by erosion (Holliday 2004: 5). Because this research is focused on landscape change, the mixed nature of the plowed horizon is noted by identifying it as ABp where appropriate. In deference to tradition, A is listed first in all cases; the inferred relative contributions of each horizon's characteristics are provided in the notes.

the pedostratigraphic unit, the second to ongoing pedogenic processes. Where the origin or past state of the unit is difficult to identify with certainty, the first designation is given in parentheses.

An apostrophe after a horizon designation indicates continuation of a superjacent horizon after an interruption (interbedding), such as a horizon that includes A / C / 2C / C' horizons. This generally is present only in fluvial environments.

Depth:

By convention, depth is measured from the top of the mineral soil. Where an O horizon is present, its thickness is given as +n, and the depth of the A horizon will be 0 – n. All depth measurements given here are in centimeters.

Munsell Color:

Colors are estimated in the field by comparing sediments to a Munsell Soil Color Chart. All colors given here are for dry sediments, unless otherwise noted.

Structure:

Structure describes the physical characteristics of peds, natural soil aggregates. It is characterized according to type, size, and grade.

Type describes ped shape and is divided into 5 classes: granular, angular blocky, subangular blocky, prismatic, columnar, and platy. The class designations are self-explanatory.

Size also is divided into five classes, from very fine to very coarse:
Very fine..... granules or plates < 1 mm, blocks < 5 mm, prisms <10 mm.
Fine..... granules or plates 1 – 2 mm, blocks 5 – 10 mm, prisms 10 – 20 mm.
Medium..... granules or plates 2 – 5 mm, blocks 10 – 20 mm, prisms 20 – 50 mm.
Coarse..... granules or plates 5 – 10 mm, blocks 20 – 50 mm, prisms 50 – 100 mm.
Very coarse..... all peds larger than the coarse category.

Grade describes the distinctness of peds and the degree of structural development:
Single grain..... no aggregation, dry sediments do not hold a face.
Massive..... enough aggregation to hold a face, but no discernible ped structure.
Weak..... peds are barely observable in place. Most of the material is unaggregated and few entire peds remain intact when the stratum is disturbed.
Moderate..... peds are observable but not distinct in place. Many entire peds can be separated mechanically from the horizon.

Strong..... peds are distinct in place and sediments removed from the horizon will be mostly entire peds.

Gravel:

The gravel content of a deposit is estimated visually by passing sediments through a 2 mm soil sieve and comparing the amount of material larger and smaller than 2 mm. The number or range given as "% Gravel (est)" is the estimated percent gravel by volume. The degree of rounding of the gravels also is given, divided into four classes of angular (a), subangular (sa), subrounded (sr), and rounded (r). Where the degree of rounding is variable, a range is noted (e.g., a – sr). Size ranges for gravels taken out of the soil sieve are given, and larger clasts in a unit are described separately in the notes.

Texture:

Texture is estimated by observing dry consistence and several characteristics of a moistened sample. Dry consistence is measured by recording the degree of strength necessary to crush a ped. After the soil is passed through the sieve, it is moistened and wet consistence, stickiness, plasticity, the ability to form a stable ball and ribbon, the degree to which the moist sample soils hands, and the grittiness or smoothness of the sample are observed and recorded. Based on the percentages of sand, silt and clay-sized particles, sediments are classified into the categories of sand, loamy sand, sandy loam, loam, clay loam, sandy clay loam, sandy clay, silt loam, silty clay loam, silty clay, silt, and clay.

Clay Films:

Clay film morphology is observed in the field by examining peds with a 10x hand lens. The films (sometimes called clay skins) are classified according to amount, distinctness and location.

Amount is classified into four categories:
None..... none observed.
Very few..... covers < 5% of described surface.
Few..... covers 5 – 25% of described surface.
Common..... covers 25 – 50% of described surface.
Many..... covers > 50% of described surface.

Distinctness is classified into three categories:
Faint..... films are evident only at 10x magnification and create a weak contrast with unaltered material.

Distinct..... films are visible to the naked eye and create distinct contrasts with unaltered material.
Prominent..... films are conspicuous without magnification and create sharp contrasts, appear thick.

Location includes the following:
ped face, pores, bridges (between grains), and coatings (on grains).

Lower Boundary:

The lower boundaries of strata are characterized according to distinctness and topography.

Distinctness is divided into four categories:
Abrupt..... < 2 cm thick.
Clear..... 2 – 5 cm thick.
Gradual..... 5 – 15 cm thick.
Diffuse..... > 15 cm thick.

Topography is divided into four categories:
Smooth..... parallel to the soil surface.
Wavy..... pockets of each stratum are wider than they are deep.
Irregular..... pockets of each stratum are deeper than they are wide.
Broken..... pockets of the horizon are entirely disconnected from other pockets.

(This information is summarized primarily from Birkeland 1999: Appendix 1, 347 – 359. See also Buol *et al.* 1997; Holliday 2004: Appendix 1, 338 – 342; Soil Survey Staff 1975, 1993; Schoenberger *et al.* 2002. The form used for in-field recording is slightly modified from one initially developed by Dr. Bill Doleman for the Office of Contract Archaeology, University of New Mexico.)

Soil Description Tables, Floodplain Exposures:

1992 Survey Area, Fluvial Study Unit 1

Date: June 10, 2003
Location: East bank of arroyo below (south of) Queimada
Coordinates: 29S 606440E, 4162293N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 3	A	2.5 Y 6/3	moderate, fine subangular blocky	1/ 2-15mm	loam	none	clear, smooth	high organic content, abundant roots and insect krotovina
3 – 37	Bt	2.5 Y 6/3	moderate, medium to coarse, subangular blocky	10/ 2-15mm	clay loam	few, faint pore & co-br	clear, smooth	small (~5mm) red mottles, ~5% of area. Abundant roots, some krotovina, mostly insect?
37 – 54	2Bt	5 Y 6/2	moderate, medium subangular blocky	30/ 2-15mm	clay loam	few, faint pore	clear, wavy	small (~5mm) mottles, ~30% of area. Some roots and insect krotovina. A few larger clasts present, to 3cm m.d. Some vertical platy structure present.
54 – 78	ABb	2.5 Y 6/2	moderate, coarse angular blocky	5/ 2-15mm	silty clay	common, distinct pore and very few, faint ped face	clear, smooth	small (~5mm) mottles, ~30% of area. Few roots and krotovina. Lower boundary is rock line. Wetland/ riparian deposit?
78 – 88	rock line	5 Y 6/2 (moist)	too wet to determine	>60/ sr – sa, 5-15cm	clay loam	too wet to observe	clear, smooth	clast supported stratum, clasts are horizontal, imbricated. Rock line is 1-3 clasts thick. Old streambed? Roof tile fragments included in this stratum.
88 - 115	2AB (?)	5 Y 6/2 (moist)	too wet to determine	5-10/ a – sr, 2-20mm	clay loam	too wet to observe	water	clasts increase downward, become coarser to ~10cm m.d. 2nd possible rock line at 105 – 115cm. small (~5mm) red mottles
115 – 135	ABg (?)						bedrock	Sediments are saturated and mostly under water. Localized gleying.

Notes: Area has been plowed where possible. There is a narrow unplowed band along the banks of the arroyo. Drainage basin area: .242 km^2.

Interpretation: This profile exposes a complicated series of soils and strata that appear to reflect multiple periods of deposition and erosion. The upper 54 cm

are relatively homogeneous, fine upwards, and together represent a weakly developed cumulic soil. The degree of development suggests that this sediment was deposited relatively recently; it is probably related to the extensive plowing of hill slopes in the area beginning in the 20^{th} Century. The increased expression of structure relative to hillslope soils of similar age and the presence of clay films are most likely due to the greater abundance of water and fine-grained sediment entering the solum from the fluvial system. The subjacent ABb stratum appears to be turbated, reflecting characteristics of both A and B horizons. Some pedogenic features also may have been obscured by soil welding and groundwater effects. The structure and clay film morphology, however, indicate a significant degree of soil development; this deposit was exposed at the surface for an extended period of time in the past. The texture and color also are consistent with significant soil formation and they suggest a relatively high organic content, implying that this soil may have formed in a moist, vegetated channel bed. Below this, there is a stone line at a depth of 78 to 88 cm, with the clast-supported stratum consisting of >60% gravels and cobbles. The clasts are subrounded to subangular and visibly imbricated, indicating transport by running water. The stratum is most likely the bedload of an older stream similar to the incised ephemeral stream system present today. The degree of rounding and the size of the clasts indicate a period of heightened stream competence, probably related to increased runoff due to removal of plants and sediments from the adjacent hillslopes. The presence of fragments of roof tiles and small flecks of charcoal suggest that the channel formed during or after the Islamic period occupation at Queimada. A single-grain optical age from the analogous stratum in soil test pit 5, nearby, supports an Islamic period age for this deposit. From 88 cm to the water table at a depth of 115 cm is a single moist stratum with clasts coarsening downwards to a second possible weak stone line just above standing water, at 105 – 115cm. The clasts are angular to subrounded, suggesting relatively rapid deposition and minimal transport by moving water. Mottling and localized gleying indicate long-term saturation with groundwater, and gleying increases below the water level. These deepest strata are difficult to interpret because they are saturated with groundwater, and the designation as buried soils with characteristics of both the A and B horizons must be considered tentative. The lack of artifacts, however, suggests that they antedate the occupation of Queimada. In sum, this profile records at least two cycles of deposition and erosion. The stone line, with the inclusion of the roof tile fragment and charcoal, represents a period of significant erosion during or at some time after the Islamic period. The superjacent stratum most likely was deposited during a period of landscape stability with reduced stream competence and the stabilization of the streambed by a riparian plant community. Finally, the upper strata and the current channel represent recent erosion on the hillslopes and deposition along the stream channel. Currently, incised channels are forming because the removal of plants and soils from hillslopes increases runoff and, therefore, stream competence.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area, Fluvial Study Unit 2

Date: June 11, 2003
Location: West bank of arroyo, downstream from Queimada
Coordinates: 29S 606586E, 4162138N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 3	A	2.5 Y 6/3	moderate, medium subangular blocky	30/ sa, 2-15mm	sandy loam	none	abrupt, smooth	high organic content, abundant roots and krotovina, sand fraction is very fine, may be loam?
3 – 15	(ABpb?) >Bw	10 YR 6/3	moderate, coarse subangular blocky	40/ sa, 2-25mm	loam	very few, faint co-br	clear, wavy	numerous roots, some insect krotovina
15 – 40	Bt	5 Y 6/2	moderate, coarse subangular blocky	40/ sa, 2-50mm	clay loam	few, distinct pore, very few, faint ped face	gradual, smooth	clasts coarsen downward
40 – 80	C	5 Y 6/2	massive	>50/ sa, 2-50+mm	clay loam	none	bedrock	

Notes: profile is located where the active channel cut into hillslope deposits. The area does not appear to have been plowed recently, probably because of steepness and the presence of the channel. Drainage basin area: .351 km^2.

Interpretation: This profile presents a moderately developed soil. The soil appears to have developed in hillslope deposits without appreciable inputs from the fluvial system. The uniformly high content of subangular gravel, with slight increases with depth, probably reflects a combination of deposition of materials from higher on the hillslope, *in situ* weathering, and aeolian inputs of fine materials at the surface; the lack of any preserved bedding structures, size sorting, significant rounding or stone lines supports a non-fluvial origin. The magnetic susceptibility data also support a scenario in which pedogenic alteration outpaced the rate of deposition in a relatively stable environment. The degree of soil development relative to that observed in dated deposits in the study area suggests emplacement during roughly the past millennium. While the weak clay film morphology may imply more recent deposition, it is more likely related to hillslope position. The clear lower boundary of the Bw horizon probably reflects past plowing, before incision of the stream channel made plowing difficult in this location.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

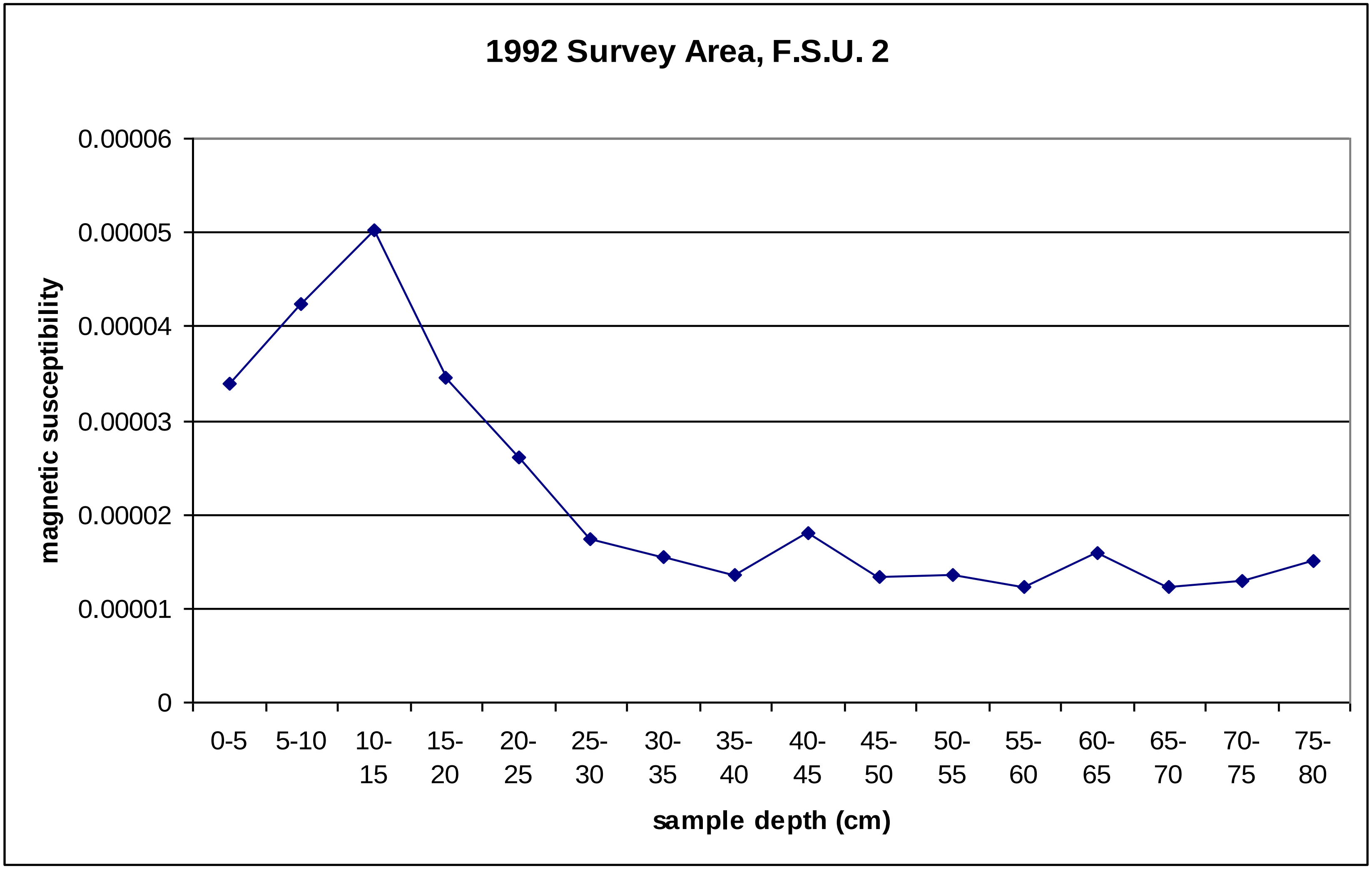

Figure A1 - 1: Magnetic susceptibility by depth, 1992 survey area, fluvial study unit 2

1992 Survey Area, Fluvial Study Unit 3

Date: June 13, 2003
Location: East bank of arroyo below Cerro da Loiça
Coordinates: 29S 604577E, 4160394N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 5	AB	10 YR 6/3	moderate, fine subangular blocky	40/ sa, 2-15mm	silty clay loam	common, distinct ped face	clear, smooth	high organic content, abundant roots and krotovina
5 – 25	Ab	10 YR 6/4	weak, coarse subangular blocky	<5/ sa, 2-5mm	loam	none	gradual, irregular	abundant krotovina, probably highly bioturbated. Irregularity of lower boundary is probably related to bioturbation. A few larger clasts to ~25mm.
25 – 45	Btb	2.5 Y 6/3	moderate, medium subangular blocky	<5/ sa, 2-10mm	silt loam	common, distinct pore and ped face	gradual, wavy	small (~1mm) red mottles cover ~5% of surface. Major increase in clasts at lower boundary
45 – 59	ABb/ rock line	2.5 Y 6/2	moderate, coarse subangular blocky	10/ a – sa, 2-20mm + rock lines	silty clay loam	few, distinct pore	gradual, smooth	there are distinct rock lines at the upper and lower boundaries of this unit, clast supported with clasts to 50cm. small (1-3mm) red mottles cover ~5% of surface. Few krotovina are present. Stratum includes roof tile fragments and plainware ceramic sherds, probably derived from nearby Roman site.
59 – 96	2 AB	2.5 Y 6/3	moderate, fine subangular blocky	50/ a – sr, 2 – 50mm	clay loam	common, distinct ped face and pore	bedrock	some large clasts < 50 cm m.d. present, appear imbricated. Probably emplaced by fluvial processes. No artifacts.

Notes: the profile is located in what appears to be a recently-formed arroyo. The area along the wash has not been plowed recently. Drainage basin area: .175 km^2.

Interpretation: The soils and strata exposed in this profile record multiple episodes of erosion, deposition and relative stability. The angularity and abundance of clasts in the thin A horizon suggest recent deposition of materials derived from nearby hillslopes and surface deflation before the formation of the modern arroyo. The strong expression of clay films is probably due to high inputs of water and clay along the stream and may have been augmented by localized ponding prior to the formation of the arroyo. The underlying buried A horizon exhibits weak soil development, suggesting recent deposition and a short period of exposure at the surface although there is abundant evidence of bioturbation and this process might have reduced the expression of some pedogenic characteristics. The subjacent buried B horizon shows moderate soil development, similar to that seen in deposits elsewhere in the study area that were emplaced during or after the Islamic period. This deposit is therefore likely older than the Ab horizon and was at or near the surface in the past, prior to the deposition of the latter. Since burial, however, bioturbation and soil welding have masked any horizonation that may have existed within this unit. On the other hand, the presence of mottling suggests that some of the observed differences between the Ab and Btb horizons could be due to the differential effects of groundwater and bioturbation and not to significantly different ages; there are insufficient data to differentiate with certainty between these two possibilities. The underlying ABb stratum contains distinct stone lines, and the color, texture and structure are consistent with weak soil development in the past; these are

probably old streambed facies. The relative lack of rounding of the clasts indicates a brief exposure to running water and short transport distances, probably because the profile is in a location where the stream drains a relatively small area. Also, the unusually deep soils in this drainage basin (compared to the rest of the study area) may have facilitated a relatively rapid stabilization of the landscape following arroyo formation. The artifacts in this stratum were almost certainly derived from the nearby Roman period site, suggesting arroyo formation during or after the Roman occupation. Subrounded to angular clasts make up approximately 50% of the basal stratum. Some of the larger clasts are imbricated, and there are no visible artifacts. The stratum probably represents rapid deposition by a mixture of fluvial and colluvial processes, most likely related to major climate changes prior to significant human occupation of the area. There is no clear evidence of soil formation at the top of the deposit, suggesting that pre-Roman soils were stripped in this location by the incised stream, although soil welding might have obscured pedogenic characteristics. Based on other exposures that were observed nearby, the basal deposit appears to be the parent material for subsequent soil formation throughout the upper reach of the basin. The relative abundance of clasts in the parent material suggests that the superjacent strata in the profile are composed largely of soils that developed on the adjacent hillslopes and were subsequently transported to low points on the landscape by erosion. Although some of the data are equivocal, this profile appears to represent initial deposition, then erosion and the formation of an arroyo during or after the Roman period. A period of relative stability most likely ensued, represented by the Btb horizon. This was, in turn, followed by rapid deposition, probably during the 20th Century, and finally a recent episode of surface deflation immediately prior to the formation of the modern arroyo.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area, Cerro da Loiça OSL Soil Test Pit

Date: July 3, 2007
Location: East bank of arroyo below Cerro da Loiça
Coordinates: 29S 604578E, 4160392N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 12	ABp	2.5 Y 6/3	moderate, coarse granular	25/ a – sa, 2-40mm	loam	common to few, distinct ped face	abrupt, wavy	Not plowed this year. Hillslope B horizon? Relatively high organic content. Sand fraction is very fine.
12 – 23	Ab	2.5 Y 6/3	weak, medium subangular blocky	5/ a – sa, 2-8mm	sandy loam to loamy sand	none	clear, smooth	Abundant krotovina, probably highly bioturbated. Sand fraction is very fine. Hillslope A?
23 – 62	2ABb	2.5 Y 6/3	moderate, coarse subangular blocky	20/ sa – r, 2-20mm	loam	common, distinct ped face	clear, smooth	Larger clasts are present. Quartz is angular. Clasts are imbricated. There is a weak stone line at the top, a strong stone line at the bottom. Roof tile fragments are present throughout.
62 + (base 98)	C>2Bt	2.5 Y 5/3	strong, coarse granular	50/ a – sa, 2-30mm	clay loam	many, prominent ped face		A few subrounded clasts are present. Also some clasts larger than 30mm. The stratum is clast supported. No artifacts are present. Ped size and shape is determined by the spaces between clasts.

Notes: This profile is located a few meters away from Fluvial Study Unit 3. Drainage basin area: approximately .175km^2.

Interpretation: The soils and strata exposed in this cut are similar in all significant respects to those described in FSU 3, with minor differences representing variability in the solum at the scale of several meters as well as changes in my preferences regarding soil descriptions. The surficial stratum in this location is less eroded and shows clear evidence of recent plowing, especially the abrupt lower boundary. As in FSU 3, the clay film morphology and texture imply that the unit consists of redeposited hillslope B horizon soils. The buried A horizon very likely was plowed in the past, although soil welding and bioturbation have altered the expected abrupt lower boundary. It probably originated as a mixture of an *in situ* A horizon with the addition of A horizon materials from the adjacent hillslopes during the early stages of soil erosion caused by increased plowing during the 20th Century. The subjacent deposit is again very likely significantly older, exhibiting moderate soil development in the structure and clay film morphology. The clay film morphology in particular suggests a greater age for this deposit, implying that the differences between the 2ABb and the Ab horizons are not primarily related to the affects of groundwater as posited in the initial description of FSU 3. The deposit includes the streambed facies that were separately described in FSU3; soil welding has effectively eliminated the pedogenic differences between the two deposits although the original interpretation of depositional history is still supported. The description and interpretation of the basal unit remains essentially unchanged. As in FSU 3, the profile represents initial deposition in the very distant past, followed by erosion and arroyo formation during or after the Roman period. This was followed by a period of relative stability, and then by hillslope erosion, floodplain deposition, and arroyo formation during the 20th Century.

Radiocarbon samples were recovered by flotation from the upper and lower portions of the 2ABb horizon to constrain the age of that deposit and to

test the possibility of slow, long-term accumulation. Samples were recovered by flotation of sediments collected at depths of 30 – 35cm (CL-2) and 40 – 45cm (CL-3). In addition to small flecks of charcoal, flotation recovered numerous roots, rootlets and what appeared to be pieces of ants. Although care was taken to separate these from the charcoal, the likelihood of recent organic material introduced by natural mixing processes is high. Both radiocarbon assays returned overlapping dates in the mid-17th Century. Taken at face value, this result suggests that the sediments were emplaced relatively rapidly in the middle to later 17th Century. One possible interpretation is that, by that time, sediments had accumulated on adjacent hillslopes and these were mobilized, probably following a fire, and entered the fluvial system. Alternatively, it is possible that the samples reflect widespread burning during the 17th Century and the subsequent incorporation of burned materials into an existing sediment matrix. This scenario seems likely given the remarkably similar age of the two separate samples, the evidence of bioturbation in this location, and the fact that the radiocarbon ages correspond well to that of sample AL-3a from a similar context but at a different site.

OSL samples were taken at the lower boundary of the buried A horizon (19 – 24cm, CL-1), and from the upper and lower portions of the 2ABb horizon (30 – 35cm, CL-2, and 40 – 45cm, CL-3). Sampling below that depth was impractical due to high clastic content. Preliminary results based on multiple-aliquot readings returned ages of 1440 and 1800 years for CL-1 and CL-2, respectively. At face value, these suggest channel formation and filling during the Roman and Late Roman periods, followed by landscape stability until the 20th Century. A reanalysis of sample CL-2, however, shows that (as in other locations) the multi-aliquot ages overestimate the actual ages of the deposits significantly. The single grain date, based on 156 grains out of 4800, demonstrates that partial bleaching caused the anomalously old ages returned by multi-aliquot dating and also reflects the high degree of post-depositional mixing that has impacted these sediments. Given the large number of accepted grains, however, the single grain date should be reliable. It suggests channel formation and initial filling during the later Islamic period, and it corresponds remarkably well with the radiocarbon assay from the most reliable context encountered during this study, sample SU5 FS#47, from Fluvial Study Unit 5. It is particularly significant that the date shows channel formation during the later Islamic period and not during the Roman occupation of the adjacent site. Because the sampling site is located nearest a Roman era archaeological site, this is strong evidence that human activities caused widespread arroyo formation during the later Islamic period, not just localized erosion near sites whenever they were occupied. This interpretation requires that both radiocarbon samples be intrusive, mixed downward through the soil profile, perhaps by ants. This certainly is possible given the small size of the samples and the evidence for mixing from both the single grain optical assay and observations made when recovering the radiocarbon samples from the floated materials.

* colors given are for dry sediments unless otherwise noted

** structure designations after Birkeland 1999

*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

Radiocarbon Data:

Sample	Description	Depth/ Stratum	14C Age B.P.	Calibrated year ranges A.D. (2 sigma)	Median Date	Lab Number
CL-2a	charcoal fragment, 4.4 mg, recovered by flotation	30 – 35 cm/ 2ABb (upper)	252 +/- 35	1517 – 1594 1618 – 1681 1739 – 1751 1762 – 1802 1937 – 1951	1653	AA 76889
CL-3a	charcoal fragment, 3.9 mg, recovered by flotation	40 – 45 cm/ 2ABb (above stone line)	261 +/- 32	1515 – 1598, 1617 – 1647, 1778 – 1799, 1942 – 1951	1645	AA 76890

OSL Data:

Sample	Depth/ Stratum	Optical Age (+/- 1 σ)	Measurement Type	Lab Number
CL-1	20 – 25 cm/ Ab-2ABb boundary	1440 +/- 220 [560 C.E.]	multiple aliquot	UNL-1859
CL-2	30 – 35 cm/ 2ABb	1800 +/- 220 [200 C.E.]	multiple aliquot	UNL-1860
CL-2	30 – 35 cm/ 2ABb	880 +/- 70 [1120 C.E.]	single grain	UNL-1860
CL-3	40 – 45 cm/ lower 2ABb	sample not analyzed		

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1992 Survey Area, Fluvial Study Unit 4

Date: June 13, 2003
Location: North bank of arroyo, downstream from study unit 3, near Cerro da Loiça
Coordinates: 29S 604676E, 4160282N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	A	2.5 Y 6/3	weak, coarse subangular blocky	5-10/ sa - sr, 2-10mm	loamy sand	none	clear, smooth	high organic content, abundant roots and krotovina
15 – 47	Bw	10 YR 6/4	weak, medium subangular blocky	5-10/ sa - sr, 2-10mm	loamy sand	none	clear, smooth	slightly redder than A horizon, numerous roots, some krotovina
47 – 60	Bw2	10 YR 6/3	moderate, medium to fine subangular blocky	10/ sa, 2-5mm	loamy sand	very few, faint pore	clear, smooth	slight color change from Bw, some increase in gravel, appears granular when in place. Very slight red mottling.
60 – 75	ABb	2.5 Y 6/3	moderate, medium angular blocky	<5/ sa, 2-10mm	loam	few, distinct pore	abrupt, smooth	abundant red mottling, 2-10mm, covers ~20% of surface. Possibly cemented by something in groundwater?
75 – 79	C (rock line)	10 YR 6/3	weak, medium granular	60/ sa - sr, 2-20mm	loamy sand	none	abrupt, smooth	Clast supported. Laterally continuous gravels – bedload deposit. Analogous to rock line in SU 3, but mostly smaller clasts. 20% of clasts reddened – mottled.
79 – 112	2C	2.5 Y 6/3	moderate, medium subangular blocky	10 – 20/ sa, 2-15mm	sandy loam	few, distinct pore	bedrock	a few larger clasts present. Common red mottling, ~30% of surface. Retains some bedding, clasts imbricated – fluvial deposits.

Notes: the area along the wash has not been plowed recently. The wash cuts through a broad floodplain with a standing crop of wheat.
Drainage basin area: .207 km^2.

Interpretation: Although there are no visible artifacts and few clasts, the strata exposed in this profile can be correlated with those observed in the study units upstream. The generally thicker strata and coarser sediment textures in these facies are due to higher discharges and greater inputs of water and sediment lower in the fluvial system. The relative lack of large clasts suggests both that the stream system generally has not been competent to transport clasts larger than a few centimeters and that the fluvial system has mostly reworked and transported materials that originated as soils that developed in the rocky parent material in the upper basin. The clay film morphology and soil structure in the upper 60cm of deposits are indicative of weak soil development and rapid, episodic accumulation. The characteristics are consistent with deposition during the 20th Century. Unlike the analogous horizons upstream, the A horizon is not enriched in gravels. Most likely, fine-grained sediments were eroded from upstream, creating a gravel-enriched surface there, and deposited lower in the system or flushed into the local trunk stream prior to and during the earlier stages of the recent arroyo incision. The Bw and Bw2 horizons appear to correspond to the Ab horizons upstream. The slight changes in color and structure in the Bw2 horizon are due to seasonal saturation with water, as indicated by the observed mottling. The ABb horizon is similar to the ABb and 2ABb horizons upstream. Structure and texture indicate moderate soil development, suggesting a

protracted period of pedogenesis with this deposit at or near the surface. The weaker clay film morphology may indicate more significant reworking of the materials at this position lower in the fluvial system. The abrupt nature of the lower boundary might imply that the pedogenic characteristics did not form *in situ*, but it is more likely related to the major change in texture at the level of the rock line. The rock line, a clast-supported C horizon, is analogous to the stone lines at the lower boundaries of the ABb and 2ABb horizons upstream, stream bedload deposits. Again, the size of the clasts in FSU 4 suggests that the stream was not capable of moving larger cobbles; the larger clasts upstream probably were not moved far from their original locations in the parent material. The subjacent 2C deposit is relatively homogeneous. It retains some original bedding structures and the clasts are imbricated, indicating rapid fluvial deposition. These deposits also appear to correspond to the ABb and 2ABb horizons upstream; pedogenic features, gravel percentages and the degree of rounding indicate a hillslope origin for these deposits and relatively limited reworking by an active stream. There is no deposit in profile 4 that appears to correspond to the basal strata upstream. It is likely that, due to its position lower in the basin and the consequently higher stream discharge, the parent materials were reworked or transported out of the lower parts of the fluvial system, either during the pre-Roman episode of landscape change that moved these materials into the upper parts of the basin from the surrounding hillslopes or during the cycle of erosion recorded by the bedload deposits that incorporate Roman cultural materials upstream. Profile 4, like the profiles upstream, is consistent with a cycle of erosion during or after the Roman occupation, during which hillslope materials were transported to the floodplain and an entrenched stream formed. The lack of significant rounding of clasts and the absence of well-developed soil horizons in the fluvial deposits indicate that the entrenched stream system did not persist for a long period of time. Instead, the hillslopes rapidly stabilized and a long period of relative stability and gradual aggradation of the floodplain ensued, recorded in the ABb horizon. Finally, recent changes in land use patterns caused renewed erosion of the hillslopes, leading to rapid deposition on the floodplains and the formation of the current incised arroyo system.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area, Fluvial Study Unit 5

Date: June 16, 2003

Location: West wall of tributary arroyo cutting through floodplain and locally derived sediments, leading into Ribeira do Carreiras.

Coordinates: 29S 604379E, 4158457N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 2	A	10 YR 4/3	single grain, fine granular	0	loamy sand	none	abrupt, smooth	abundant organic matter, dense vegetation
2 – 4	C	10 YR 6/3	moderate, coarse, platy	<1/ sa, 2-3mm	loam	none	abrupt, smooth	overbank deposits from ribeira
4 – 17	Btb	10 YR 5/3	weak, medium subangular blocky	0	loamy sand	few, faint pore	clear, wavy	abundant krotovina, bioturbation
17 – 48	2Bt	10 YR 6/4	weak, medium subangular blocky	<1/ sr, 2-5mm	silt loam	few, faint pore	abrupt, smooth	abundant krotovina and bioturbation. Some original depositional layering (2-5mm laminae) still faintly visible
48 – 49	2C	10 YR 6/3	massive, fine granular	10 – 20/ sa, 2-10mm	loamy sand	none	abrupt, smooth	probably deposition from a large flood
49 – 71	2Bt'	10 YR 6/4	weak, coarse subangular blocky	2 – 5/ sa, 2-10mm	silt loam	common, distinct pore	clear, wavy	abundant krotovina and bioturbation. Krotovina mostly ~2-3mm diameter, insect?
71 – 88	2Bt2	10 YR 6/4	weak, medium subangular blocky	5 – 10/ sa, 2-20mm	loam	few, faint pore	abrupt, wavy	very few larger clasts. Small (~2mm) red mottles cover <5% of surface. Harder than overlying with fewer krotovina.
88 – 102 (127)	3C	10 YR 6/3	weak, coarse granular	60/ sa – sr, 2-30mm	sandy clay loam	none	abrupt, smooth	gravelly channel deposit with lenticular shape, fines upward. Clast supported. Laterally discontinuous. Lack of rounding of clasts suggests tributary.
102 – 109	4C	10 YR 6/3	weak, medium subangular blocky	2 – 5/ sa, 2-10mm	loam	few, faint pore	clear, smooth	cross-cut by channel (3C). Horizontal and laterally continuous – floodplain deposit. No visible krotovina. Some small (~2mm) red mottles, cover <5% of surface.
109 – 123	5C	7.5 YR 6/3	weak, medium subangular blocky	10/ sa – sr, 2-10mm	loamy sand	none	clear, smooth	cross-cut by channel (3C). horizontal and laterally continuous – floodplain deposit. No visible krotovina. Small (~2mm) red mottles, cover 5-10% of surface.
123 – 130	6C	2.5 Y 6/3	weak, medium subangular blocky	~2/ sa – sr, 2-10mm	silt loam	none	clear, wavy	cross-cut by channel (3C). horizontal and laterally continuous – floodplain deposit. No visible krotovina. Few small (>2mm) red mottles cover >5% of surface.

130 – 151	7C	2.5 Y 6/3	weak, fine subangular blocky	20/ sa – sr, 2-10mm	loamy sand	none	abrupt, irregular	a few clasts to >60mm present. Few tiny flecks of charcoal are visible. Distinct reddening at base of unit – probably groundwater. There are pockets of larger clasts. Appears to be a flood deposit. Small (2mm) red mottles cover ~10% of surface.
151 – 172	8C	2.5 Y 6/3	weak, medium subangular blocky	40/ a – r, 2mm-10cm	clay loam	none	gradual, wavy	larger clasts tend to be angular. Red mottles to 5mm cover ~20% of surface. Lower boundary defined partly by stone line – large (>20cm), horizontal, imbricated clasts, matrix supported, local source, reworked by ribeira flooding?
172 – 213	9C	2.5 Y 5/3	moderate, medium subangular to angular blocky	40/ a – sa, 2mm - >40cm	silty clay loam	none	bedrock	very few mottles, some areas clast supported. Abundant artifacts, including roof tiles, burned clay, ceramics, charcoal, a califal period melado sherd. Larger clasts not rounded – probably not transported in ribeira. Charcoal collected for dating.

Notes: the study unit is located near the edge of the floodplain of the ribeira. The floodplain does not appear to have been plowed in this location. Drainage basin area: .298 km^2.

Interpretation: This profile exposes a series of strata that include floodplain deposits derived from the Ribeira do Carreiras as well as sediments emplaced by the small, seasonal tributary stream that cut down to expose the section. Flooding of the ribeira probably deposited the majority of the upper 1.5 m of sediments. The uppermost 2 cm at the surface comprise an A horizon rich in organic materials. The subjacent 2cm are a C horizon with no evidence of pedogenesis. Together, these strata suggest very recent deposition, and observations of vegetation, geomorphology and clasts on the surface of the floodplain corroborate the impression that it is an active surface. From 4 to 48cm, there are two weakly developed Bt horizons. Some original depositional structures are preserved in the lower of the two. The preservation of original structures and lack of significant soil development indicate rapid alluviation and burial, and the texture is consistent with deposition by overbank flooding of the ribeira. A 1cm thick gravelly deposit at a depth of 48cm was probably emplaced by a particularly strong flood event or pulse capable of moving gravel-sized clasts. The subjacent Bt horizons continue to a depth of 88cm and again are consistent with episodic deposition by overbank flooding of the ribeira and subsequent rapid burial. A lenticular, horizontally discontinuous gravelly deposit from 88 to 102cm appears to be a small, filled stream channel; it continues to a maximum depth of 127cm next to the column that was measured and described. Channel morphology and the lack of rounding of the gravels suggest that the channel probably carried water and sediments from the small tributary and not the ribeira. From 102 to 151cm, there are two pairs of upward-fining strata. The morphology and lack of soil development again suggest flood deposition and rapid burial. In sum, the upper 151cm of the profile appear typical of weakly developed, cumulic soils on an actively aggrading floodplain. The strata record a series of flood events that were not separated by significant periods of time during which the floodplain was stable. It is likely that this rapid aggradation is related to regional changes in land use during the 20th Century and the subsequent erosion of hillslopes in the region.

The deposits in the lower 52cm, on the other hand, contain a significantly higher proportion of gravels. The minimal degree of rounding relative to clasts in the active channel of the ribeira suggests that these strata were likely deposited by the small tributary. The clasts in the stratum at a depth of 151 to 172cm include large (>10cm), angular cobbles and smaller, subangular to rounded gravels, possibly reflecting multiple sources for this deposit. Although there is little evidence of pedogenesis, this stratum may have been deposited and reworked over a significant period of time. The local geomorphology and topography suggest that this was the mouth of the small tributary channel, with locally derived sediments emptying onto the floodplain of the ribeira and being reworked by water from the main channel. The continual deposition, erosion and reworking would have removed fine sediments and hindered soil formation. A fragment of charcoal recovered by flotation from near the base of this unit was dated to AD 1464, suggesting that the small channel filled and became inactive approximately during the 15th Century. The deepest stratum, from 172cm to bedrock at 213cm, again has a high proportion of clasts, including numerous cobbles >40cm. The clasts are all angular to subangular, suggesting a local source and very little reworking or transport by water; they were emplaced by the small tributary and relatively rapidly buried. In addition, this unit yielded abundant artifacts, including roof tile fragments, burned clay, a sherd

of a Califal-period *melado* ware bottle, or *redoma*, some non-diagnostic utilitarian ceramics, and a fragment of charcoal. These were almost certainly derived from the small Islamic period site upstream on the tributary, suggesting that this deposit resulted from an episode of erosion in the basin containing the site. The charcoal fragment was AMS dated to AD 1130 +/- 110, 2-sigma, calibrated (Geochron sample GX-30696). Because charcoal is relatively fragile and highly mobile in fluvial systems, this gives a reasonable estimation of the maximum age of the episode of erosion. In sum, the deposits exposed in profile #5 record hillslope erosion in the past, probably during the 12th Century. This was followed by a period of relative stability during which the tributary channel contributed sediments to a lower-elevation floodplain, with only the larger clasts remaining in place while smaller particles were removed by the fluvial system. A radiocarbon age estimate suggests that this period of relative stability persisted into the 15th Century. Subsequently a series of large flood events deposited over 1.5 meters of sediment on the floodplain. While aggradation probably began by the 15th Century, the timing of the depositional events was such that only very limited pedogenesis occurred in each deposit before burial by subsequent flood events. The majority of deposition may have occurred as recently as the 20th Century. Currently, the ribeira has cut down through these floodplain deposits, creating an incised channel, but flood events continue to inundate the floodplain with sufficient frequency to keep mature soils from developing at the surface.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

Radiocarbon Data:

Sample	**Description**	**Depth/ Stratum**	**14C Age B.P.**	**Calibrated year ranges A.D. (2 sigma)**	**Median Date**	**Lab Number**
92FS5a	charcoal fragment, 4.9 mg, recovered by flotation	170 – 175 cm/ 8C (upper limit of stone line, bottom of overlying unit)	417 +/- 32	1426 – 1520, 1592 – 1620	1464	AA 76891
SU5 FS#47	large charcoal fragment, ~ few grams (not weighed), picked out while cleaning profile	180 - 200 cm/ 9C (below upper portion of stone line)	890 +/- 40	1035 – 1219	1137	GX-30696

1992 Survey Area, Fluvial Study Unit 6

Date: June 19, 2003
Location: Spring in wash northeast of Alcaria Longa
Coordinates: 29S 601340E, 4157306N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 7	Bw	10 YR 6/3	weak, medium granular	30/ a – sa, 2-30mm	loamy sand	none	gradual, wavy	A horizon has been removed by erosion. Bw is slightly redder than subjacent material. Abundant roots, few krotovina.
7 – 52	C	10 YR 6/3	moderate, medium subangular blocky	10/ a - sa, 2-20mm	loam	none	clear, smooth	rare larger clasts, to 10cm, m.d. clay content and hardness appear to increase near the bottom of the stratum. Large krotovina at ~30cm, roots and krotovina present.
52 – 90	C2	10 YR 6/3	weak, medium granular	50/ sa – sr, 2-50mm	sandy clay loam	none	abrupt, smooth	rare larger clasts to 30cm, m.d. gravelly stratum, mostly matrix-supported. Few red mottles to 5mm, cover <5% of surface. Rock line visible at lower boundary.
90 – 123	C3	10 YR 6/3; 7.5 YR 4/3 moist	too wet	50-60/ sa - sr, 2mm-10cm	sandy clay	too wet	clear, smooth	red mottles to 5mm cover ~5% of surface. Purplish mottling is abundant, covering ~40% of surface. Very gravelly deposit, clast supported. Lover boundary is defined by gleying.
123 – 164	Cg	G1 7/10 Gy; G1 6/5 G moist	too wet	50-60/ sa - sr, 2mm-10cm	silty clay	too wet	bedrock	uniformly gleyed at the top. orange mottles increase with depth to cover ~50% of surface. Gleyed last 5cm above bedrock – possible water on clay-rich layer in top 15cm and water at bedrock. Mottles seem to be associated with pockets of sand/ fine gravel.

Notes: The spring has been cleaned out recently, apparently by backhoe, exposing the described profile. The spring is also fenced off to restrict animal entry. It produces a small trickle of water. Drainage basin area: .121 km^2.

Interpretation: This profile exposes a series of spring deposits that exhibit little or no evidence of soil development. The upper 7cm are a weakly developed B horizon, indicating a limited period of pedogenesis in the recent past and subsequent erosion of the A horizon. The localized erosion may be due to trampling by animals coming to the spring before the fence was constructed. Given the pattern visible throughout the study area, it is likely that this upper layer represents relatively recent deposition, probably related to changing land use practices since the early 20th Century. The color characteristics indicating soil development are likely at least partially inherited. The stratum probably reflects rapid, recent deposition that may have buried the spring, prompting the people who use the land to clean it out. From 7 to 123cm, there are three C horizons, coarsening downward, with a rock line visible at a depth of 90cm between the second and third strata. In these strata, constant deposition and reworking of materials by the spring effectively kept soils from forming. The relative abundance of gravels below 52cm is probably related to increased spring flow in the past, as might be expected during periods when thicker soils facilitated greater water storage in hillslope sediments and, therefore, caused more sustained spring flow throughout the year. The deepest stratum, from 123 to 164cm is saturated with water and strongly gleyed. While it is possible that the stone line at 90cm indicates a period of dramatically increased spring flow, it is difficult to interpret the stratigraphy in general without tracing it laterally in a much larger exposure than was available. Consequently, this exposure is not particularly informative regarding landscape changes before the 20th Century. Samples collected from the deeper strata did not yield preserved pollen. The lack of pollen suggests that the sediments have not been uniformly wet since deposition; it is likely that spring flow has nearly or completely ceased several times in the past.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area, Fluvial Study Unit 7

Date: June 21, 2003
Location: In wash southeast of Alcaria Longa
Coordinates: 29S 601653E, 4156912N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 28	Bt	10 YR 6/3	weak, medium subangular blocky	5/ sr, 2-5mm	loamy sand	few, faint pore	gradual, smooth	occasional clasts to 15mm. numerous krotovina including insect and small mammal. A obliterated by recent erosion, mixing or plowing?
28 – 50	2Bt	2.5 Y 6/3	moderate, coarse subangular blocky	5/ sr, 2-5mm	loamy sand	few, faint pore	gradual, smooth	occasional clasts to 15mm. fewer large krotovina than overlying, still numerous small (insect) krotovina. Slightly lighter than overlying.
50 – 86	3Bt	2.5 Y 6/3	moderate, coarse subangular blocky	2-5/ sa - sr, 2-5mm	silt loam	common faint ped face and distinct pore	clear, smooth	slightly fewer insect krotovina and harder and more homogeneous than overlying.
86 – 100	4Bt	2.5 Y 6/4	moderate, coarse subangular blocky	2/ sr - sa, 2-5mm	loam	few, faint pore	abrupt, smooth	lower boundary defined by dramatic increase in gravels. Matrix is more porous and appears coarser than superjacent
100 – 135	C	2.5 Y 6/2	weak, coarse subangular blocky	30/ sr – sa, 2-30mm	sandy clay	common, distinct coatings	abrupt, smooth	clay films probably related to groundwater. Lower boundary is defined by a stone line and a change in moisture, color. Rare red mottling, covers <2% of surface, may be related to Fe-rich clasts. Localized rodent krotovina present.
135 – 175	(ABb?) >C2	2.5 Y 6/2	moderate, medium subangular blocky	40/ sa – sr, 2-40mm	sandy clay loam	common, distinct pore and coatings	abrupt, smooth	clay films are probably due to groundwater. Occasional larger clasts are present. Lower boundary is defined by a stone line of large clasts, >30cm, m.d. They are imbricated with the long axis downstream. Possibly initially deposited by the ribeira, then reworked by the tributary. There are numerous artifacts (roof tiles, sherds, burned clay) associated with the stone line. Red mottling, 2-5mm covers <5% of surface.
175 – 204	(AB2?) >C3	10 YR 6/1	weak, fine subangular blocky	50/ a – sa, 2-50mm	sandy clay loam	too wet	clear, smooth	common red mottling up to 10mm covers 30% of surface. There are a few artifacts (roof tile fragments, a sherd) in this stratum. Stratum is mostly clast-supported. Clasts appear to fine and decrease downward.
204 – 214	Cg	5 Y 6/2; 2.5 Y 4/2 moist	too wet	20-30/ sa, 2-20mm	silty clay loam	too wet	bedrock	stratum is saturated with ground water; water seeps out continually. Strong mottling and gleying are present.

Notes: The arroyo exposes floodplain deposits near where a wash enters the ribeira. It is the same wash that has the spring, described in study unit 6. The area has been plowed. Drainage basin area: .310 km^2.

Interpretation: The stratigraphy exposed in this arroyo bank is broadly similar to that of profile 5, with recent deposits probably related to the ribeira over older deposits laid down by the tributary stream. To a lesser extent, the stratigraphy also mirrors that of Alcaria Longa soil test pit 6, although the inputs from the fluvial system are significantly stronger here, reflecting the location closer to the ribeira. There is no distinct A horizon preserved at the surface; it may have been altered by plowing before the formation of the modern arroyo. In addition, recent erosion caused by cultivation and by sheep going to water in the ribeira has probably removed surface deposits. The Bt and 2Bt horizons exhibit weak soil development, indicating relatively short periods of exposure at the surface; these deposits are probably related to widespread hillslope erosion during the 20th Century. The 3Bt horizon shows signs of slightly more advanced pedogenesis, including a greater abundance of clay films, but groundwater effects cannot be ruled out as an important contributor to this characteristic. Structure, color, texture and clay film morphology do not indicate strong soil development, so it is unlikely that this stratum represents a period of landscape stability on the order of a millennium or more. The 4Bt horizon again shows weak soil development, indicating rapid deposition and burial.

In the C horizons, there is a dramatic increase in gravels, suggesting that fine sediments were removed by water. At the base of the uppermost C horizon there is a weak stone line and the rounding of the clasts suggests exposure to flowing water for a prolonged period of time and probably indicates inputs from the ribeira. This was most likely the bed of the tributary stream, and it was probably stable at this elevation for some time. The stone line may correspond to the one between C2 and C3 in study unit 6, possibly indicating a period of increased spring flow. The lack of pedogenic characteristics that indicate strong soil development is probably due to constant reworking of sediments by the fluvial systems. The two subjacent strata, C2 and C3, are dominated by angular clasts, suggesting a local origin and relatively less transport by or exposure to running water. At approximately 175cm, between the two units, there is a strong, imbricated stone line that includes large cobbles, many >30cm. This feature indicates an incised stream channel that was stable at that elevation for some period of time. In both strata, and especially associated with the stone line, there are numerous fragmentary artifacts, including roof tiles, utilitarian ceramics and burned clay. These are almost certainly derived from Alcaria Longa. The artifacts in the lower unit (C3) suggest that it was deposited during or after occupation of the site. That there is not a stone line at the base of that unit suggests that it was emplaced due to hillslope erosion. Subsequently, an incised channel formed, as reflected by the stone line. The abundance of ceramic artifacts in the stone line, coupled with the paucity of charcoal, suggests that this is a lag deposit created by reworking of sediments over an extended period of time. The cultural materials above the stone line most likely are present due to the movement of artifacts into and within the fluvial system as it aggraded at a later date. The stratigraphy therefore suggests a period of hillslope erosion during, or possibly after the occupation of the site. Hillslope erosion increased runoff and eventually caused arroyo formation, as indicated by the stone line. A charcoal fragment collected by flotation from within or slightly above the stone line yielded a median age estimate of AD 1648. Given the size of the fragment (6.5 mg), its proximity to the current surface, and the evidence for bioturbation in superjacent strata, it may be intrusive. If it is not, it suggests that an incised channel persisted in this location into the 17th Century. The persistence of the channel here for longer than the analogous channel in Study Unit 5 may be attributable to the spring upstream. Alternatively, it could represent more extreme erosion adjacent to the larger site (Alcaria Longa) during the Islamic period; the length of time required for sediments to accumulate on hillslopes that could then be transported into the fluvial system and eventually fill the channel would be longer as a consequence of the greater erosion. In any case, the deepest stratum has fewer clasts, yielded no artifacts, and is saturated with water and strongly gleyed. It probably represents parent material or streambed deposits that antedate significant occupation of the site.

The strata exposed in profile 7, then, record multiple cycles of erosion and deposition at different scales. The C2 and C3 strata suggest at least two cycles of local erosion and deposition in the valleys. The first was probably associated with the occupation of Alcaria Longa. The stone line between them indicates the formation of an incised channel, probably because of increased runoff after the majority of sediments were removed from adjacent hillslopes. The concentration of heavy, durable artifacts within the stone line suggests that finer sediments and cultural materials were flushed from the channel over the course of an extended period of time. The radiocarbon assay suggests that the channel may have persisted until the 17th Century. The remarkable correspondence

between the radiocarbon date here and those at the Cerro da Loiça OSL profile suggest widespread burning during the 17th Century, perhaps associated with a significant increase in population following initial recolonization of the rural areas. If the hypothetical widespread burning occurred, it may be responsible for subsequent hillslope erosion that led to filling of the channel in this location. Islamic period artifacts in the C2 stratum are likely reworked from higher points in the fluvial system. The superjacent C stratum appears to reflect a period of relative stability following filling of the channel. The top 100cm of the profile, on the other hand, were probably deposited not by the tributary stream but primarily by the Ribeira. The texture and morphology of the deposits is consistent with multiple events of rapid deposition by overbank flooding of the larger fluvial system. Given the weak indications of pedogenesis, these are likely related to the regional changes in land use practices during the 20th Century.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

Radiocarbon Data:

Sample	Description	Depth/ Stratum	14C Age B.P.	Calibrated year ranges A.D. (2 sigma)	Median Date	Lab Number
AL-3a	charcoal fragment, 6.5 mg, recovered by flotation	170 – 185 cm/ C2 – C3 (stone line)	258 +/- 32	1517 – 1594 1618 – 1676 1768 – 1771 1777 – 1799 1941 – 1951	1648	AA 76888

1992 Survey Area, Fluvial Study Unit 8

Date: June 23, 2003
Location: Base of hill east of Alcaria Longa
Coordinates: 29S 601586E, 4157094N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films** *	Lower Boundary	Comments/ Notes
0 – 23	Ap	2.5 Y 6/3	moderate, coarse granular	30/ a - sr, 2-15mm	loam	none	clear, smooth	Large clasts, 15 – 30cm m.d., are common at the surface and a few are dispersed throughout the horizon. Clasts 2 – 10cm increase at the base/ top of Bt.
23 – 44	Bt	2.5 Y 6/4	moderate, medium subangular blocky	15/ sa - sr, 2-15mm	silty clay loam	common, distinct ped face	diffuse, smooth	clasts 2 – 5cm numerous throughout. Pieces of roof tile present at 30cm along with small flecks of red – burned clay? Lower boundary is defined by decrease in clasts.
44 – 82	ABb >Bt2	2.5 Y 5/4	strong, coarse subangular blocky	1-2/ sa, 2-5mm	silty clay	common, prominent ped face,	bedrock	rounded clasts are present on bedrock. Some areas are darkened, a few red flecks are present. Possible color changes with depth are obscured by soil moisture.
Notes: Profile is located in a plowed area between Alcaria Longa and the ribeira. Soil accumulation appears to be mostly from the hill.								
Interpretation: The soil exposed in this test pit is very similar to those described as Alcaria Longa soil test pit 5 and the Alcaria Longa OSL soil test pit; the test pits are located near each other. As they were described in different years, the similarities reflect favorably on the field descriptions of soils in terms of replication of results. As in the case of stp 5, the soil appears to be polygenetic. The structure of the A horizon and the structure, color and clay film morphology of the upper B horizon show moderate expression of time-dependent pedogenic characteristics. The magnetic susceptibility data suggest recent deposition and mixing of surface deposits, probably related to plowing at and on the hillslope above the test pit. The inclusion of artifacts in the upper two strata suggests a maximum age of deposition during or after the Islamic period. The relatively strong expression of clay films in the Bt horizon, however, implies that the sediments may be older. The small artifacts that are present may have been mixed downward into the deposit by plowing or other post-depositional processes. Alternatively, soil formation may have been accelerated in this geomorphic position by increased inputs of water due to runoff and by the addition of sediments derived from relatively mature soils eroded from the slope above. The gradual transition to the Bt2 horizon probably reflects both ongoing pedogenesis (soil welding) and the cumulic nature of the Bt horizon. Color, structure, texture and clay film morphology of the Bt2 horizon suggest great antiquity for the deposit and this impression is corroborated by the absence of included artifacts. The presence of rounded clasts at the base of the profile, in contact with the bedrock, suggests a major period of erosion in the very distant past during which all of the sediments on the hill slopes were removed from the area. Given the likely age of this deposit and the lack of included artifacts, this erosion was probably related to major climatic changes before significant human occupation of the area; it may be correlative with the period of hillslope erosion reflected in the basal sediments exposed in study unit 3.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

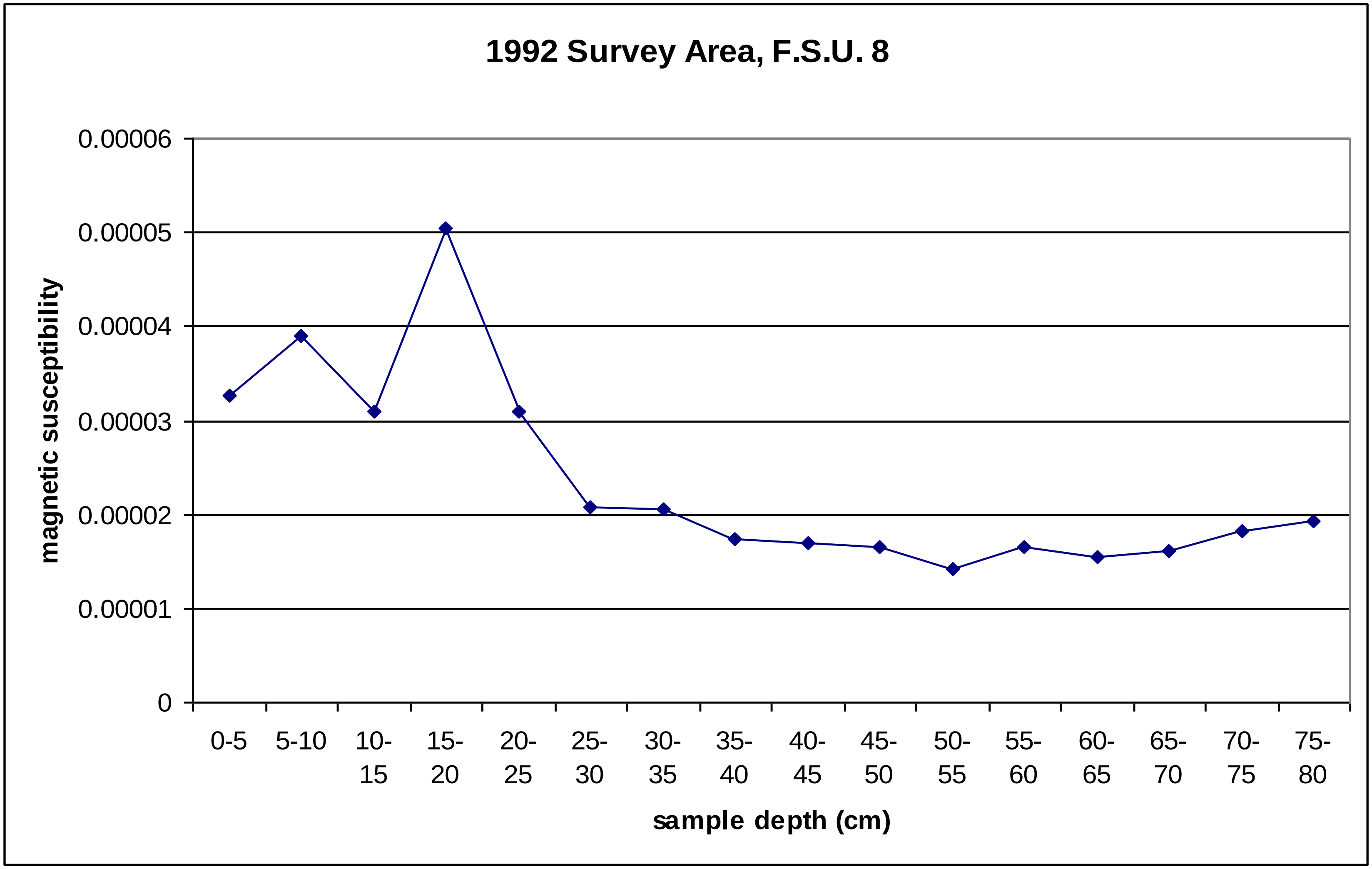

Figure A1 - 2: Magnetic susceptibility by depth, 1992 survey area, fluvial study unit 8

2004-05 Survey Area, Fluvial Study Unit 04-01

Date: August 3, 2004
Location: Arroyo in floodplain, above confluence from the East, in the upper reaches of the Barranco do Corcho.
Coordinates: 29S 612825E, 4178840N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 2	A	7.5 YR 5/4	weak, medium granular	20/ a-sr, 2-20mm	loamy sand	few, faint co-br	clear, smooth	clay films probably due to surface water in arroyo. High organic content.
2 – 23	C	7.5 YR 6/4	moderate, medium subangular blocky	<5/ a-sr, 2-7mm	sandy loam	few, faint ped face, pore and co-br	clear, wavy	clays probably inherited, not all pedogenic. Sediments probably originated on hillslopes, rapid deposition.
23 – 38	C2	7.5 YR 6/4	moderate, coarse subangular blocky	30/ sa-sr, 2-30mm	sandy loam	few, faint ped face, pore and co-br	clear, smooth	Unit fines upward. Probably same origin as overlying. Clays are probably not all pedogenic. Rounding of clasts suggests water transport. Flecks of charcoal are present. Rodent burrows are apparent near the base of the unit.
38 – 51	2C	7.5 YR 6/4	weak, coarse granular	40/ sa-sr, 2-30mm	loamy sand	few, faint ped face, common, distinct pore and co-br	clear, wavy	soil characteristics (clay films) likely due to inputs of water and clay along stream. Numerous larger clasts to >8cm are visible in unit, it is continuous with a stone line – an old channel deposit. Increase in gravels – lag deposit.
51 – 64	3C	7.5 YR 6/4	strong, fine granular	50/ sa-sr, 2-50mm	loamy sand	few, faint co-br	abrupt, smooth	less clay/ silt than overlying. Very granular; structure and clay films probably related to stratigraphic position over relatively impermeable layer. Lower part of unit is a stone line with larger clasts numerous. Rocks are surprisingly angular – rapid deposition and burial.
64 – 77	ABb	10 YR 6/2	moderate, coarse subangular blocky	<5/ sa-sr, 2-40mm	silty clay loam	few, distinct ped face and co-br, common, distinct pore	clear, wavy	orange mottles visible. Probably an old floodplain deposit. Pinches out ~4m north.
77 – 110	4C	10 YR 6/3	moderate, medium granular	60/ sa-sr, 2-80mm	sandy clay	common, distinct pore and co-br	bedrock	slightly moist from groundwater. Numerous large clasts to 10cm are present. Texture is clay with coarse sand and larger clasts included.

Notes: Area along arroyo has not been plowed. Nearby hillslopes have been plowed recently. Drainage basin area: 2.28km^2

Interpretation: The series of strata exposed in this profile appears to represent several recent episodes of deposition over basal deposits that were probably a stable surface for a long period of time prior to recent landscape changes. The thin A horizon is enriched in gravel relative to the subjacent deposit. This may be the result of deflation due to rapid stream flow at the banks of the current arroyo or deflation of the entire floodplain surface prior to arroyo formation. The degree of pedogenesis in (and inferred age of) the two subjacent C horizons is somewhat ambiguous. In both, structure is moderately expressed, but clay films are weak. This suggests that the structure may have formed rapidly due to the presence of pedogenic clays inherited from hillslope parent materials as well as the relative abundance of water and fine sediments in the fluvial system, combined with annual cycles of inundation and desiccation. These two units may have been deposited during a single flood event, with deposition of clasts occurring before finer materials settled as the floodwaters slowed. The rounding of clasts in the lower unit suggests extended exposure in a fluvial system for some of the clasts. The range of rounding, however, implies multiple origins for the clasts. The simplest explanation is that the unit includes clasts from hillslopes as well as from stream beds higher in the fluvial system. Together, the two units most likely were at the surface of a floodplain without an incised stream for a period of time on the order of decades. The peak in magnetic susceptibility in the lower of the two probably also is an inherited characteristic. It is likely related both to soil formation and to burning, as charcoal flecks are present in this unit. The clay film morphology in the 2C horizon is more strongly expressed while the structure is weaker. This again suggests that some of the pedogenic characteristics may be inherited. The unit is laterally continuous with a stone line; it may be a channel bedload deposit. The overall weak soil development, lack of color change, and variability in clast rounding all suggest, however, that the channel was not present for an extended period of time before it filled. The 3C stratum again has relatively strongly expressed structure coupled with weakly developed clay films. In this case, the structure may be related to groundwater effects due to the position of the stratum over a relatively impermeable unit. The presence of a stone line made up of angular to subangular clasts at the base of the unit and the abrupt lower boundary suggest rapid deposition and burial during a high-magnitude flood event, one that might have caused localized channel incision prior to aggradation. The changes in texture, color, structure, clast content and clay film morphology in the subjacent ABb horizon all provide evidence that this unit was at or near the surface for a protracted period of time in the past. The low magnetic susceptibility measurement at this depth may reflect eluviation while the sediments were exposed at the surface, but the presence of groundwater very likely has altered patterns in magnetic susceptibility. The unit pinches out approximately 4 meters to the north, suggesting that past erosion removed it in some areas. Soil characteristics suggest that this unit formed in moist conditions at a low point on the landscape, probably during an extended period of stability. The color, texture, clay film morphology, and clast characteristics of the basal unit all suggest a similar origin for this deposit.

In sum, the profile suggests a protracted period of landscape stability in the past followed by recent, rapid hillslope erosion and deposition. The multiple strata and rock lines in the recent deposits most likely reflect complex response of the fluvial system to increased water and sediment inputs when the surrounding hillslopes were plowed; multiple, discontinuous channels formed as bodies of sediment were transported to the trunk stream, before the more recent formation of a continuous channel throughout at least the lower parts of the system. The lack of artifacts and datable organic material makes it difficult to discern when each of the units was deposited. Pedogenic and clast characteristics are consistent with deposition of the upper 64cm during the past century. Structure, color and clay film morphology suggest greater antiquity for the basal units. Given the uncertainties created by the removal of an unknown amount of overlying material prior to the recent deposition and the various ways groundwater can alter soil characteristics, it is not possible to discern with the present data whether the earlier period of landscape stability persisted for centuries or millennia.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

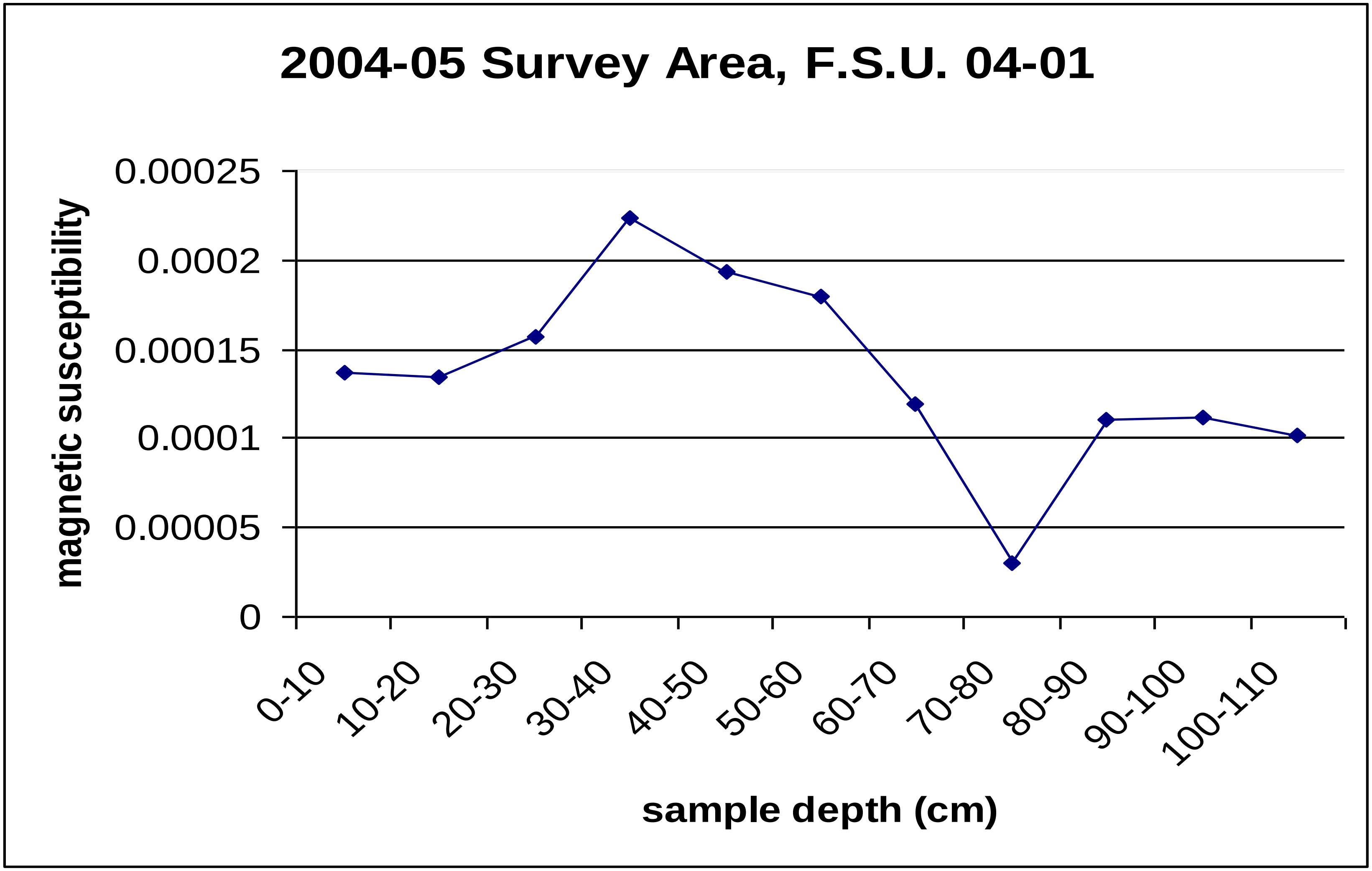

Figure A1 - 3: Magnetic susceptibility by depth, 2004-05 survey area, fluvial study unit 1

2004-05 Survey Area, Fluvial Study Unit 04-02

Date: August 4, 2004
Location: Arroyo in floodplain, near confluence with unincised drainage from the East. Small tributary to the Barranco do Corcho.
Coordinates: 29S 612096E, 4178850N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 4	A	10 YR 5/4	single grain	20/ a-sa, 2-15mm	silt	none	clear, smooth	O horizon above, ~3cm. Very high organic content. High aeolian inputs, trapped by vegetation.
4 – 10	C	7.5 YR 5/4	weak, medium granular	35/ a-sr, 2-15mm	loamy sand	few, faint pore and co-br	clear, smooth	fines upward. Fluvial deposit.
10 – 36	2C	7.5 YR 6/4	moderate, coarse subangular blocky	<3/ a-sa, 2-10mm	sandy loam	few, distinct co-br, many, prominent pore	clear, smooth	a very large rodent burrow is present, filled in. Flecks of charcoal are visible, not collected. The sand is very fine.
36 – 49	3C	7.5 YR 5/3	weak, medium granular	40/ sa-sr, 2-20mm	loamy sand	few, faint ped face, pore and co-br	clear, smooth	clay films are probably related to groundwater. Original fluvial depositional structures are preserved, platy clasts are horizontal, imbricated.
49 – 54	4C	10 YR 6/3	moderate, medium, subangular blocky	<3/ a-sa, 2-4mm	sandy loam	few, faint ped face, common, distinct pore and co-br	clear, smooth	This stratum appears to create a minor hydrological barrier based on precipitates visible on the face of the arroyo. Texture may be sandy clay loam.
54 – 75	5C	10 YR 5/4	weak, coarse granular	40/ sa-sr, 2-30mm	loamy sand	few, faint ped face, common, distinct pore and co-br	clear, wavy	few original fluvial structures are preserved, including discontinuous stone lines of small clasts. Clay films are variable and probably related to groundwater. Lower boundary is a stone line of platy clasts, horizontally imbricated, 10 – 15cm m.d.
75 – 104	(ABb)>6C	2.5 Y 6/4	moderate, medium subangular blocky	40/ sa, 2-35mm	clay loam	common, distinct ped face	bedrock	larger clasts are common, especially concentrated in the stone line at the top of the stratum. They are horizontal in the stone line, random orientation below. The stratum is not related to the modern arroyo, it is the same as parent material seen downstream where the arroyo has moved and cut into previously undisturbed material.

Notes: Area along arroyo has not been plowed. Nearby hillslopes have been plowed recently. Drainage basin area: 0.3km^2

Interpretation: The strata exposed in this profile generally mirror those exposed in unit 04-01, with a series of recent deposits over a much older stratum. An O horizon has accumulated at the surface because of the relatively dense vegetation present in the unplowed area along the arroyo. The A horizon at the top of the mineral soil does not show any signs of soil development; it is a recent deposit and the texture suggests that it is derived from aeolian materials trapped by vegetation with additional inputs from overbank flooding and possibly insect (earthworm) bioturbation. The subjacent stratum also exhibits very weak soil development. This is a fluvial deposit, as shown by the preservation of depositional structures and the fact that it fines upward. The relatively coarse texture suggests that deposition may have preceded the formation of an incised channel in this location. The moderate expression of structure and the texture of the underlying unit suggest a somewhat longer period of exposure at the surface, but the clay film morphology suggests that this could not have been a stable surface in this geomorphic position for more than a few decades. In addition, the angularity of clasts shows that they were not reworked by flowing water for an extended period of time. This stratum may represent overbank deposits laid down when a channel had formed in this location or an extended period without flashy, high discharge flows. The structure, clay film morphology and preservation of original fluvial structures in the underlying stratum suggest rapid fluvial deposition and burial after a short period of exposure at the surface. The subjacent 4C horizon is similar in many respects to the 2C horizon, with texture, structure and clay film morphology suggesting stability for as long as a few decades. The angularity of clasts again shows no extended exposure to running water. The structure, clay film morphology and preservation of original fluvial structures show that the underlying stratum was deposited and buried rapidly. Although the clear boundaries between deposits suggests otherwise, it is possible that 5C-4C, 3C-2C, and C-A represent flood couplets, each couplet having been deposited during a single flood, with coarse materials settling out first and finer materials settling during the waning phase of the flow. The basal deposit is capped by a line of imbricated clasts, 10 to 15 cm in maximum dimension. The similarity to the randomly-oriented clasts in the basal deposit implies that this is a lag deposit that was created when a channel incised into and reworked materials from the basal deposit. Observations a few meters away suggest that this lowest deposit is the parent material in this part of the basin and clay film morphology, color, texture and structure all indicate that it was at or near the surface for a period of time on the order of centuries to millennia. While it is not possible to determine the age of the deposit with greater accuracy from the current information, analogy to deposits in the 1992 survey area, study unit 3, suggest that it may have been initially emplaced by colluvial and fluvial processes during a period of landscape change related to major climate changes, perhaps at the Pleistocene – Holocene boundary. In sum, the strata exposed in this profile suggest an extended period of landscape stability followed by recent (20th Century) hillslope erosion and floodplain deposition. The stratigraphy is consistent with multiple recent episodes of deposition and channel formation, as described in complex response models, prior to the formation of a continuous channel through this reach of the fluvial system.

* colors given are for dry sediments unless otherwise noted

** structure designations after Birkeland 1999

*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area, Fluvial Study Unit 04-03

Date: August 5, 2004
Location: Upper end of drainage basin, near headcut. Small tributary to Barranco do Corcho.
Coordinates: 29S 613670E, 4178141N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	ABp	10 YR 6/4	weak, medium subangular blocky	50/ a-sa, 2-50mm	sandy loam	few, faint ped face	abrupt, smooth	clasts are randomly oriented. Appears to be *in situ* soil. Larger clasts are common.
15 – 32	Bt	2.5 Y 7/4	moderate, coarse granular	60/ a-sa, 2-35mm	clay loam	many, distinct ped face	gradual, smooth	structure is strongly affected by high gravel content. Larger clasts are common. Texture might be sandy clay.
32 – 50	C>Bt2	5 YR 7/6	strong, medium angular blocky	5/ sa-r, 2-10mm	sandy clay loam	many, prominent ped face	bedrock	stratum is decomposing bedrock. Orange mottling is prominent – frequent saturation with groundwater. Bedrock is friable, very weak.

Notes: Area has been plowed and has a standing crop of wheat. Arroyo appears to be cutting through *in situ* soils. Drainage basin area: 0.02 km^2

Interpretation: This profile exposes a relatively simple soil with no clear evidence for massive erosion or significant accumulation in the recent past. The weak expression of structure and clay film morphology in the ABp horizon reflect both ongoing plowing in the area and, most likely, deposition in low points on the landscape due to erosion higher on the slopes. The relatively coarse texture of this unit and the magnetic susceptibility data also suggest some degree of mobility for surface sediments. Clay films in the Bt horizon suggest a long period of pedogenesis. The structure does not reflect as significant a period of stability, but the development of structure appears to be inhibited by the abundance of gravels. The expression of time-dependent pedogenic characteristics in the basal stratum is as strong as any encountered in this study, suggesting a period of landscape stability and soil formation on the order of millennia. The stratum is made up of decomposing bedrock and prominent mottling is evidence of frequent, prolonged saturation with groundwater. The relative lack of clasts suggests that the overlying strata formed during very long periods of weathering and removal of finer sediments.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

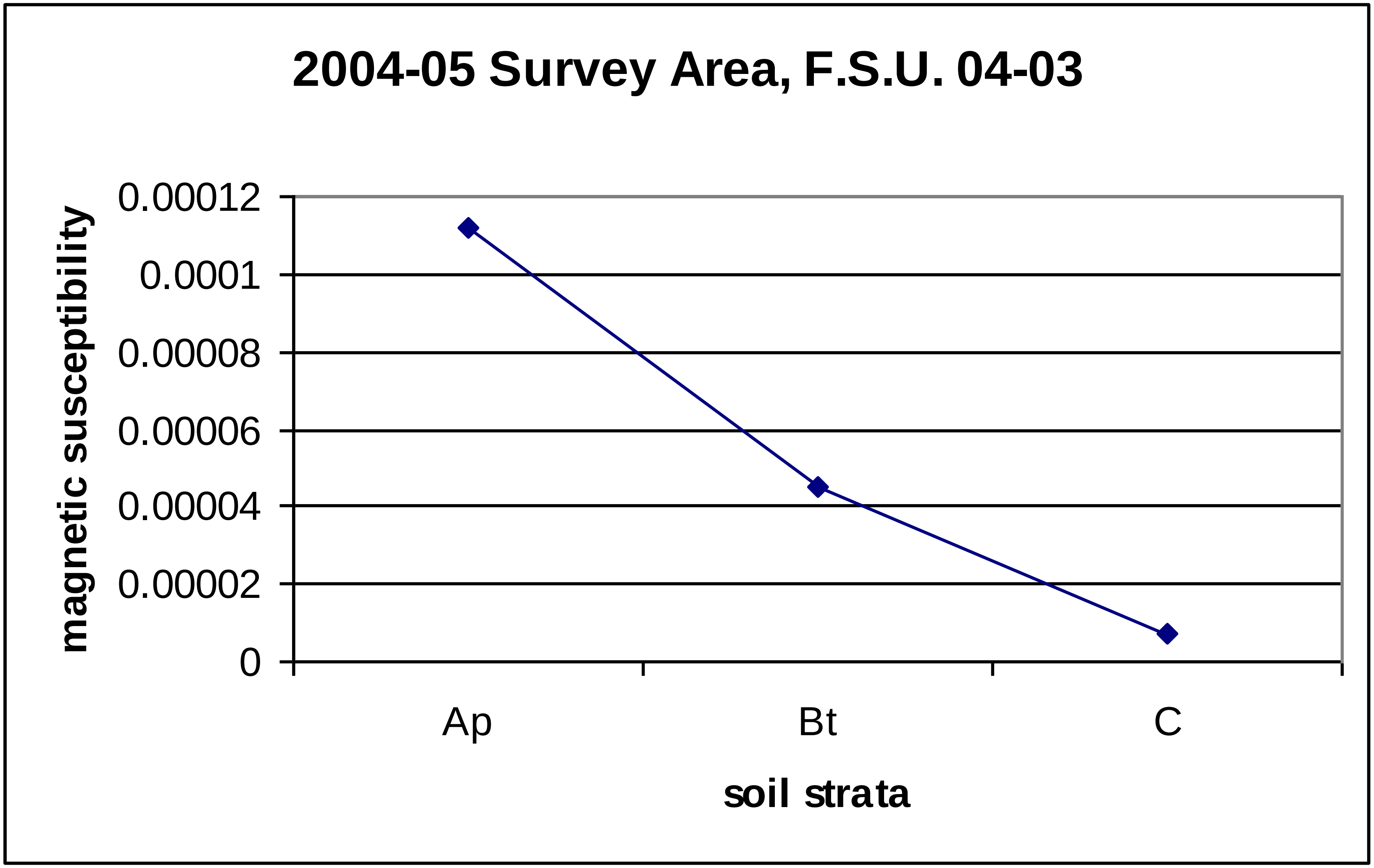

Figure A1 - 4: Magnetic susceptibility by depth, 2004-05 survey area, fluvial study unit 3

2004-05 Survey Area, Fluvial Study Unit 04-04

Date: August 5, 2004
Location: Same arroyo as unit 04-03, ~ 180m downstream. Small tributary to Barranco do Corcho.
Coordinates: 29S 613699E, 4178318N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	C	5 YR 6/4	massive	50/ a-sa, 2-25mm	sand	none	clear, smooth	Massive structure appears to be mostly due to roots. May be a very weak A at the surface, <1cm thick. Stratum appears to be rapid deposition following plowing.
14 – 25	2C	7.5 YR 6/3	weak, fine granular	40/ sa-sr, 2-10mm	loamy sand	none	clear, smooth	fines upward. Depositional unit, no evidence for pedogenesis.
25 – 31	3C	7.5 YR 7/4	weak, fine subangular blocky	10/ sa, 2-7mm	loam	common, faint co-br	clear, wavy	waviness of lower boundary is due to krotovina, not deposition. Orange mottling is prominent. There is evidence of bioturbation in about 20% of the exposed area.
31 – 38	4C	7.5 YR 5/4	weak, fine granular	40/ a-sa, 2-10mm	loamy sand	none	clear, smooth	unit fines upward. This is a depositional unit, there is no significant evidence of pedogenesis.
38 – 42	5C	10 YR 7/4	massive	<1/ a, 2mm (quartz)	sandy loam	none	clear, wavy	orange mottling is visible but not prominent. Fine laminae (original depositional structures) are preserved. Sand fraction is very fine.
42 – 45	Ab	10 YR 6/3	moderate, coarse granular	5/ sa-sr, 2-4mm	silty clay loam	common, distinct pore	gradual, wavy	orange mottling is prominent, pores are stained orange. Slightly moist. Riparian deposit?
45 – 53	Btb	10 YR 6/3	moderate, coarse subangular blocky	<5/ a-sr, 2-25mm	silty clay loam	few, faint ped face and common, distinct pore	gradual, smooth	stone line with horizontal clasts to 20cm. Orange mottling is prominent. Lower boundary is defined by decrease in clasts and decrease in mottling.
53 – 66	Bt2	10 YR 6/3	moderate, coarse subangular blocky	<5/ sa-sr, 2-7mm	loam	common, distinct pore	gradual, smooth	some reddish mottling. Similar to overlying stratum, no stone line and more sand.
66 – 80	6C>3B	2.5 Y 7/6	moderate, medium subangular blocky	<5/ sa-sr, 2-4mm	silty clay loam	few, faint ped face, prominent, distinct pore	bedrock	unit not excavated to bedrock across entire exposure, depth of bedrock is variable. Stratum looks like decomposing bedrock.

Notes: Area has been plowed to very near the edge of the arroyo, there is a standing crop of wheat. Drainage basin area: 0.14 km^2

Interpretation: The strata exposed in this profile again reflect recent deposition over sediments that are probably considerably older. The lack of clay films and very weak structure in the two surface strata show that they have been in place for a short period of time, on the order of years. The subjacent 3C deposit exhibits weak structure and clay films, suggesting a short period of exposure at the surface, perhaps on the order of a few decades. The weak development of ped structure and lack of clay films in the subjacent two strata again suggest rapid deposition and burial. The thin, buried A horizon has a moderately developed granular structure, weakly developed clay films and mottling that suggests prolonged and repeated exposure to groundwater. The degree of soil development implies a period of exposure at the surface on the order of decades, although groundwater may have enhanced the pedogenic characteristics. The subjacent horizon consists of a stone line, representing a period of erosion and channel formation in the past. The degree of soil development is stronger than in superjacent deposits, suggesting a period of stability after the channel formed. While the structure suggests moderate pedogenesis, the clay film morphology implies weaker soil development. Some characteristics may be inherited; this stratum probably does not represent a channel that was stable for centuries. The underlying deposit is similar in terms of color, structure, texture and clay film morphology, suggesting that the two were probably laid down at roughly the same time and that they were derived from the same source. That the stone line is in the upper of the two units suggests that the initial period of arroyo formation was followed by filling before the channel stabilized at the elevation of the upper stratum. The color change in the basal deposit, and comparisons to nearby strata, suggest that it is composed of weathered bedrock; it must have been in place for many centuries to millennia. The moderate degree of soil development implies that it was deeply buried in the past, below the zone of rapid soil development, before the overlying sediments were removed by arroyo formation. As a whole, then, the strata record a period of stability, probably on the order of millennia, in the past. Within approximately the past century, a channel formed and removed an unknown amount of sediment. Since then, the channel partially filled, stabilized for as long as several decades, then the floodplain rapidly aggraded before the recent formation of the current channel.

* colors given are for dry sediments unless otherwise noted

** structure designations after Birkeland 1999

*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area, Fluvial Study Unit 04-05

Date: August 5, 2004
Location: Channel is located in a narrow valley with a poorly defined floodplain. Small tributary to Barranco da Vila.
Coordinates: 29S 612652E, 4175793N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 7	Ap	7.5 YR 6/4	moderate, medium granular	40/ a-sa, 2-50mm	loam	common, faint co-br	clear, wavy	recent, rapid deposition, probably related to plowing of adjacent hillslopes
7 – 27	Bt	10 YR 6/4	moderate, medium subangular blocky	20/ sa-sr, 2-30mm	clay loam	few, faint ped face	gradual, smooth	few larger clasts are visible. Low clay content for a clay loam, may grade to loam. Combination of buried Ap and weak B, recent deposition?
27 – 66	Bt2	7.5 YR 6/4	moderate, coarse subangular blocky	20/ sa-sr, 2-20mm	clay loam	few, distinct ped face, many, prominent pore	gradual, smooth	slight rubification possibly due to groundwater. Few larger clasts visible. Similar to overlying.
66 – 80	Bt3	10 YR 6/4	moderate, medium subangular blocky	40/ sa-r, 2-15mm	clay loam	common, prominent ped face	bedrock	probably a mix of decomposing bedrock and fluvial deposition. Few larger clasts visible.
Notes: Channel is located in a relatively small drainage basin and becomes discontinuous 10's of meters upstream. Area has been plowed recently. Relatively thick soils (~30cm) remain on nearby hillslopes. Drainage basin area: 0.21 km^2								
Interpretation: The strata exposed in this study unit appear to reflect recent movement of hillslope deposits to lower points on the landscape. The weak clay films, minimal degree of clast rounding and clear lower boundary of the A horizon suggest recent deposition and minimal transport. The granular structure may be due to plowing, either before or after transport from the hillslopes. The subjacent horizon exhibits moderate structure and weak to moderate clay film morphology, implying a period of stability and exposure at or near the surface on the order of decades to centuries. While the gradual, smooth lower boundary suggests *in situ* soil formation, the differences from the overlying and underlying deposits imply some hillslope inputs. This unit probably includes recent hillslope sediments and *in situ* deposits, mixed by past plowing and bioturbation. Mixing probably also obscured evidence of a buried A horizon. The underlying deposit is similar, with slightly stronger expression of time-dependent pedogenic characteristics. This unit is probably also cumulic, representing slower, long-term aggradation due to minor hillslope erosion and aeolian inputs. The clay films and structure of the basal unit show moderate to strong pedogenesis, suggesting landscape stability and exposure at or near the surface for a period of time on the order of many centuries to millennia. Given the gradual boundaries between the three lowest units, it appears as though all three represent gradual deposition and pedogenesis over the course of a protracted period of landscape stability, with inputs from hillslopes increasing recently. The surface stratum represents rapid, recent deposition, most likely due to plowing within the past century.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area, Fluvial Study Unit 04-06

Date: August 6, 2004
Location: The arroyo is in a broad floodplain, in the upper reaches of the Barranco da Vila.
Coordinates: 29S 612648E, 4176440N

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 6	C	7.5 YR 6/4	massive	<1	loamy sand	none	clear, wavy	minor accumulation of organic material at the surface, could be described as and O horizon, < ½ cm, no visible A. Fine-grained depositional unit, appears to be overbank after arroyo formation, sand is very fine. Some orange mottling is present.
6 – 9	Ab	10 YR 5/4	moderate, coarse, granular	2/ sa-sr, 2-3mm	silt	few, distinct pore	clear, wavy	Some subangular blocky structure present. Lots of roots and organic material (leaves etc.), recently buried surface. Texture difficult to determine due to organics. Weak soil development.
9 – 12	2C	10 YR 6/4	moderate, medium subangular blocky	< 1	loamy sand	few, faint pore	clear, smooth	some laminae (original depositional structures) visible. Some orange mottling present. Overbank? Rapidly buried.
12 – 23	3C	10 YR 6/3	moderate, medium granular	40/ sa-r, 2-10mm	loamy sand	common, distinct co-br	clear, smooth	unit fines upward. Clay films (coatings) are especially prominent in lower portion – very granular – suggests groundwater. Floodplain deposit, sand is coarse. High clay content due to groundwater?
23 – 25	4C	10 YR 6/3	moderate, medium subangular blocky	2/ sa-sr, 2-3mm	sandy loam	few, distinct pore	clear, smooth	similar to 2C. some laminae observed. Some orange mottling is visible.
25 – 34	5C	10 YR 6/4	moderate, medium granular	30/ a-sr, 2-15mm	loamy sand	few, faint ped face, common, distinct co-br	clear, wavy	similar to 3C. Some subangular blocky structure is present. Unit fines upward. Finer layer in the middle (depositional) with fewer clasts. Some mottling is visible.
34 – 44	6C	2.5 Y 7/3	moderate, coarse subangular blocky	10/ sa-sr, 2-15mm	loam	few, faint ped face, common, distinct pore	clear, smooth	stone line, larger clasts common, most larger clasts horizontal. Many clasts are stained black (Mg?). Mostly reworked subjacent with some organic or hillslope inputs. Some weak orange mottling is present.
44 – 105	7C	10 YR 7/6	moderate, medium subangular blocky	25/ a-sr, 2-15mm	clay loam	few, distinct co-br	bedrock	undifferentiated with weak soil development, probably deeply buried in the past & not exposed at surface for long. Increase in moisture and mottling is visible at 95cm. Orange mottling is common throughout. Larger clasts are common, but decrease somewhat with depth. *In situ* decomposing bedrock/ parent material.

Notes: Channel is in a broad, well-defined floodplain with a large drainage basin. Floodplain has not been plowed recently and is covered with shrubs (esteva etc.). Nearby hillslopes have been farmed recently. Drainage basin area: 0.59 km^2

Interpretation: The strata exposed in this profile appear to reflect relatively recent channel formation and multiple episodes of deposition. The structure, lower boundary and lack of clay films in the surface deposit suggest recent deposition by overbank flooding with minimal time for pedogenesis. The incorporation of identifiable organic remains (leaves etc.) into the subjacent buried A horizon also implies very recent burial. The structure, clay films and lower boundary of that horizon suggest a short period of exposure at the surface, on the order of years to a few decades. The preservation of original depositional structures in the four subjacent units (2C – 5C) is a characteristic commonly observed in weakly developed, rapidly buried cumulic floodplain soils. The color, structure, clay film morphology and boundaries of each unit corroborate the impression of rapid deposition followed by burial after a period of years to a few decades. The 6C horizon incorporates a stone line, with imbricated large clasts; this was the bedload of a channel. The structure, color, texture and clay film morphology suggest a period of relative stability for the channel at this elevation perhaps as long as a few decades. On the other hand, the lower boundary and lack of differentiation within the subjacent deposit show that the channel did not persist for a period of time long enough to cause pedogenic alteration of near-surface deposits; the channel was not present for more than a few decades. The color, clasts and texture of the basal deposit show that it consists of *in situ* decomposing bedrock and parent material. The moderate structure and especially the weak clay film morphology suggest that this stratum was relatively deeply buried in the past, during a protracted period of landscape stability before the initial channel formation. The profile, then, suggests a period of landscape stability, followed by initial channel formation and the removal of an unknown amount of sediment within approximately the past century. This was followed by several episodes of deposition separated by at most a few decades, and then the recent formation of the current channel.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

Soil Description Tables, Hillslope Shovel Test Pits:

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 1

Date: July 5, 2004
Location: Top of hill above ribeira at Alcaria Longa (east end of site)
Coordinates: 29S 601488E, 4157039N Slope: 2* Aspect: ENE, 72*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 8	A	10 YR 6/3	moderate, medium granular	30/ a – sr, 2-20mm	loam	few, faint pore, ped face & co-br	bedrock	depth of soil is highly variable, mostly less than 8cm. Bedrock outcrops are common in the vicinity of the test pit and numerous larger clasts are visible at the surface. Texture might grade to sandy loam with a very fine sand component. Artifacts are present throughout.

Notes: STP is within 2 m of Islamic period structure. There is no clear evidence for recent plowing at the top of the hill. Bedrock is exposed in much of the area nearby.

Interpretation: This soil is thin and poorly developed. The thinness of the deposits and lack of clear horizonation suggest that the area was completely stripped of loose sediments within the past millennium and that there has not been a sufficient period of time for a clearly expressed soil to develop in the more recent deposits. The sediments in place now most likely originated from a combination of aeolian deposition and weathering of bedrock. The structure and clay film morphology indicate incipient soil development and suggest that the locus has not been plowed repeatedly. The magnetic susceptibility data are also consistent with incipient soil development, indicating slightly increased susceptibility with depth.

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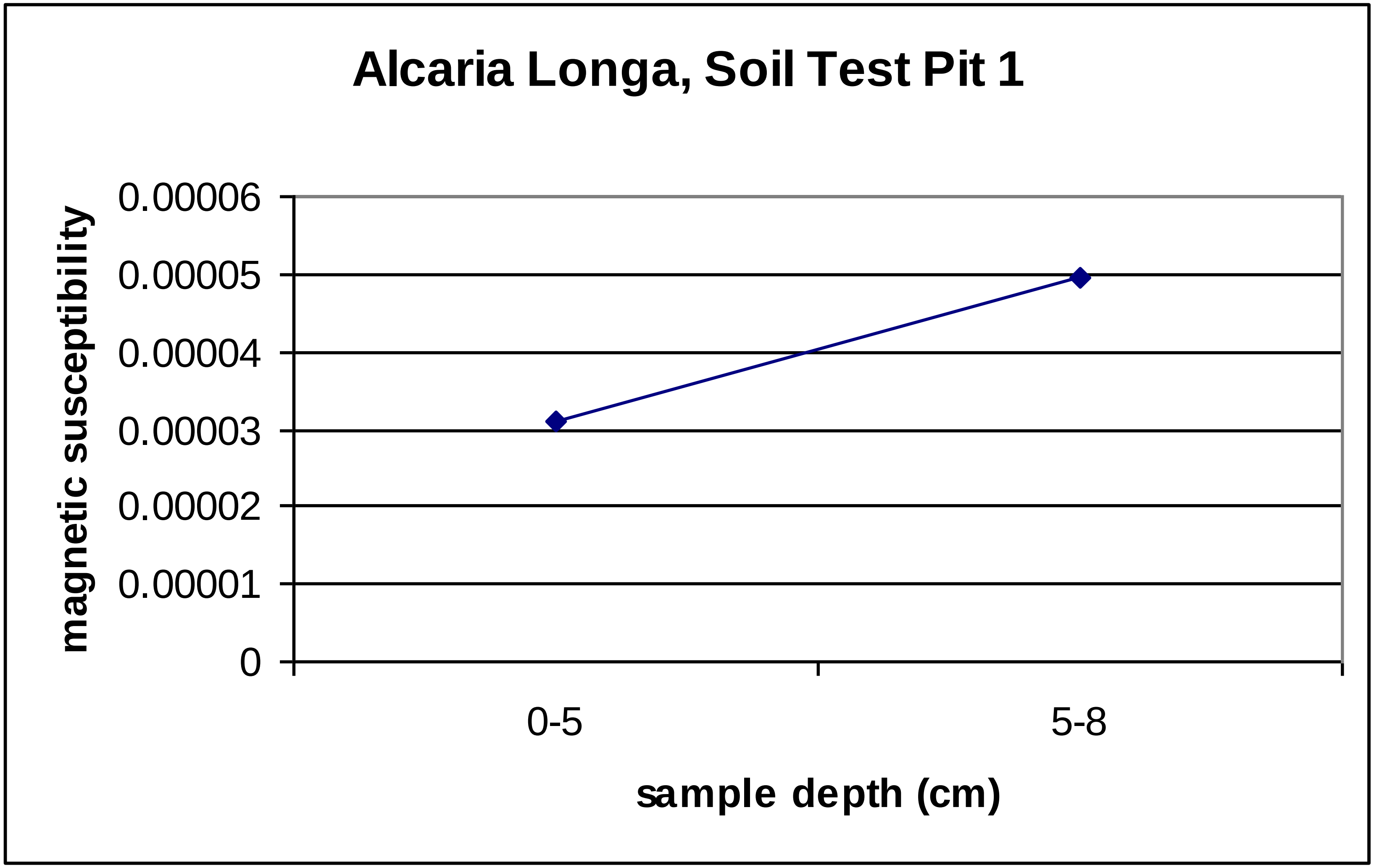

Figure A1 - 5: Magnetic susceptibility by depth, Alcaria Longa soil test pit 1

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 2

Date: July 5, 2004
Location: Shoulder of slope east of Alcaria Longa
Coordinates: 29S 601505E, 4157042N   Slope: 16*   Aspect: ENE, 75*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	AB	2.5 Y 6/3	moderate, medium granular to subangular blocky	35/ sa – sr, 2-40mm	loam	common, distinct ped face, pore & co-br	gradual, smooth	clasts to ~20cm m.d. visible in stratum. Sherd of coarse red-brown at 5cm.
15 – ~33	Bt	10 YR 6/2	moderate to strong, medium to coarse, subangular blocky	40/ a – sr, 2-70+mm	silt loam	common, distinct to prominent ped face, pore & co-br	bedrock	some granular structure present. Slightly darker than superjacent, otherwise generally similar. Clasts to ~15cm m.d. visible in stratum. Large piece of roof tile at 30cm, other artifacts present to base. Gravel increases with depth.
Notes: Area not recently plowed. It may have been disked in the past to remove esteva although nearby bedrock outcrops would make plowing difficult. Locus was chosen for study because it appeared to be relatively undisturbed compared to the rest of the slope.								
Interpretation: The soil profile exposed in pit 2 exhibits moderate to strong soil development in relatively thick hillslope deposits. Structure, clay film morphology and boundary characteristics in the AB horizon suggest that the area has not been plowed recently. The presence of a relatively distinct B horizon and the increase in magnetic susceptibility to a peak at 20-25cm are also consistent with pedogenesis occurring in relatively undisturbed deposits, with some sediment input from higher on the slope possible. Artifacts at the base of the exposure indicate that the area was stripped of soil in the past, during or after the Islamic period occupation. Observations of the soils higher on the hillslope suggest that the pedogenic characteristics are probably not inherited. The degree of soil development suggests that sediments must have been deposited soon after the Islamic period occupation, with pedogenesis altering them since. The greater degree of soil development in STP2 relative to STP1 is probably due to increased inputs of water and sediment at this location due to runoff from areas higher on the slope. The relatively strong expression of time dependent pedogenic characteristics in this deposit is probably at the upper limit of what might be observed in soils forming in sediments deposited on hillslopes since the Islamic period.								

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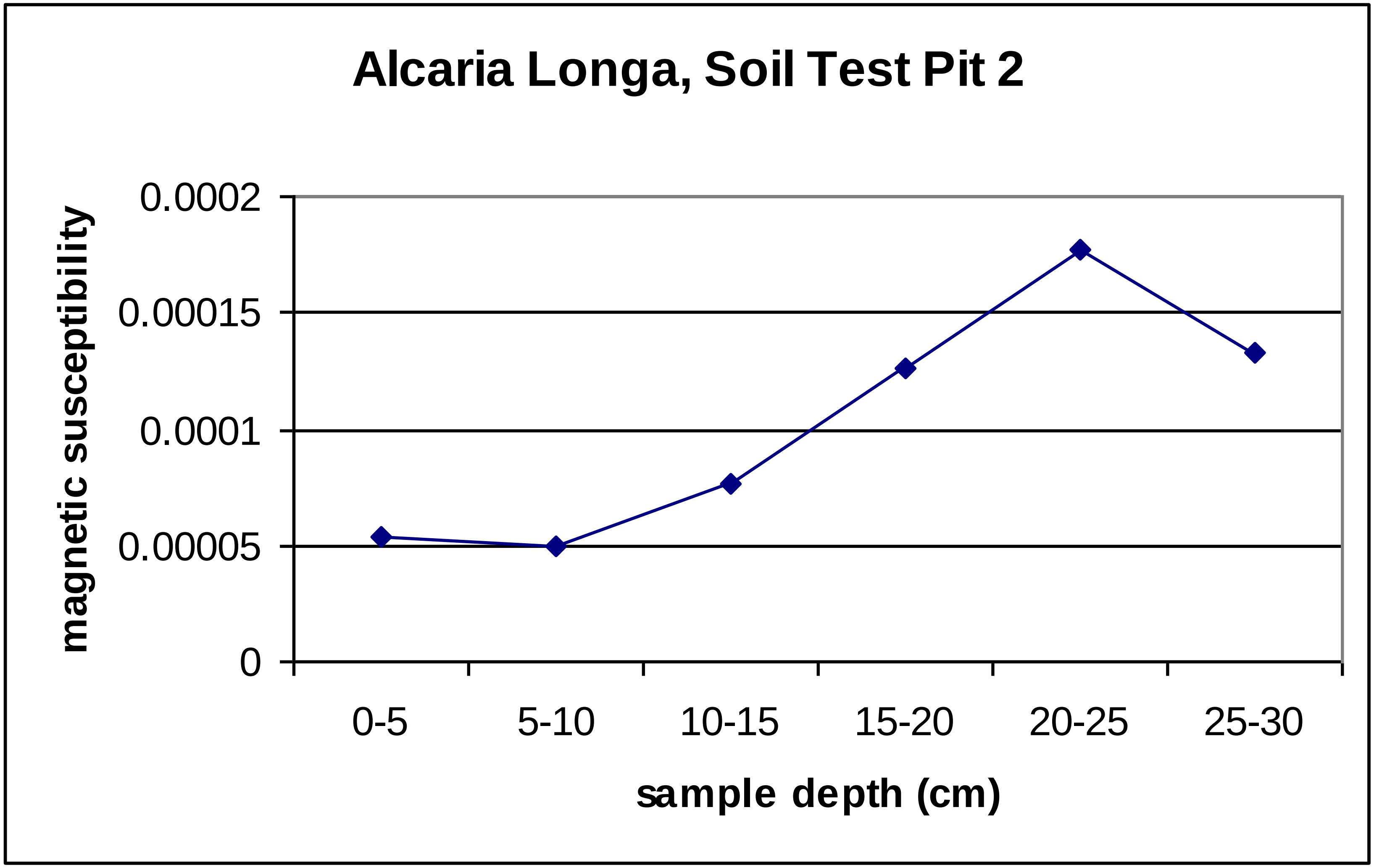

Figure A1 - 6: Magnetic susceptibility by depth, Alcaria Longa soil test pit 2

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 3

Date: July 5, 2004
Location: Back slope east of Alcaria Longa
Coordinates: 29S 601538E, 4157056N Slope: 21* Aspect: ENE, 70*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	2.5 Y 6/3	weak, medium granular to subangular blocky	50/ a – sa, 2-50mm	sandy loam	few, faint ped face, pore & co-br	clear, wavy	structure is mostly granular with a somewhat porous appearance. Some large (1cm diameter) krotovina are visible. Several artifacts, including sherds and roof tile fragments, are concentrated at the lower boundary.
10 – ~20	Bt	2.5 Y 6/3	moderate, medium subangular blocky	40/ sa, 2-40mm	loam	few, distinct ped face, pore & co-br	bedrock	depth to bedrock is variable, from 15 – 20cm. Color is redder at the base due to inclusions of weathering bedrock. Flecks of roof tile are present at 17cm. Gravel increases dramatically at ~15cm, becomes clast supported near bedrock. The bedrock is weathered and friable.

Notes: Vegetation indicates that the area has not been plowed in the past ~5 years or more.

Interpretation: The soil profile exposed in pit 3 exhibits moderate soil development similar to that in test pit 2. Although vegetation suggests no plowing in the past ~ 5 years, structure in the A horizon and the clear lower boundary suggest plowing at some time in the recent past (<<100 yr). The concentration of artifacts at the base of the stratum was likely created by plowing and/ or bioturbation. The similarities in color, structure, clastic content and clay film morphology between the A and B horizons lend support to this interpretation in preference to the artifact concentration being the result of past surface deflation. On the other hand, abundant clasts in the upper A horizon and at the base of the profile indicate significant deflation both in the past, prior to deposition of the sediments in which a soil is forming, and at present. The peak in magnetic susceptibility at 10 – 15 cm is consistent with moderate pedogenesis and ongoing erosion. Artifacts in the B horizon in and above the concentration of clasts at the contact with bedrock indicate that the past erosion occurred during or after the Islamic period, and the weathered, eroded appearance of the bedrock suggests that this area was completely stripped of soil at that time.

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*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

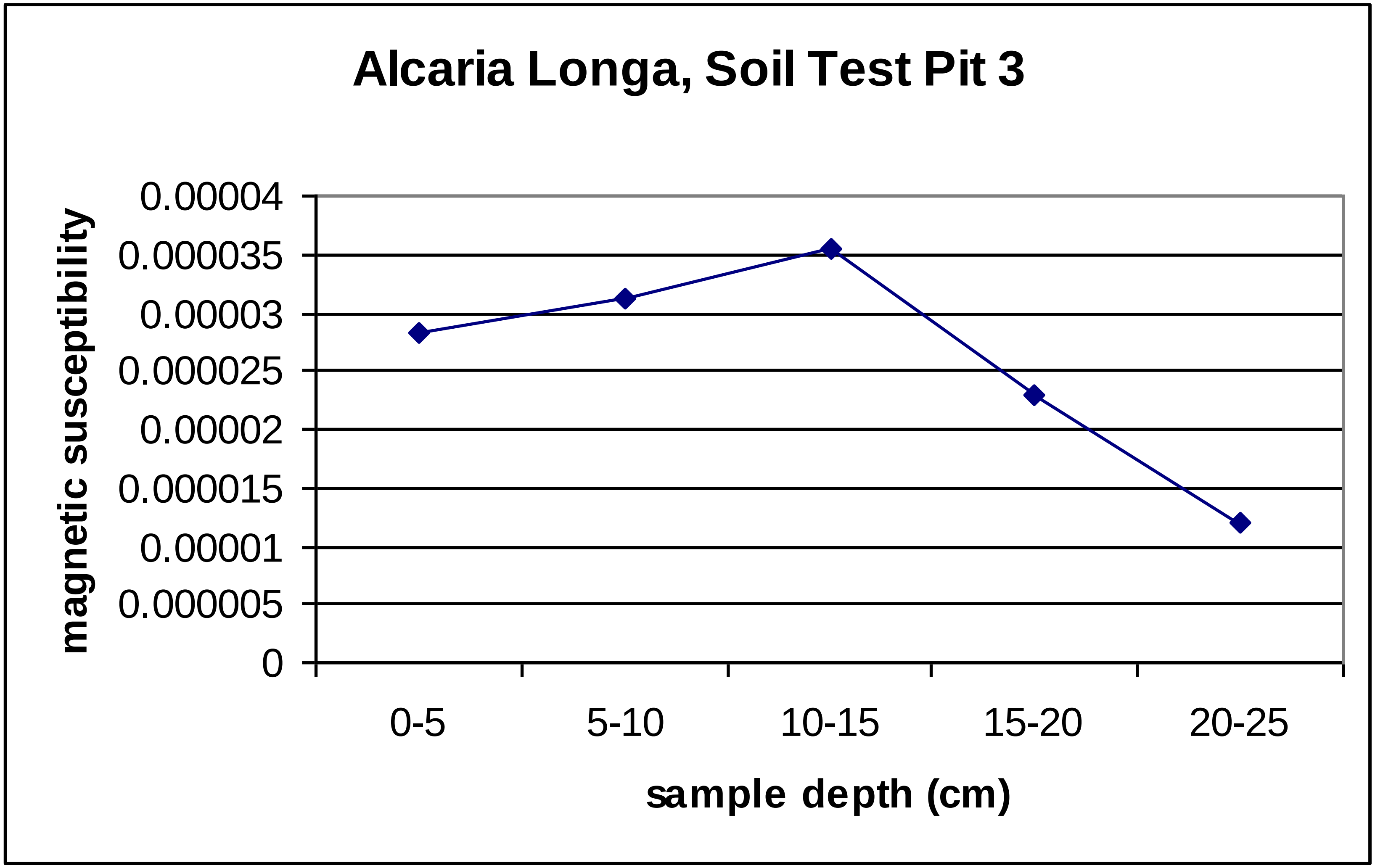

Figure A1 - 7: Magnetic susceptibility by depth, Alcaria Longa soil test pit 3

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 4

Date: July 5, 2004
Location: Foot of slope east of Alcaria Longa
Coordinates: 29S 601576E, 4157080N Slope: 10* Aspect: ENE, 76*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	2.5 Y 6/3	weak, medium granular to subangular blocky	35/ a – sr, 2-25mm	loam	few, faint ped face, pore & co-br	clear, wavy	plow zone. structure is primarily granular with a porous appearance and some sbk peds. Faint clay films are related to high clay content, precipitation and run-on.
10 – ~30	Bt	2.5 Y 6/3	moderate, medium to coarse, angular blocky	50/ a – sa, 2-40mm	clay loam	common, distinct ped face, pore & co-br	bedrock	depth to bedrock varies from 20 – 30 cm. Clasts increase with depth, becomes clast supported. Differentiated from overlying mostly by texture.

Notes: There is clear evidence that this area has been plowed recently.

Interpretation: As in the preceding two test pits, the soils exposed here show moderate development. The structure and boundary characteristics of the A horizon reflect recent and repeated plowing and the clastic content suggests moderate, ongoing erosion. The relatively strongly expressed structure in the B horizon is probably related to the high clay content; both the structure and the clay content may be due to increased soil moisture and deposition related to geomorphic position at the base of a slope. The increase in clasts at the base of the profile suggests that this area was stripped of soil in the past, leaving a gravelly lag deposit. The degree of soil development shows that this was at least roughly contemporaneous with past erosion higher on the slope. The angularity of the clasts, the high clay content of the matrix in the B horizon, and the magnetic susceptibility data, on the other hand, imply that some remnant sediments might have been preserved during the past cycle of erosion and that these have subsequently been mixed with more recent deposits.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

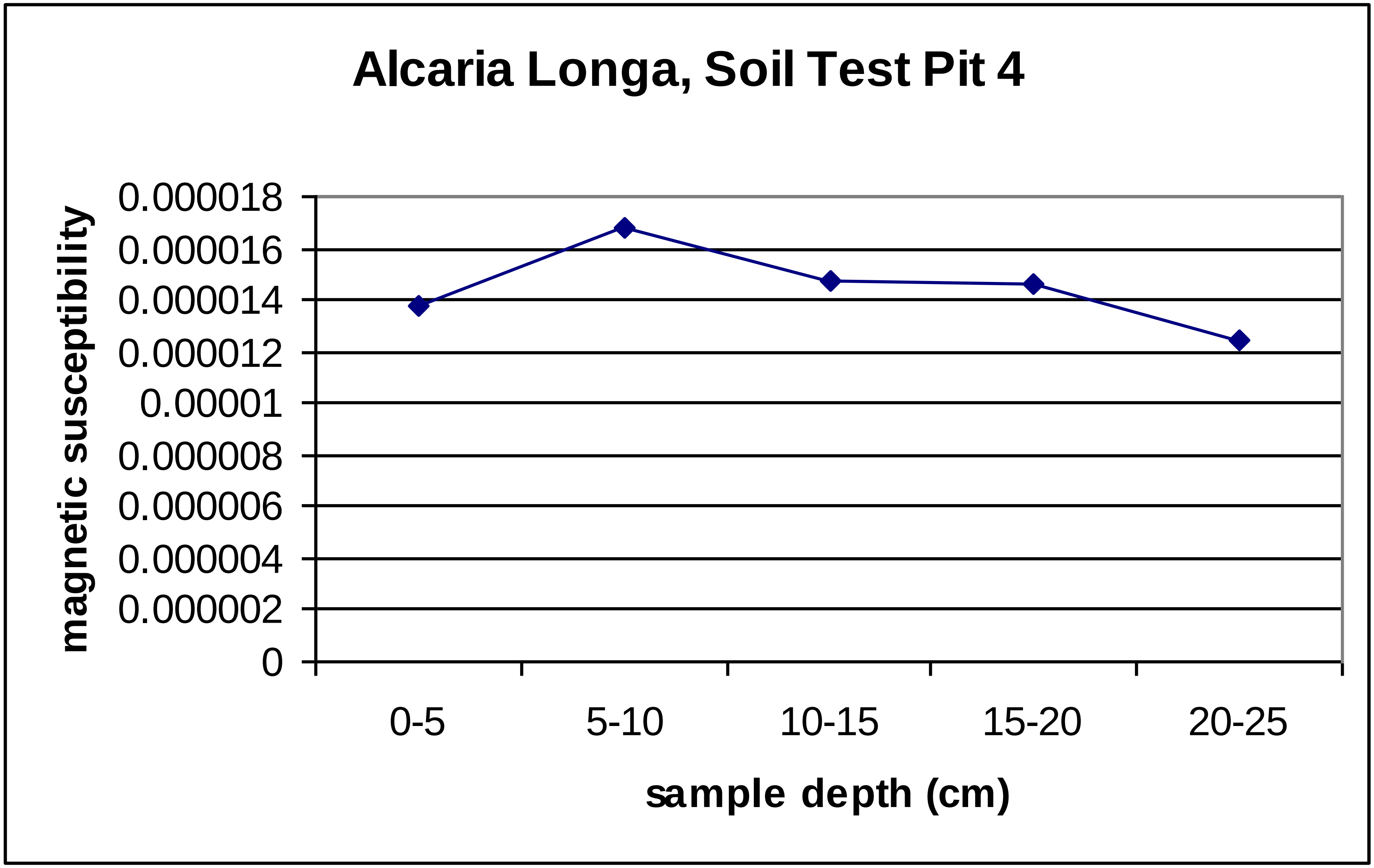

Figure A1 - 8: Magnetic susceptibility by depth, Alcaria Longa soil test pit 4

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 5

Date: July 3, 2004
Location: Toe of slope east of (below) Alcaria Longa
Coordinates: 29S 601589E, 4157094N Slope: 5* Aspect: ENE, 68*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 23	ABp	2.5 Y 6/3	moderate, coarse, subangular blocky	25/ sa – sr, 2-30mm	loam	very few, faint ped face, common, distinct pore & co-br	clear, smooth	rare angular blocky peds, deposit has a porous appearance. Rare rounded clasts. Larger clasts (cobbles) are visible at the surface. Small pieces of roof tile and small (<1cm) krotovina present.
23 – 43	ABb>Bt	10 YR 6/3	moderate, coarse to very coarse angular blocky	15-20/ sa – sr, 2-25mm	clay loam	common, prominent ped face, pore & co-br	gradual, smooth	some flecks of roof tile present, abundance decreases with depth. Peds much more distinct than ABp. Clasts to 10cm m.d. present but rare.
43 – 75	Btb (2AB?) > Bt2	10 YR 6/3	strong, coarse to very coarse angular blocky	<5/ sa – r, 2-8mm	silty clay	common to many prominent ped face, pore and co-br	bedrock	differentiated from overlying primarily by clast content. High clay content, large soil cracks – shrink-swell? No artifacts visible.

Notes: There is clear evidence that this area has been plowed recently.

Interpretation: The soil exposed in this test pit appears to be polygenetic; the pedogenic features of the soil related to the previous surface(s) have been obscured by soil welding as features related to soil development at the modern surface have become more prominent. The structure of the A horizon shows slightly stronger development than the analogous horizon higher on the slope. The structure, color and clay film morphology of the upper B horizon also show significantly stronger expression of time-dependent pedogenic characteristics than soils higher on the slope. These characteristics are at least in part the result of the long-term impact of additional water inputs due to geomorphic position at the base of the slope as well as recent accumulation of sediments as opposed to erosion.

There are two possible scenarios of the history of erosion and deposition in this location: On one hand, the inclusion of artifacts suggests that the upper ~ 43 cm of deposits do not antedate the Islamic period. If that is the case, the pedogenic characteristics of the ABb>Bt horizon are inherited; it is made up of relatively mature soils that eroded off of the hillslope above during the Islamic period. The gradual transition to the Btb (2AB?)>Bt2 horizon then must reflect both ongoing pedogenesis (soil welding) and the cumulic nature of the ABb>Bt horizon. In this scenario, the Btb (2AB?)>Bt2 horizon was at or near the surface prior to the Islamic period occupation of Alcaria Longa, and the pedogenic characteristics that would help to identify a paleosol have been obscured by soil welding. The past surface was buried by sediments that were transported off of the slope above either during or after the Islamic period.

Alternatively, it is possible that the ABb>Bt horizon was at or near the surface during the Islamic period and that erosion removed sediments from this location during the occupation of Alcaria Longa. This is consistent with the degree of soil development observed in the ABb>Bt horizon and with the gradual transition

to the underlying Btb (2AB?)>Bt2 horizon. This scenario requires that the artifacts noted in the ABb>Bt horizon be intrusive. That all of the artifacts were very small (< 5mm), and that they are very rare or absent in the lower portions of the unit suggest that this is certainly possible. The small fragments of rooftiles could have moved downward through the soil column due to bioturbation and soil cracking. It also is likely that this location was plowed during the Islamic period occupation, which would have broken apart larger rooftile fragments and mixed them downward into the soil. Trampling is another mechanism that might have buried the artifacts, although it probably is a significantly less important process given the soil texture and the size of the observed artifacts. In either case, the color, structure, texture and clay film morphology of the Btb (2AB?)>Bt2 horizon suggest great antiquity for that deposit and this impression is corroborated by the absence of included artifacts. In addition, the bedrock does not appear particularly weathered or friable at the base of this test pit, suggesting that it was not exposed at the surface for any significant length of time in the past. With the current data, it is not possible to distinguish with any certainty between the two possible scenarios.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Alcaria Longa, OSL Soil Test Pit

Date: June 26, 2007
Location: Toe of slope east of (below) Alcaria Longa
Coordinates: 29S 601587E, 4157092N Slope: 6* Aspect: ENE, 60*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 20	ABp	2.5 Y 6/3	moderate, coarse, granular	40/ a – sr, 2-22mm	loamy sand	few, faint ped face	abrupt, wavy	OSL samples taken immediately below the base, 20 – 25 cm.
20 – 45	ABb>Bt	10 YR 6/4	moderate, medium subangular blocky	40/ sa – sr, 2-25mm	clay loam	common, distinct ped face	gradual, smooth	Clasts appear weathered. OSL samples taken at 30 – 35, 40 – 45 cm. Rooftile fragments are present, decrease with depth.
45 – 78	Btb> Bt2	10 YR 5/6	strong, coarse angular blocky	<5/ sa, 2-5mm	silty clay	many, distinct to prominent ped face	bedrock	Appears redder below 55 cm. OSL sample taken at 53 – 61 cm. No visible artifacts.

Notes: There is clear evidence that this area has been plowed recently.

Interpretation: The soil horizons exposed in this pit generally mirror those exposed in STP5, located a few meters away. There is a somewhat surprising degree of difference in the clastic content of the two upper horizons and some difference in the texture of the ABp horizon between the two pits. The meaning of these differences is obscure, but the clasts and coarser grain size would seem to indicate that past erosion removed more fine materials in the location of the OSL test pit. There are no topographic features (i.e., shallow swales) that would indicate why this might be. In any case, the general interpretation of a polygenetic soil with two possible histories of erosion also is consistent here. The ABp horizon clearly includes sediments recently redeposited from higher on the hillslope. As in test pit 5, the inclusion of artifacts in the ABb>Bt horizon suggests that it was deposited during or after the Islamic period, and the high clastic content appears to support relatively rapid deposition. The radiocarbon date for sample AL-1a appears to suggest that the ABb>Bt horizon was stable at the surface for several centuries following the Islamic period and before the recent cycle of hillslope erosion, and it is broadly consistent with the radiocarbon date from Fluvial Study Unit 7 (sample AL-3a). The post-bomb date for sample AL-2a, however, clearly indicates that that sample is intrusive due to post-depositional mixing. Both radiocarbon dates should probably be viewed with suspicion, and the clear evidence they provide for turbation also implies that the artifacts in the ABb>Bt horizon may be intrusive. Finally, if the ABb>Bt horizon were deposited during the Islamic period, past erosion must have removed, or soil welding must have obscured, any characteristics that would allow the identification of a buried A horizon.

The optical ages for the sediments also are problematic, but they generally support a second scenario in which sediments were removed from this location by erosion during the Islamic period. The stratigraphic position of artifacts and comparison to the single grain dates on deeper sediments show that the multi-aliquot age for the uppermost portion of the ABb>Bt horizon massively overestimates its actual age because of partial bleaching. The optical age of sample AL-2, however, is based on 209 out of 2000 grains, and the age estimate for AL-3 is based on 100 out of 1500 grains. The large samples should correct well for the partial bleaching and post-depositional mixing that clearly have affected these deposits. As in STP 5, it is possible or even likely that the rooftile fragments in the stratum are present due to post-depositional mixing as all were small (< 5 mm) and they were not particularly abundant. This would suggest that erosion removed sediments from this location during the Islamic period and that various processes such as bioturbation and plowing moved the rooftile fragments

downward through the soil column. Assuming that the artifacts are intrusive, the optical dates are consistent with slow accumulation of sediments due to minor hillslope erosion in the millennia prior to the Islamic period. This scenario is consistent with the observed degree of pedogenic alteration of the ABb>Bt and Btb>Bt2 horizons and with the lack of clear boundaries or a buried A horizon between them. It also suggests that the high clastic content in the ABb>Bt horizon is due to erosion during the Islamic period. In any case, pedogenic characteristics show that the basal Btb>Bt2 deposit is ancient and that it was near the surface, within the zone of pedogenesis, for a period of time on the order of millennia. At present, it may not be possible to reconcile with certainty the radiocarbon and OSL dates, the observed degrees of soil development, and the stratigraphic location of artifacts. Given that the rooftile fragments are small and relatively few, and that post-depositional mixing clearly has affected one and possibly both radiocarbon samples, the second scenario in which the ABb>Bt horizon was at the surface and affected by erosion during the Islamic period seems to be better supported.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

Radiocarbon Data:

Sample	**Description**	**Depth/ Stratum**	**14C Age B.P.**	**Calibrated year ranges A.D. (2 sigma)**	**Median Date**	**Lab Number**
AL-1a	charcoal fragment, 4.5 mg, recovered by flotation	30 – 35 cm/ ABb>Bt	180 +/- 32	1652 – 1969 1725 – 1814 1835 – 1877 1917 – 1952	1772	AA 76886
AL-2a	charcoal fragment (seed?), 2.5 mg, recovered by flotation	40 – 45 cm/ base of ABb>Bt	post-bomb			AA 76887

OSL Data:

Sample	**Depth/ Stratum**	**Optical Age (+/- 1 σ)**	**Measurement Type**	**Lab Number**
AL-1	20 – 25 cm/ uppermost ABb>Bt	10,300 +/- 1600	multi-aliquot	UNL-1855
AL-2	30 – 35 cm/ upper ABb>Bt	2210 +/- 180 [210 BCE]	single grain	UNL-1856
AL-3	40 – 45 cm/ lower ABb>Bt	2340 +/- 190 [340 BCE]	single grain	UNL-1857
AL-4	53 – 61 cm/ middle Btb>Bt2	sample not analyzed		

1992 Survey Area Hillslope Soils: Alcaria Longa, Soil Test Pit 6

Date: July 3, 2004
Location: Below the toe of slope east of (below) Alcaria Longa, between the slope and the ribeira.
Coordinates: 29S 601615E, 4157074N Slope: 3* Aspect: ESE, 104*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 24	ABp	5 Y 6/2	moderate, coarse, subangular blocky	20/ sa – sr, 2-20mm	clay loam	few, faint ped face, pore & co-br	clear, smooth	some angular blocky peds present. Most gravels in the 2 – 10mm size range. High sand content, texture could be sandy clay. Much of the matrix appears porous. Krotovina (~1cm) are present. Roof tile fragments are present throughout. Numerous sr – r cobbles are present at the surface, few large clasts are visible in the profile. Lower boundary is identified by a change in color and possibly moisture.
24 – 52	Bt	2.5 Y 6/4	moderate to strong, coarse subangular blocky	10/ sa – sr, 2-10mm	sandy clay	common, distinct ped face, pore & co-br	gradual, smooth	some angular blocky peds present. Abundant small flecks of roof tile are present, appear to diminish somewhat towards the bottom of the stratum. One large fragment is visible at 40cm. Very clay rich – possibly inputs from the ribeira?
52 – 84	ABb> Bt2	10 YR 6/3	strong, coarse angular blocky	5/ sa – sr, 2-8mm	clay loam	many, prominent ped face, pore and co-br	gradual, smooth	no artifacts visible. High clay content.
84 +	Bb>Bt3	5 YR 5/3	strong, medium, angular blocky	<5/ a – r, 2-8mm	sandy clay loam	few, distinct pore, ped face and co-br	not observed	Pit was excavated to 1m without reaching bedrock. Angular clasts are quartz. No artifacts are visible. Stratum is mottled due to seasonal groundwater. Clay films may decrease with depth.

Notes: There is clear evidence that this area has been plowed recently.

Interpretation: The complex soil exposed in this test pit is polygenetic and reflects inputs both from the hillslopes and from the fluvial systems of the ribeira and the tributary flowing along the base of the hill. The structure and clay film morphology of the A horizon display a greater degree of soil development than the analogous horizon in test pit 5 at the base of the slope. The presence of large, rounded clasts at the surface and the relatively high clay content of this stratum suggest that flooding along the trunk stream (the ribeira) has contributed material and water to this area; these inputs are probably responsible for the increased expression of pedogenic characteristics here. The Bt horizon shows weaker development and coarser texture than that in test pit 5. These characteristics suggest that it originated as a mixture of fluvial deposits with soils eroded from the hillslope and that it very likely was deposited during the Islamic period. This interpretation is supported by the presence of artifacts presumably from the hillslope and site above. The increase in clay content is most likely due to deposition during flooding of the ribeira. Also, the much larger rooftile fragments provide better evidence than in the OSL pit and stp 5 that this unit was, very likely, deposited during the Islamic period due to erosion at higher points. The Bt2 horizon is analogous to that in stp 5. Color, structure and clay film morphology suggest that this deposit was at or near the surface of a stable landscape for a protracted period in the past. The lack of artifacts suggests that deposition of this stratum predates the Islamic occupation of Alcaria Longa. Although soil welding and the presence of groundwater have obscured some pedogenic characteristics, the changes in structure and clay film morphology from Bt2 to Bt3 strongly support the contention that the Bt2 horizon is a buried

land surface that includes both the A and upper B horizons of a paleosol (ABb). The Bt3 horizon is, then, a buried B horizon that represents a deeper portion of the paleosol's B horizon with relatively weakly expressed clay film morphology and moderately developed soil structure. Although complicated, the soils exposed in this test pit corroborate the observations made in stp5 and the OSL test pit. The larger artifacts and the differentiation between the Bt2 and Bt3 units in stp6 lend additional support to the scenario in which erosion removed sediments above the ABb>Bt horizons at those higher points, exposing them at the surface during the Islamic period.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

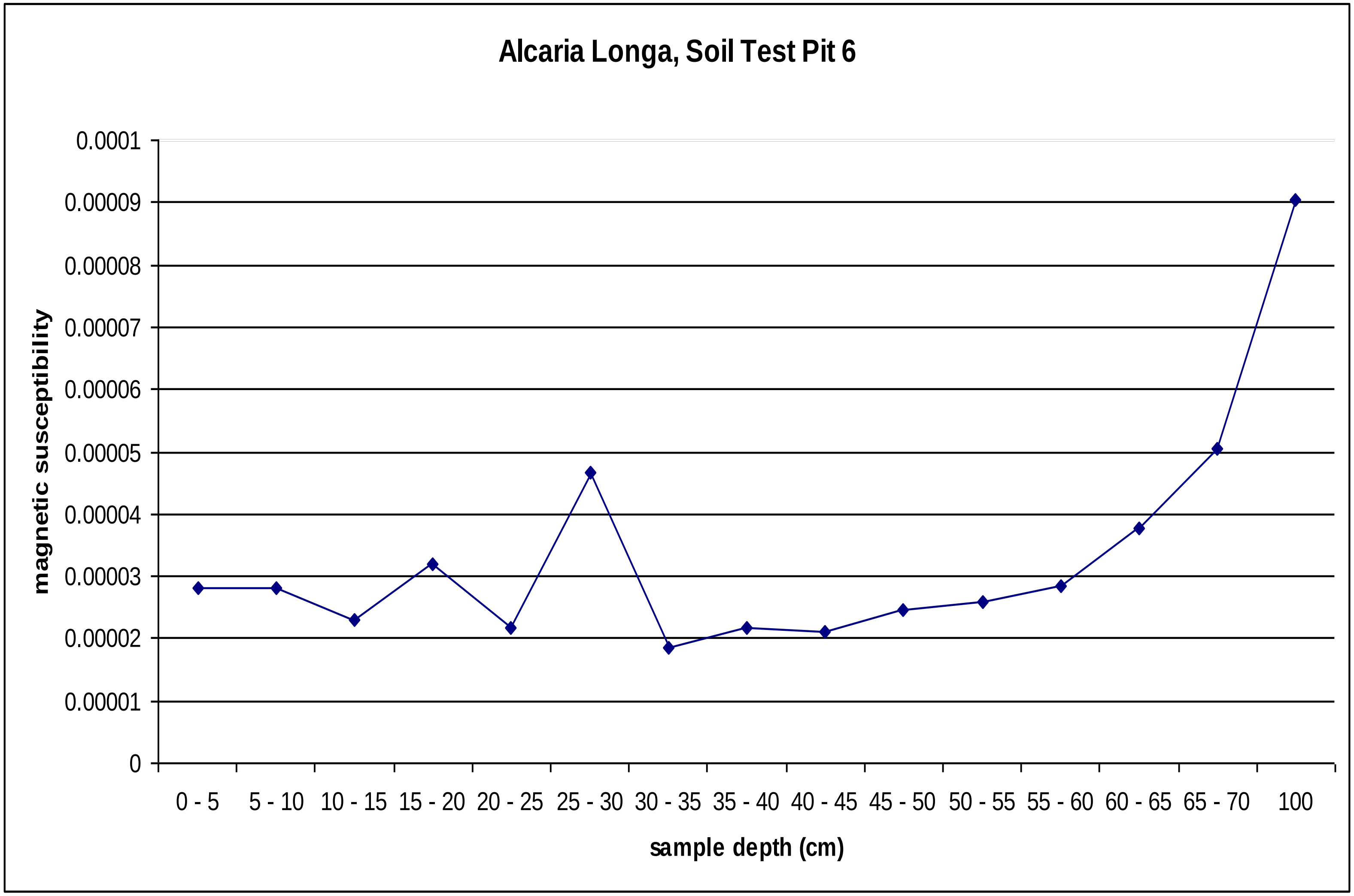

Figure A1 - 9: Magnetic susceptibility by depth, Alcaria Longa soil test pit 6

1992 Survey Area Hillslope Soils: Queimada, Soil Test Pit 1

Date: July 8, 2004
Location: Top of slope southwest of Queimada
Coordinates: 29S 606471E, 4162408N Slope: 2* Aspect: WNW, 288*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 - 7	ABp	10 YR 6/3	weak, coarse granular	20/ sa – sr, 2-15mm	loamy sand	few, faint pore & co-br	clear, smooth	mostly overlies bedrock
7 - ~20	Bw	10 YR 6/4	moderate, coarse granular	20/ sa – sr, 2-15mm	loamy sand	few, faint pore & co-br	bedrock	discontinuously preserved; only present in cracks between slabs of bedrock. Slightly redder than A horizon

Notes: Test pit is located in a stand of esteva in an area with no evidence for recent plowing, near a bedrock outcrop.

Interpretation: This is a simple profile with a thin, plowed AB horizon over a discontinuously preserved B horizon. The minor differences between the AB and B horizons probably reflect past plowing disturbance of the former and resulting admixture with organic materials and other sediments. Overall, the similarities between the two are more striking, suggesting that the majority of the A horizon has been removed by recent erosion and that the currently cultivated upper horizon is primarily made up of the previously-buried B horizon. Soil formation is very weak overall, suggesting that this area was completely stripped by erosion in the past millennium, with subsequent soil formation due to *in-situ* bedrock weathering and aeolian inputs. The magnetic susceptibility curve shows highest susceptibility in the upper 5cm of soil, consistent with recent (20th C.) erosion of soil from the surface, and the relatively low susceptibility readings for the current B horizon support this interpretation.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

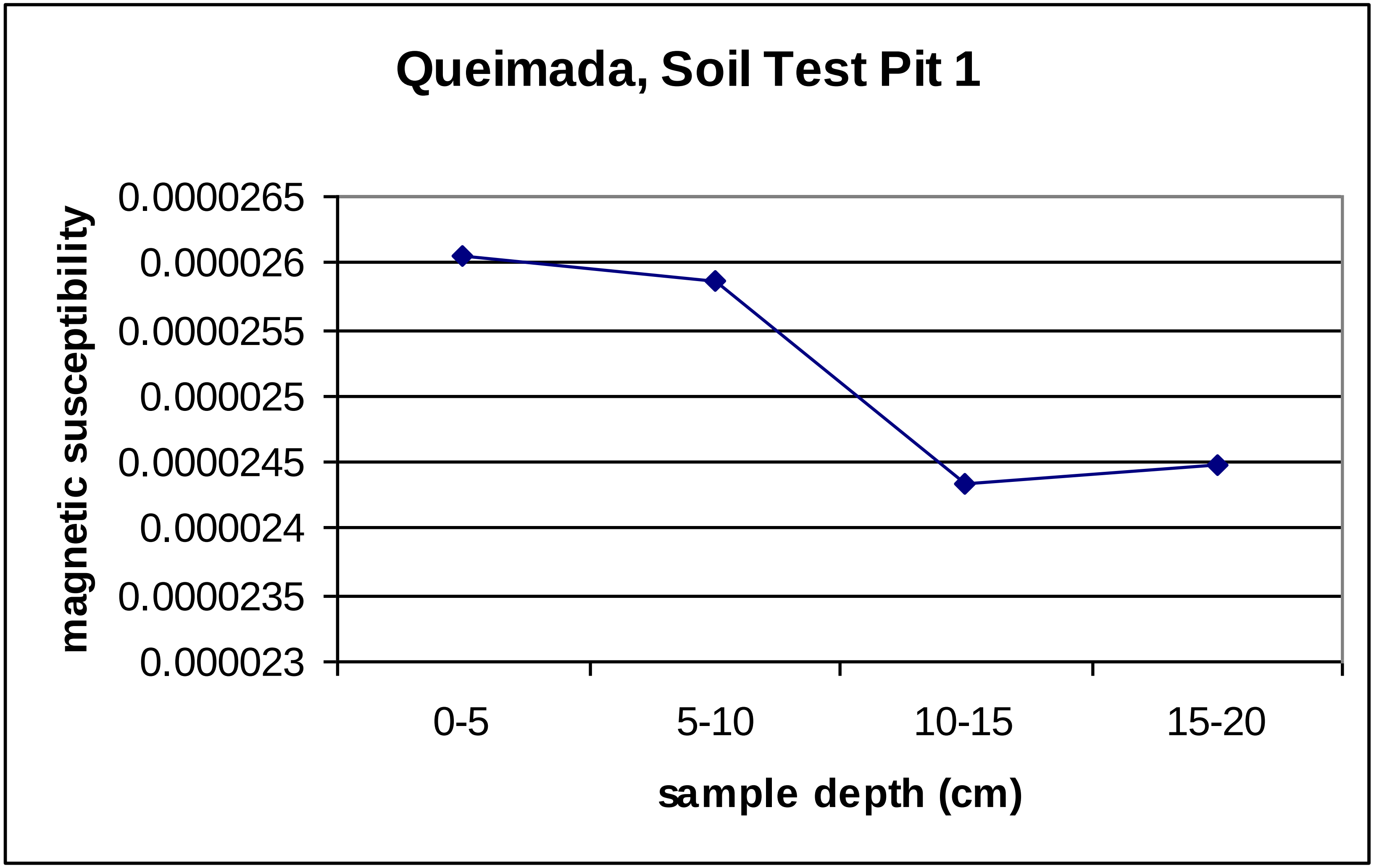

Figure A1 - 10: Magnetic susceptibility by depth, Queimada soil test pit 1

1992 Survey Area Hillslope Soils: Queimada, Soil Test Pit 2

Date: July 8, 2004
Location: Shoulder of slope southwest of Queimada
Coordinates: 29S 606456E, 4162409N Slope: 9* Aspect: W, 273*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 8	ABp	10 YR 6/3	weak, medium granular	30/ a – sr, 2-15mm	loamy sand	few, faint pore & co-br	clear, smooth	larger clasts (to 50cm) visible on surface and in upper horizon nearby. Distinctness of lower boundary probably due to plowing.
8 – ~14	Bt	10 YR 7/2	moderate, medium, angular blocky	70/ a – sa, 2-20mm	sandy clay	common, distinct ped face, pore & co-br	bedrock	clasts maintain original bedrock orientation and bedding. Texture may grade to loam; seems like majority clay with sand-sized particles of bedrock.
Notes: There is clear evidence for recent plowing.								
Interpretation: This profile presents a plowed AB horizon over a thin, argillic B horizon preserved in the interstices in the bedrock. The degree of soil development in the B horizon, as seen in the clay films and structure, suggest that it is significantly older than the AB horizon, which exhibits weak expression of time-dependent pedogenic properties. The magnetic susceptibility curve readings peak in the A horizon, suggesting 1) that the B horizon was more deeply buried in the past and 2) that the A horizon consists primarily of a recently exposed B horizon, reworked by plowing. The soil and clast characteristics (alignment and angularity) show that the B horizon is made up of bedrock that is weathering *in situ* and that has not been stripped in recent millennia. Overall, the soil profile suggests a period of erosion in the past ~1000 years that removed upper soil horizons but left the deposits that now form the B horizon intact, perhaps because they were protected in interstices in bedrock or were difficult to entrain and erode due to high clay content. Subsequently, a weak soil developed in more recent deposits. This soil has, in turn, been subjected to significant recent (20th C.) erosion, stripping the majority of the A horizon and mixing the remnants with the higher-susceptibility B horizon; there has not been sufficient time since the recent erosion for a characteristic soil with genetically related A and B horizons to form.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

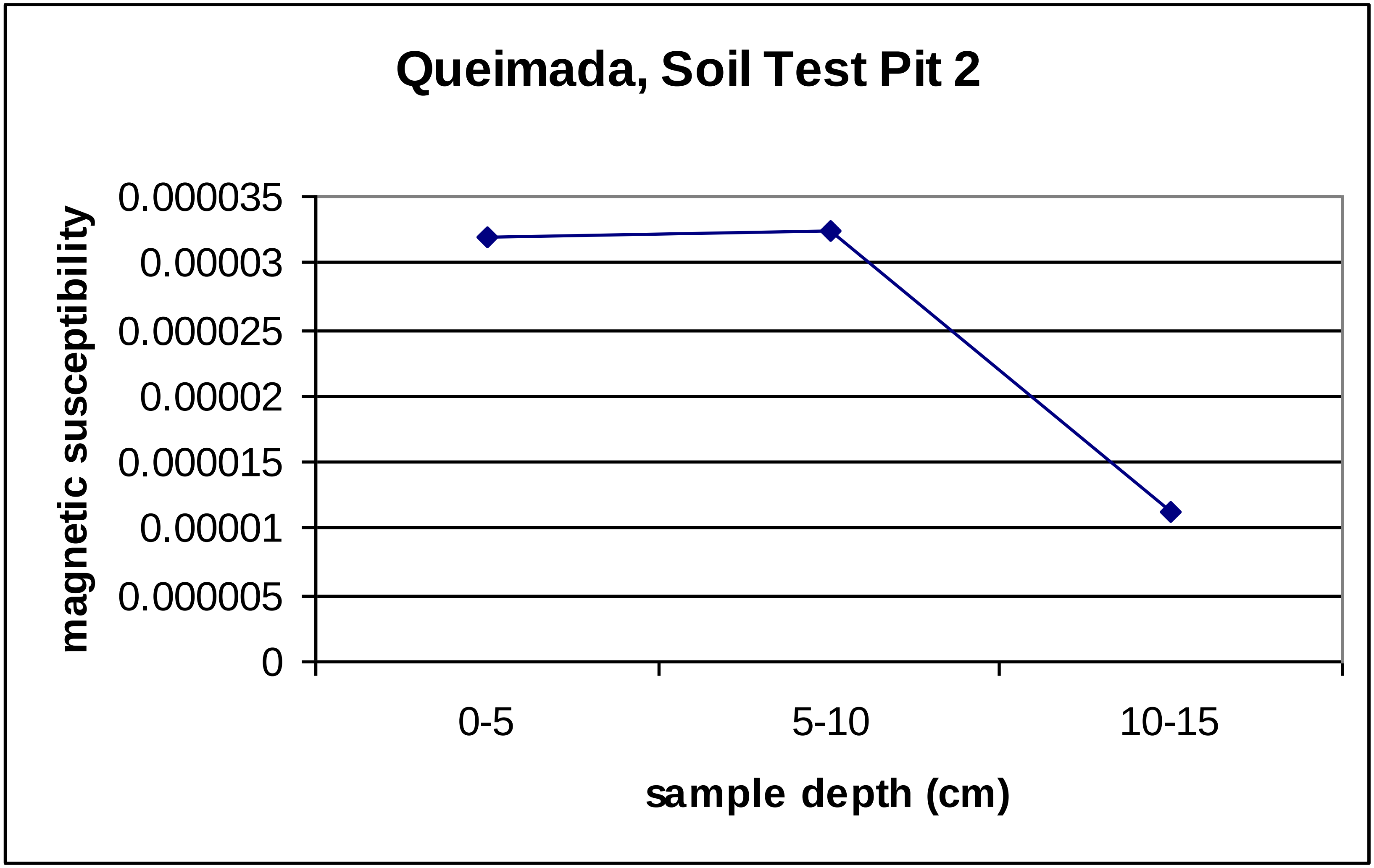

Figure A1 - 11: Magnetic susceptibility by depth, Queimada soil test pit 2

1992 Survey Area Hillslope Soils: Queimada, Soil Test Pit 3

Date: July 8, 2004
Location: Back slope southwest of Queimada
Coordinates: 29S 606425E, 4162413N Slope: 12* Aspect: W, 275*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 8	ABp	10 YR 6/3	weak - moderate, medium granular	30/ sa – sr, 2-35mm	loamy sand	few, faint pore & co-br	clear, smooth	lower boundary defined by depth of plowing, determined by bedrock. Large clasts are common at the surface.
8 – 12	Bw	10 YR 7/3	moderate, fine, angular blocky	40/ sa – sr, 2-25mm	loam	few, faint, ped face, pore & co-br	bedrock	berock is oxidized, crumbly, weathered. Slight color and texture change from overlying.
Notes: There is clear evidence for recent plowing.								
Interpretation: This soil profile is similar to that in Test Pit 1 in that there is a weakly developed soil resting directly on weathered bedrock. Again, the minor differences between the AB and B horizons probably reflect admixture due to plowing of a small amount of remnant A horizon into a B horizon exposed by erosion. The weathered appearance of the bedrock and the weak overall soil development suggest that this area was completely stripped of soil in the past millennium, with the current soil forming in more recent deposits. As above, the soil characteristics and magnetic susceptibility curve suggest that an A horizon was removed by erosion recently (20th C.) in this location.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

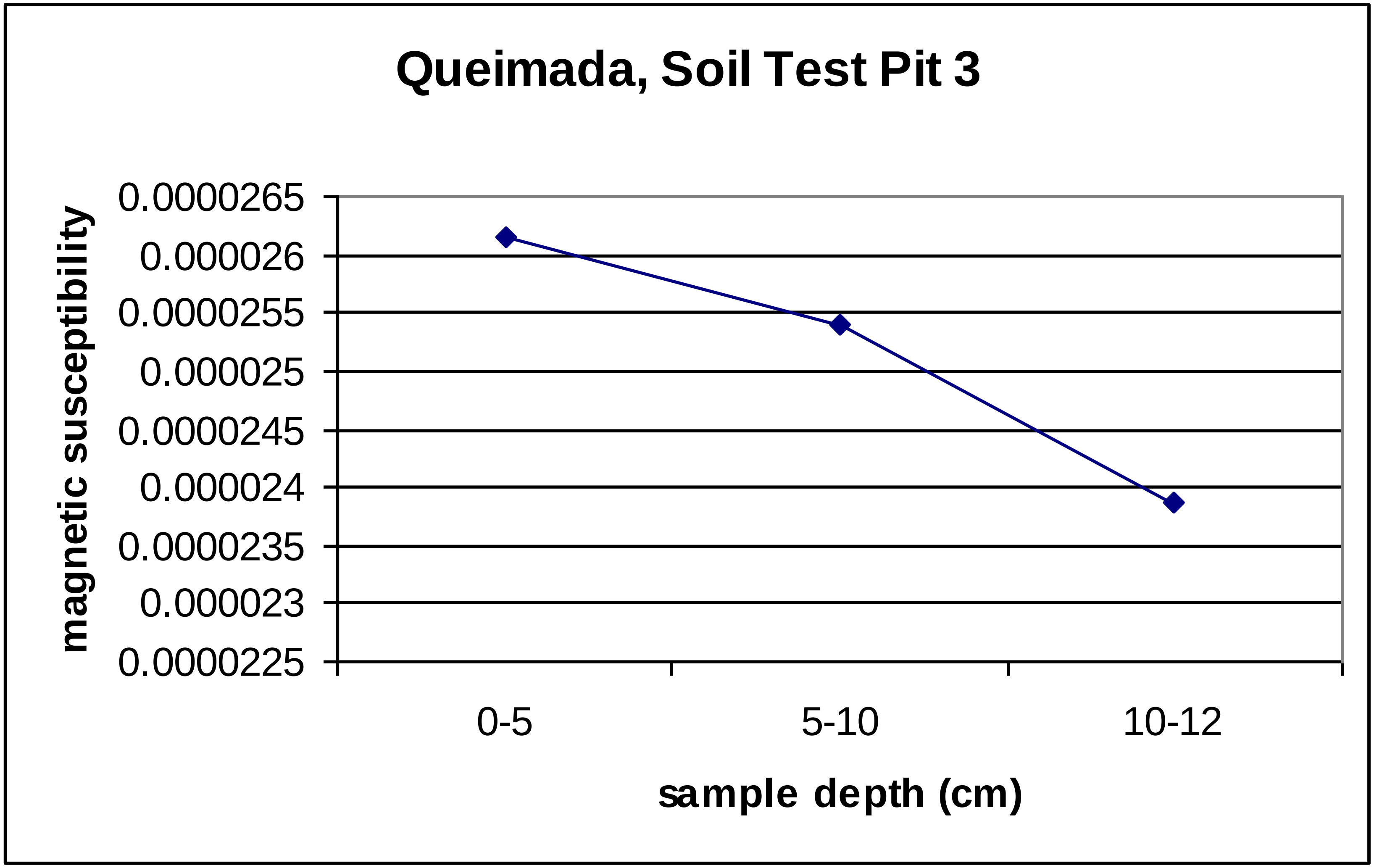

Figure A1 - 12: Magnetic susceptibility by depth, Queimada soil test pit 3

1992 Survey Area Hillslope Soils: Queimada, Soil Test Pit 4

Date: June 29, 2007
Location: Foot of slope southwest of Queimada
Coordinates: 29S 606403E, 4162415N Slope: 8* Aspect: WSW, 250*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 16	ABp	10YR 7/4	moderate, medium granular	40/ a – r, 2-20mm	sandy loam	common, faint coatings	clear, wavy	Clasts increase at the base of the unit, including rooftile fragments common up to 20cm.
16 – 51	Bt	2.5Y 6/3	weak, medium subangular blocky and platy	35/ a – r, 2-20mm	loam	few, distinct ped face	abrupt, irregular	Lower boundary marked by an increase in clasts, clasts sitting on bedrock. No artifacts are visible, unit laid down by stream before small dam built upstream? Cumulic, with hillslope inputs? Clasts mostly horizontal, imbricated. Lots of tiny red specks – red schist bedrock, also some fine red mottling.
51 + (base at 60)	2Bt, C/R	5Y 7/3	moderate, fine subangular blocky	50/ a, 2-30mm	clay loam	common, distinct ped face		Described material in interstices in bedrock. Ped shape and structure are modified by bedrock. Similarities to overlying suggest a lot of the unit is redeposited hillslope B horizon.

Notes: Plowed and planted this year.

Interpretation: This soil profile is similar to those exposed at most locations higher on the slope, with a weakly developed soil resting on bedrock. The surface unit consists of a plowed mixture of an A horizon and a weak B horizon recently exposed by erosion. The subjacent Bt horizon exhibits weak structure and weakly to moderately expressed clay films. The stronger clay films and yellower color than in analogous units higher on the slope are probably due to inputs of water and sediment from the fluvial system. That the unit is primarily made up of recent fluvial deposits with some inputs of fine sediments from the hillslope is consistent with the lack of artifacts below the plow zone. In addition, the relatively flat magnetic susceptibility curve suggests that the deposits all are recent and that pedogenesis has not proceeded to the point where a measurably different signal is present at and near the surface. The gravel lag deposit at the base of the unit suggests that erosion exposed bedrock in this location in the past. While the strong clay films in the deepest unit may imply that it is very old, the similarities of color and texture between the Bt and 2Bt horizons suggest at least some degree of admixture. This deposit probably includes materials created by *in situ* bedrock weathering mixed with recent fluvial deposits; the clay films very likely formed rapidly due to seasonal inundation and the abundance of fine sediments and water in the fluvial system.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

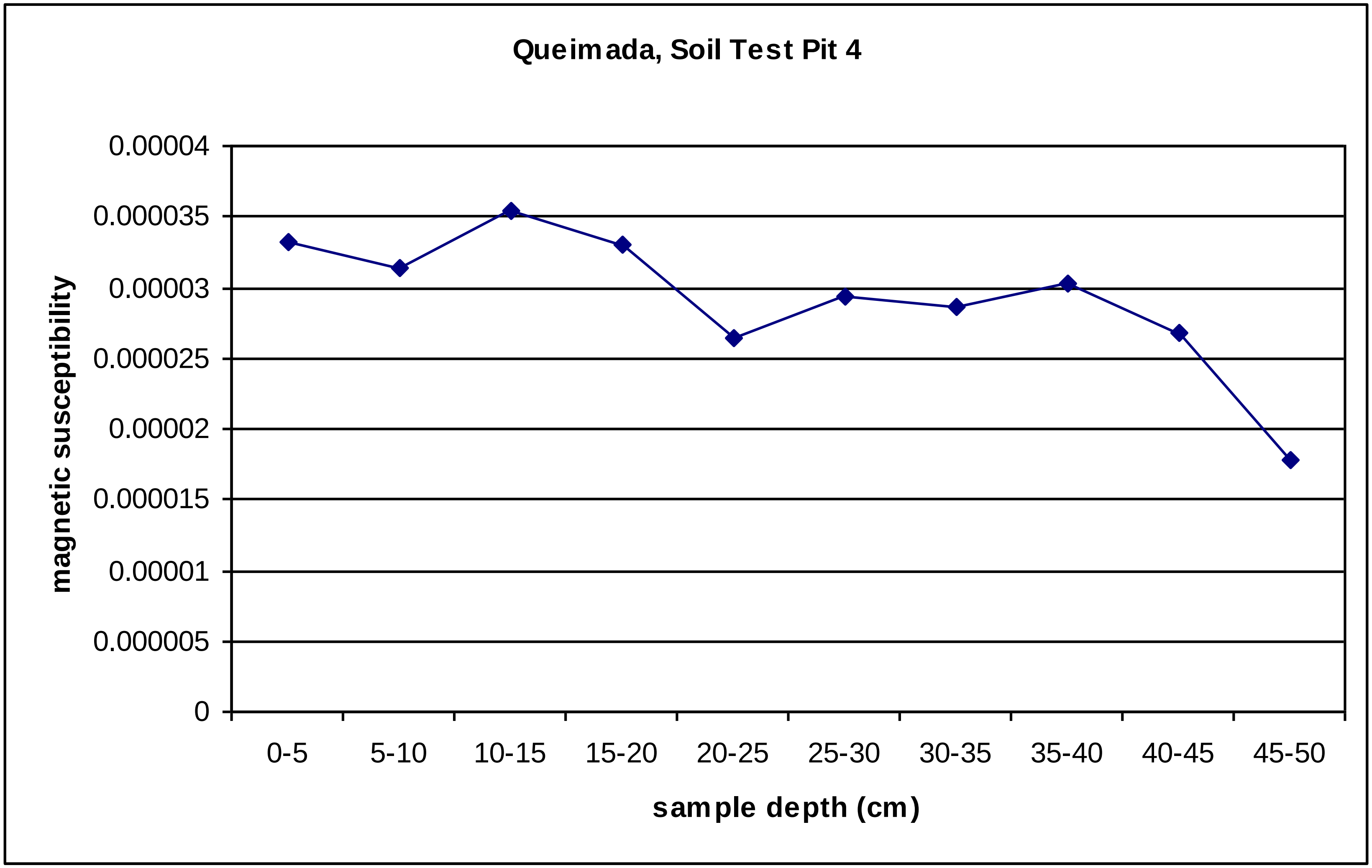

Figure A1 - 13: Magnetic susceptibility by depth, Queimada soil test pit 4

1992 Survey Area Hillslope Soils: Queimada, Soil Test Pit 5

Date: July 8, 2004
Location: Toe of slope southwest of Queimada, near arroyo
Coordinates: 29S 606396E, 4162420N Slope: 4* Aspect: SW, 230*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	2.5Y 6/1	weak, coarse, granular to subangular blocky	30/ sa – sr, 2-15mm	loamy sand	few, faint pore & co-br	clear, smooth	Several ~1cm diameter krotovina visible. Sediment appears porous. Large clasts and artifacts (roof tile fragments) are visible at the surface. Texture might be sandy clay.
10 – 33	Bt	2.5Y 7/2	moderate – weak, medium subangular blocky	25/ sa – sr, 2-20mm	sandy loam	few, distinct pore & co-br	clear, smooth	roof tile fragments in horizon, probably recently deposited with some soil characteristics developing rapidly due to water inputs
33 – 50	Ab>2Bt	10 YR 6/2	moderate, medium subangular blocky	15/ sr – r, 2-10mm	clay loam - loam	common, distinct ped face, pore & co-br	clear, smooth	very few artifacts visible. Horizon is darker than superjacent, much harder with a higher clay content. May be inherited characteristics or a long-term stable surface with riparian (or at least wetter than average) vegetation.
50 – 62	Bb>3Bt	10 YR 7/1	moderate, medium subangular blocky	30/ sa – sr, 2-25mm	loam	common, distinct ped face, pore & co-br	gradual, smooth	many more large clasts throughout, line of sr – r imbricated stones at ~55 – 60cm: old channel deposit or reworked sediments eroded from hillslope. CRB sherd and roof tile fragments present
62 – 77	Bb2> 3Bt2	10 YR 7/2	moderate, medium subangular blocky	30/ sa – sr, 2-25mm	clay loam	common, distinct ped face, pore & co-br	gradual, smooth	distinguished from superjacent by increase in mottling – groundwater effects. Artifacts are present to 72cm (plain red ware). Clasts similar to overlying – old channel deposit. Stone line, flat-lying stones at 77cm, very distinct when digging.
77 – 95	2Ab> 4Bt	2.5 Y 6/2	moderate, coarse subangular blocky	15/ sa – sr, 2-5mm	clay loam	common, distinct ped face, pore & co-br	bedrock	Fewer large clasts, no artifacts, clear mottling. Old wetland/ stable landscape?
Notes: There is clear evidence for recent plowing.								
Interpretation: This profile exposes a complicated, polygenetic soil indicating multiple periods of erosion and deposition. The surface deposits (ABp and Bt) are different in color from analogous deposits on the hillslope above, they have slightly higher clay content and the clay films are more strongly expressed. These differences probably reflect increased exposure to water due to their position at the base of the slope. Otherwise, they are similar to the hillslope deposits								

in texture, structure, and clastic content as well as magnetic susceptibility characteristics. They are probably the same age and likely were deposited when soils were eroded from the hillslope above during the 20th Century. The subjacent Ab>2Bt horizon has noticeably more rounded clasts and is darker, harder and enriched in clay relative to the overlying deposits. These qualities indicate either long-term exposure at the surface or emplacement of reworked hillslope soils and clay-rich sediments by an unincised stream; both interpretations are consistent with the increased magnetic susceptibility in the subjacent strata. The clast rounding in the Ab>2Bt horizon implies the presence of water, probably in a relatively low-energy environment judging by the clast size, supporting the second hypothesis. The distinct lower boundary also suggests relatively recent deposition.

The clasts and especially the stone lines in the subjacent two strata suggest that these are channel deposits that were emplaced and/ or reworked in a relatively high-energy fluvial environment, probably in an incised channel similar to the one that is currently present. The characteristics that distinguish the two appear to be related to the effects of groundwater and probably do not reflect differences in origin or depositional environment. The presence of artifacts suggests that these deposits were emplaced during or after the Islamic Period. Sediment samples from the lower Bb>3Bt horizon, within and below a stone line, were optically dated using both multi-aliquot and single grain techniques. (Sediments were recovered from this rocky unit using the "block" method; the clasts prohibited collection using tubes.) The greater apparent age of the sample when measured using multiple aliquots shows that partial bleaching is a significant problem for these sediments and, presumably, most sediments in analogous locations across the study area. The single grain date, however, suggests that the channel was active during the later Islamic period, significantly after the occupation at Queimada; the latest radiocarbon date related to the occupation is 903 C.E. (Boone and Worman 2007). The time difference of three centuries suggests that the channel formed and was active long after the adjacent site was abandoned. The disparity between the single grain OSL date and the radiocarbon dates obtained from the site provides strong evidence for regional landscape change during the later Islamic period, as opposed to localized erosion associated with the occupations at individual sites.

The color and clast characteristics of the basal stratum suggest that it was exposed at the surface for a period of time in the past. It is somewhat difficult to interpret many of the characteristics of this deposit because they probably have been modified or obliterated by subsequent soil welding. The deposit is, however, consistent with soil formation on a stable landscape. Many of the characteristic B horizon features, including increased magnetic susceptibility, probably are muted due to the shallowness of bedrock, seasonal saturation with groundwater and, presumably, the movement of water downhill along the upper boundary of the bedrock. Alternatively, the basal deposit may represent rapid soil erosion from the slopes above, analogous to current surface deposits. The low magnetic susceptibility, texture, structure and paucity of clasts support the former interpretation. The lack of artifacts suggests that this stratum was deposited prior to the Islamic Period occupation of the site of Queimada immediately uphill.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

OSL Data:

Sample	Depth/ Stratum	Optical Age (+/- 1 σ)	Measurement Type	Lab Number
Queimada "upper"	56 – 63 cm/ lower Bb>3Bt	1590 +/- 150 [410 C.E.]	multiple aliquot	UNL-1281
Queimada "upper"	56 – 63 cm/ lower Bb>3Bt	790 +/- 70 [1210 C.E.]	single grain	UNL-1281
Queimada "lower"	64 – 70 cm/ upper Bb2>3Bt2	sample not analyzed		

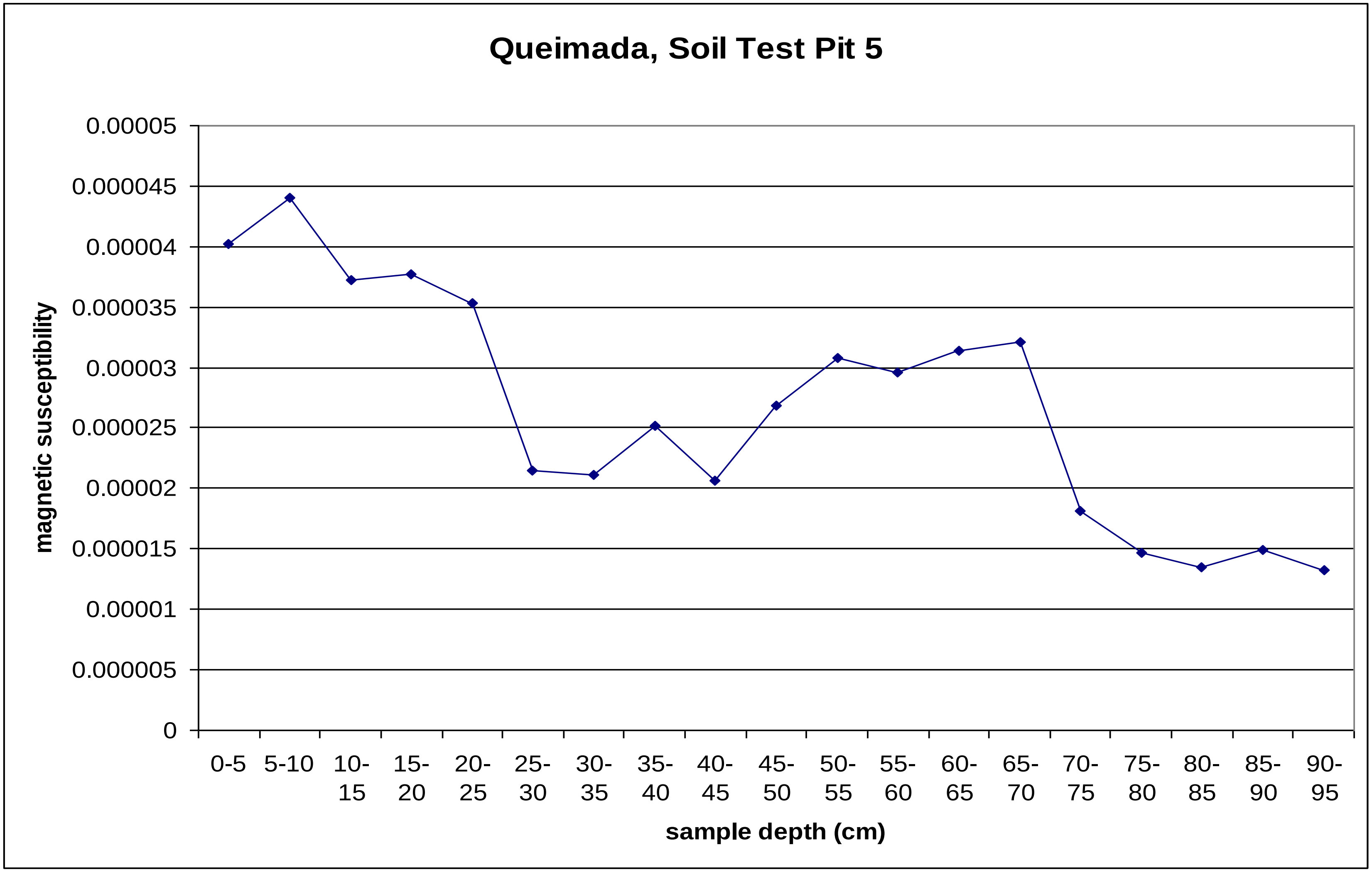

Figure A1 - 14: Magnetic susceptibility by depth, Queimada soil test pit 5

1992 Survey Area Hillslope Soils: Queimada, OSL Soil Test Pit

Date: July 2, 2007
Location: Toe of slope southwest of Queimada, near arroyo
Coordinates: 29S 606400E, 4162408N Slope: 3* Aspect: SSW, 205*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 18	ABp	2.5Y 6/3	weak, coarse, granular	30/ a – sr, 2-25mm	loamy sand – sandy loam	few, distinct co-br	abrupt, wavy	Plowed this year.
18 – 30	(ABpb) >Bt	2.5Y 6/3	moderate, coarse granular	30/ a – sr, 2-10mm	sandy loam	few, faint ped face	clear, smooth	OSL samples taken at 25 – 30.
30 – 41	ABb	2.5 Y – 10 YR 7/2	moderate, medium subangular blocky	20/ sa – sr, 2-12mm	loam – clay loam	common, distinct ped face	clear, smooth	Lower boundary is a slight color change and an increase in clasts and artifacts and the appearance of mottling.
41 – 72	2AB> Btb	2.5 Y 6/3	moderate, medium subangular blocky	30/ sa – r, 2-25mm	loam	common to few, distinct ped face	clear, wavy	OSL samples taken at 48 – 53. Stone line at 55 – 70. Artifacts are present throughout stratum. Small red mottles.
72 + (base 93)	2Bt	2.5 Y 6/3	strong, medium subangular blocky	20/ a – sr, 2-10mm	clay loam	many, prominent ped face		Lower boundary is bedrock. Mottles increase with depth, moisture increases with depth. OSL samples taken at 79 – 84.

Notes: Plowed this year, standing wheat crop.

Interpretation: The complex, polygenetic soils exposed in this test pit are similar to those exposed in Queimada STP 5 and 1992 Survey Area Fluvial Study Unit 1, each located a few meters away. Weak soil development in the upper 30 cm of sediments and similarities to hillslope deposits suggest that these were emplaced very recently. The multi-aliquot optical age calculated for sediments from the base of the (ABpb)>Bt horizon suggests that deposition began in the early 17th Century. Repeat analyses of sediments from similar settings in the study area, including one at Queimada STP 5 (Queimada “upper”) and sample Q-3 from this profile, suggest that partial bleaching is common, causing multi-aliquot ages to overestimate the actual age of the deposits systematically and often significantly. Partial bleaching, then, explains the apparent stratigraphic inversion in the optical ages of samples Q-1 and Q-2. The uppermost 30 cm of sediments most likely were deposited due to erosion on nearby hillslopes during the 20th Century and may reflect a dramatic increase in erosion associated with mechanized plowing of hillslopes in the later 20th Century. The underlying ABb horizon exhibits moderate soil development that implies a period of exposure at the surface. Many of the pedogenic characteristics, however, likely are inherited and the location at the base of the slope implies relatively rapid pedogenesis.

These sediments probably were emplaced as late as the early 20th Century when cultivation of the adjacent slopes caused a significant increase in erosion. The subjacent 2AB>Btb horizon contains numerous artifacts, suggesting that it was emplaced during or after the occupation of Queimada; it is analogous to the Bb>3Bt and Bb2>3Bt2 horizons in Queimada STP 5. The single grain age of 90 years for the upper portion of the stratum is younger than the multi-aliquot age for the overlying unit, again showing that partial bleaching and post-depositional mixing strongly affected these sediments. The single grain optical age suggests that the filled channel remained at the surface, at a stable elevation, until widespread cultivation of cereal crops began in the early 20th Century. Alternatively, all sediments above the stone line at 55 cm might have been removed by localized channel formation early in the 20th Century, prior to the formation of the current through-flowing channel system. It is not possible to determine which scenario is accurate with the current data, but the overall interpretation of relative stability for several centuries prior to the early 20th Century holds in either case. As noted above, a single-grain OSL date on sediments recovered from within and below the stone line suggests that the channel was active in the later Islamic period. The lowest unit exhibits strong structure and well developed clay films, implying significant pedogenesis and an extended period of landscape stability. The lack of artifacts suggests that it antedates the occupation of the adjacent site. The multi-aliquot optical age of 1650 years probably does not reflect timing of initial deposition, and the single-grain reanalysis shows that this unit was last exposed at or near the surface approximately 1370 years ago, during the late Roman (or transitional) period. The close correspondence of this date with radiocarbon dates for the early occupation of the site of Queimada suggests that the occupants' activities probably increased hillslope erosion to some extent. The homogeneity of the deposit suggests that the erosion initially was relatively slow, with more significant erosion and channel formation occurring later during the Islamic period. Clastic content and pedogenic characteristics also are consistent with relatively slow accumulation of sediments related to minor erosion on the adjacent hillslopes. The relatively close correspondence of the single-grain and multi-aliquot age estimates shows that partial bleaching is less of an issue for this sample than for others, as would be expected where erosion and deposition occurred more slowly. Bioturbation likely was significant, however, in this location. The single-grain date, then, probably reflects deposition due to a slight increase in erosion during the initial occupation of Queimada, after millennia of slower deposition before the Islamic period. Interestingly, the elevation of the channel deposits above the sediments exposed at the surface during the late Roman period suggests that very large quantities of soil eventually were redeposited at the base of the slope before the channel formed through them.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

OSL Data:

Sample	**Depth/ Stratum**	**Optical Age (+/- 1 σ)**	**Measurement Type**	**Lab Number**
Q-1	25 – 30 cm/ base (ABpb)>Bt	390 +/- 100 [1610 C.E.]	multi-aliquot	UNL-1852
Q-2	48 – 53 cm/ middle 2AB>Btb	90 +/- 10 [1910 C.E.]	single grain	UNL-1853
Q-3	79 – 84 cm/ middle 2Bt	1650 +/- 140 [350 C.E.]	multi-aliquot	UNL-1854
Q-3	79 – 84 cm/ middle 2Bt	1370 +/- 100 [630 C.E.]	single-grain	UNL-1854

1992 Survey Area Hillslope Soils: Queimada Site Soil

Missing paperwork, blown away in a windstorm.

The magnetic susceptibility profile suggests that relatively recent deposition has reduced the signal in the upper 10cm. The higher susceptibility in the deeper deposits is consistent with a high level of organic and other anthropogenic inputs to a depth of 50cm. The lower susceptibility at the base implies that this is a natural subfloor deposit, that the natural soils were probably dug out to create or level the floor, and that the deposits have probably been below the zone of accumulation of pedogenic clays due to protection from water during occupation of the site and subsequent deep burial as the site deterioriated.

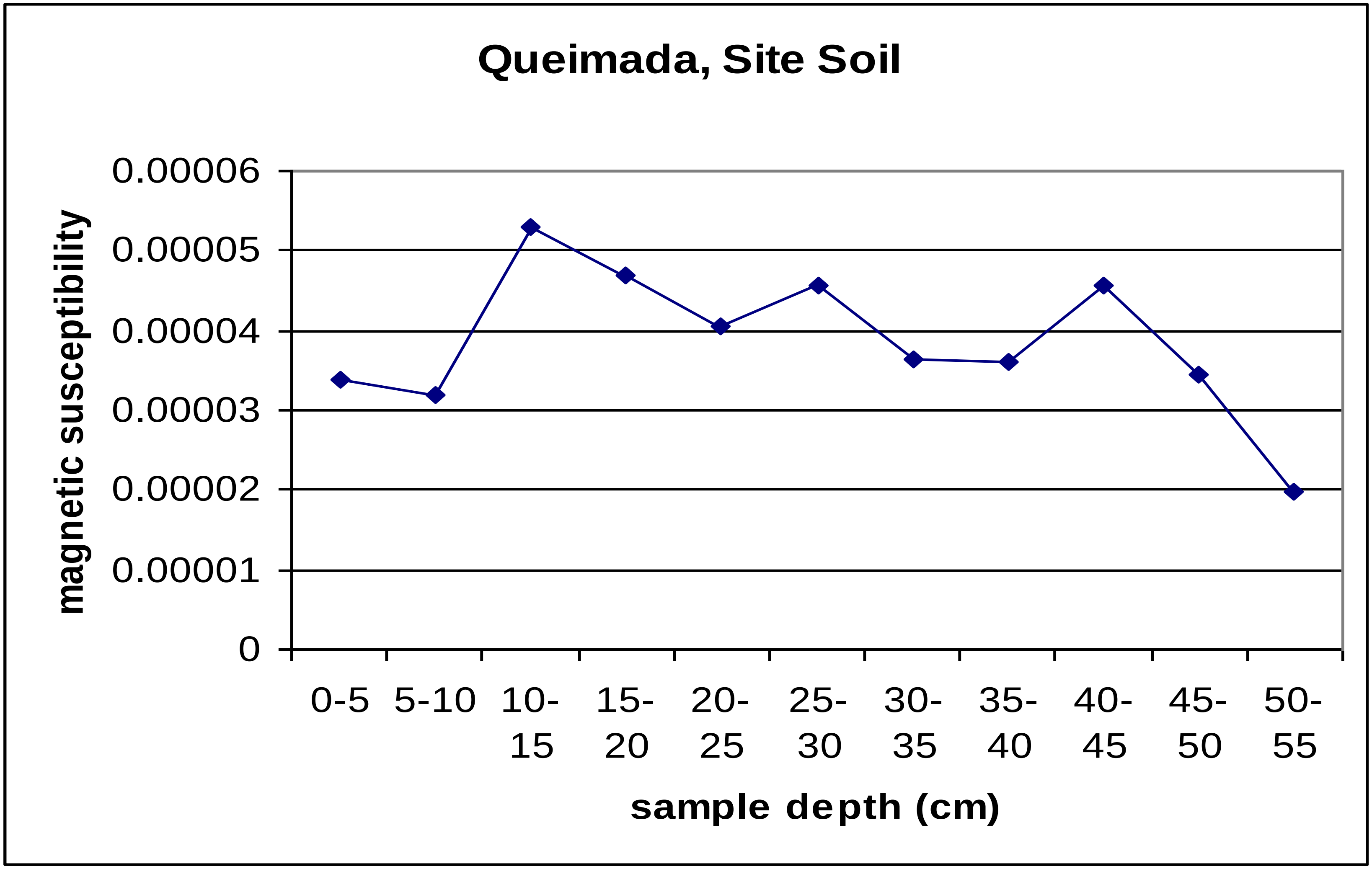

Figure A1 - 15: Magnetic susceptibility by depth, Queimada soil test pit on site

1992 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 1

Date: July 5, 2005
Location: Summit of hill west of Queimada
Coordinates: 29S 606113E, 4162332N Slope: 2* Aspect: NE, 41*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 11	ABp	10 YR 6/4	moderate, medium granular	50-60/ a, 2-40mm	loam	few, distinct ped face	abrupt, irregular (bedrock)	Rare subangular clasts. Lower boundary defined by bedrock. Sediments appear similar in crevasses in bedrock.
11 +	C/R							

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The sediments have been thoroughly mixed by plowing/ disking, which also breaks up the friable bedrock and creates loose sediments for cultivating wheat. The presence of distinct ped face clay films suggests that the deposit incorporates remnants of a moderately well-developed soil. That the sediments appear to be the same in the crevasses in the bedrock suggests that the soils were completely removed from this part of the hillslope in the past, with subsequent deposition due to bedrock weathering and aeolian inputs. The thickness of the soil is consistent with this interpretation. The peak in magnetic susceptibility at the surface suggests that recent erosion has removed surface deposits and that the current surface is comprised largely of a weak, exhumed B horizon.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 2

Date: July 5, 2005
Location: Shoulder of hill west of Queimada
Coordinates: 29S 606117E, 4162357N Slope: 17* Aspect: NNE, 21*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 8	ABp	10 YR 6/4	moderate, medium granular	40/ a-sa, 2-30mm	loam	common, distinct ped face	abrupt, irregular (bedrock)	Lower boundary defined by bedrock. Depth of deposit is somewhat variable, determined by plowing/ disking, range is from 5 – 12 cm.
8 +	R/Bt	10 YR 7/6	strong, medium, angular blocky	0	clay loam	common to many prominent ped face		Sediments described are present in cracks/ joints in bedrock.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The ABp horizon is similar to that observed in STP 1, with slightly greater expression of clay films suggesting the incorporation of a greater amount of a relatively well-developed soil. The discontinuously preserved Bt horizon is present only in interstices in the bedrock. It shows very strong soil development, with time-dependent pedogenic characteristics as strongly expressed as anywhere in the study area. This suggests that the deposit is the remnant of a soil that is significantly older than the superjacent ABp, although the clay film morphology of the latter suggests incorporation of some of the deeper deposit due to mechanical mixing. The magnetic susceptibility data suggest recent removal of surface sediments and also show that the preserved B horizon has increased susceptibility, reflecting past soil development. Together, the data suggest significant erosion in the past, removing most or all sediments above the Bt horizon, as well as the Bt horizon itself except where protected by bedrock. The erosion was followed by renewed deposition and pedogenesis and then a more recent re-mobilization of surface sediments.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

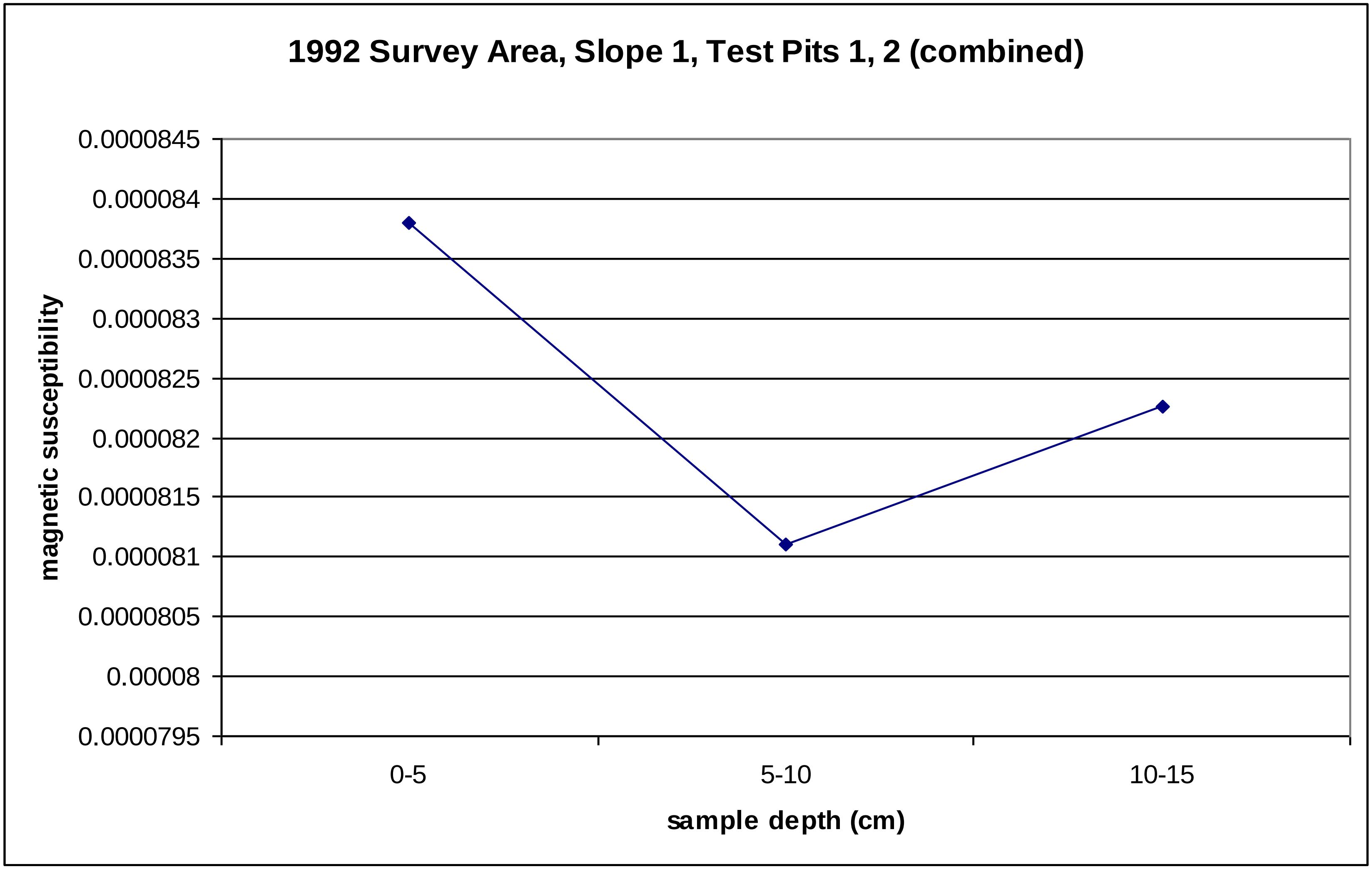

Figure A1 - 16: Magnetic susceptibility by depth, 1992 survey area, slope 1, soil test pits 1 and 2

1992 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 3

Date: July 5, 2005
Location: Backslope of hill west of Queimada
Coordinates: 29S 606126E, 4162387N Slope: 19* Aspect: NNE, 18*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	10 YR 6/4	moderate, coarse granular	20-30/ sa-a, 2-15mm	loam	few, distinct ped face	abrupt, irregular (bedrock)	Lower boundary defined by bedrock. Depth of deposit is somewhat variable, determined by plowing/ disking.
14 +	R/Bt	10 YR 6/4	strong, medium, angular blocky	0	clay loam	many prominent ped face	abrupt, irregular (bedrock)	Sediments described are present in interstices in bedrock. Very little is preserved; it is difficult to obtain a sample. Sediments appear redder than the overlying.
Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).								
Interpretation: The soils and stratigraphy are essentially the same as in STP 2. The soil is slightly thicker due to the position lower on the slope. In addition, the magnetic susceptibility data show a peak at a depth of 5 – 10 cm, suggesting somewhat less recent erosion in this area.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

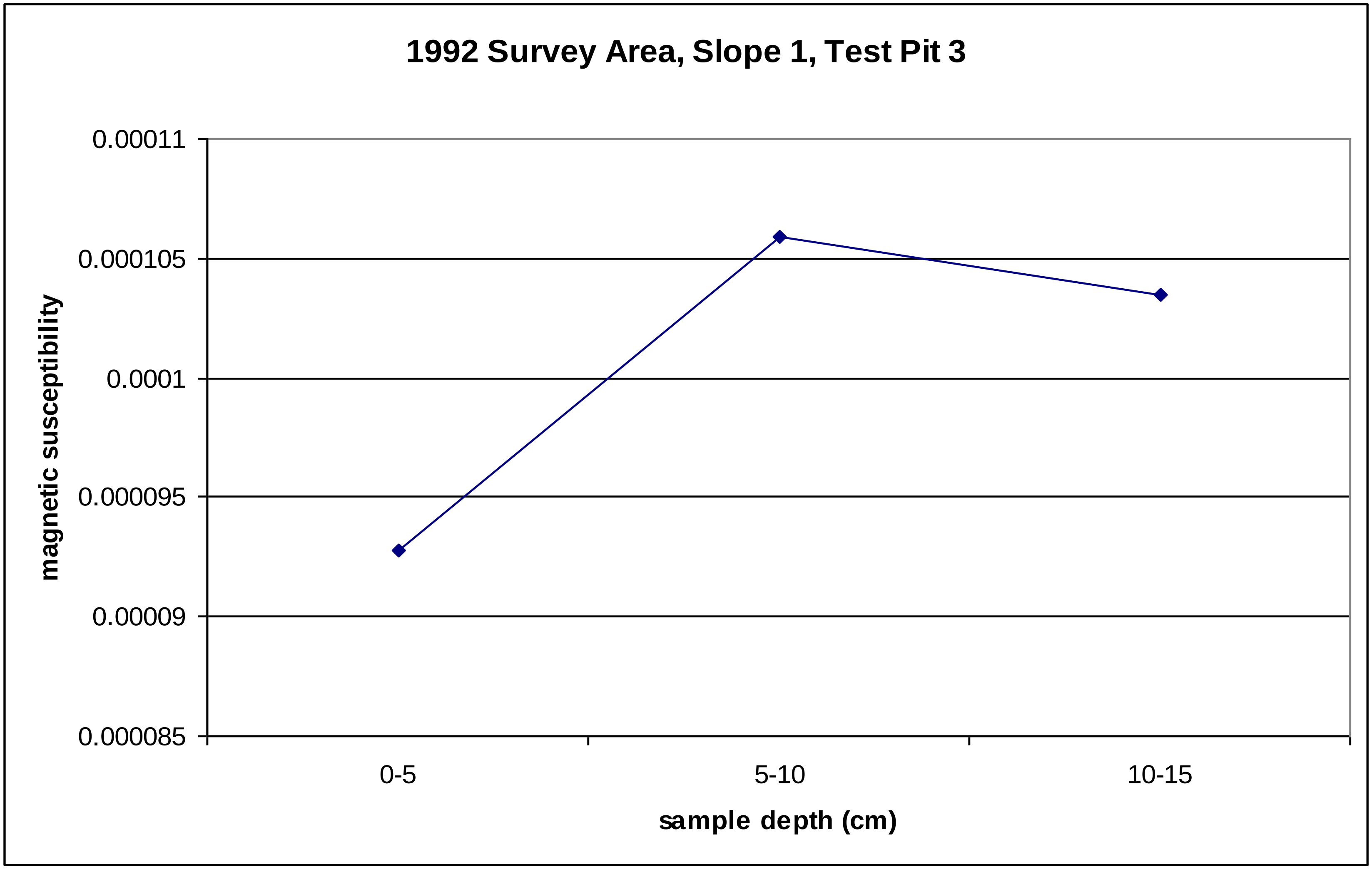

Figure A1 - 17: Magnetic susceptibility by depth, 1992 survey area, slope 1, soil test pit 3

1992 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 4

Date: July 5, 2005
Location: Foot of slope of hill west of Queimada
Coordinates: 29S 606136E, 4162403N Slope: 7* Aspect: ENE, 61*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 18	ABp	10 YR 7/4	moderate, medium granular	30/ a-sa, 2-12mm	loam	common to few, distinct ped face	abrupt, wavy	Plow zone, clearly an area of inputs from higher on the slope. The texture is odd, gritty due to sand-sized particles, but with significant clay.
18 – 22	Bt	10 YR 7/4	moderate, medium, subangular blocky	30/ a-sa, 2-12mm	loam	common, distinct ped face	clear, smooth	Not disturbed by recent plowing, but may have been affected by plowing in the past. Pedogenic B, possibly with additional slopewash material (Ab?). Color is slightly reddish like overlying, but texture is different (more clay than overlying).
22 – 52	2Bt	5 Y 7/3	moderate, fine angular blocky	50/ a-sa, 2-30mm	clay loam	many, distinct ped face	abrupt, irregular (bedrock)	Gravel = local bedrock (platy, gray). Redoximorphic features are present: gleyed color and orange flecks.
52 +	C/R							Upper boundary – numerous horizontally aligned clasts; probably exposed at the surface in the past, eroded.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The plow zone appears basically similar to higher on the slope, although it is thicker due to greater sediment thickness overall and therefore increased effective depth of plowing. Increased thickness is clearly due to inputs from higher on the slope; this is a cumulic soil profile. The Bt horizon is moderately well developed, suggesting a period of relative stability, perhaps with superjacent sediments mobile. The thickness, stratigraphic position and clear lower boundary of the horizon suggest that it could be the remnant of the lower portion of an older ABp horizon. A slightly bimodal pattern in magnetic susceptibility, with peaks at 5-10 and 20-25 cm supports the interpretation of the Bt horizon as at least incorporating an older zone of illuviation and with the mobile sediments in the plow zone (ABp) incorporating B horizon materials transported from higher on the slope. The 2Bt horizon is also moderately well developed, with relatively strong clay films and moderate structure. Redoximorphic features reflect repeated saturation and the increased groundwater inputs at the base of the slope. Presumably increased groundwater and fine sediment flux has caused faster pedogenesis than at higher geomorphic locations. Imbricated clasts and the eroded appearance of the upper surface of the bedrock suggest that it was exposed at the surface in the past. The timing of deposition of the overlying 2Bt unit, as represented by the degree of soil development, is somewhat ambiguous. If present, original horizonation within the 2Bt horizon has been hidden by soil welding and the effects of groundwater; it is also possible that the sediments at the base of the slope were deposited relatively rapidly, minimizing any original horizonation. In general, the degree of soil development is consistent with erosion and exposure of the bedrock having occurred during the Islamic period, assuming relatively rapid soil formation at lower points on the landscape. Overall, it appears that the slopes were stripped of sediments during the Islamic period, and larger clasts were transported to the base of the slope. Subsequently, clay and fine sediments accumulated at the base of the slope due to local weathering, aeolian inputs and sediment transport from higher on the slope. After soils developed on much of the slope, recent plowing re-mobilized surface sediments and they were transported to the base of the slope.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

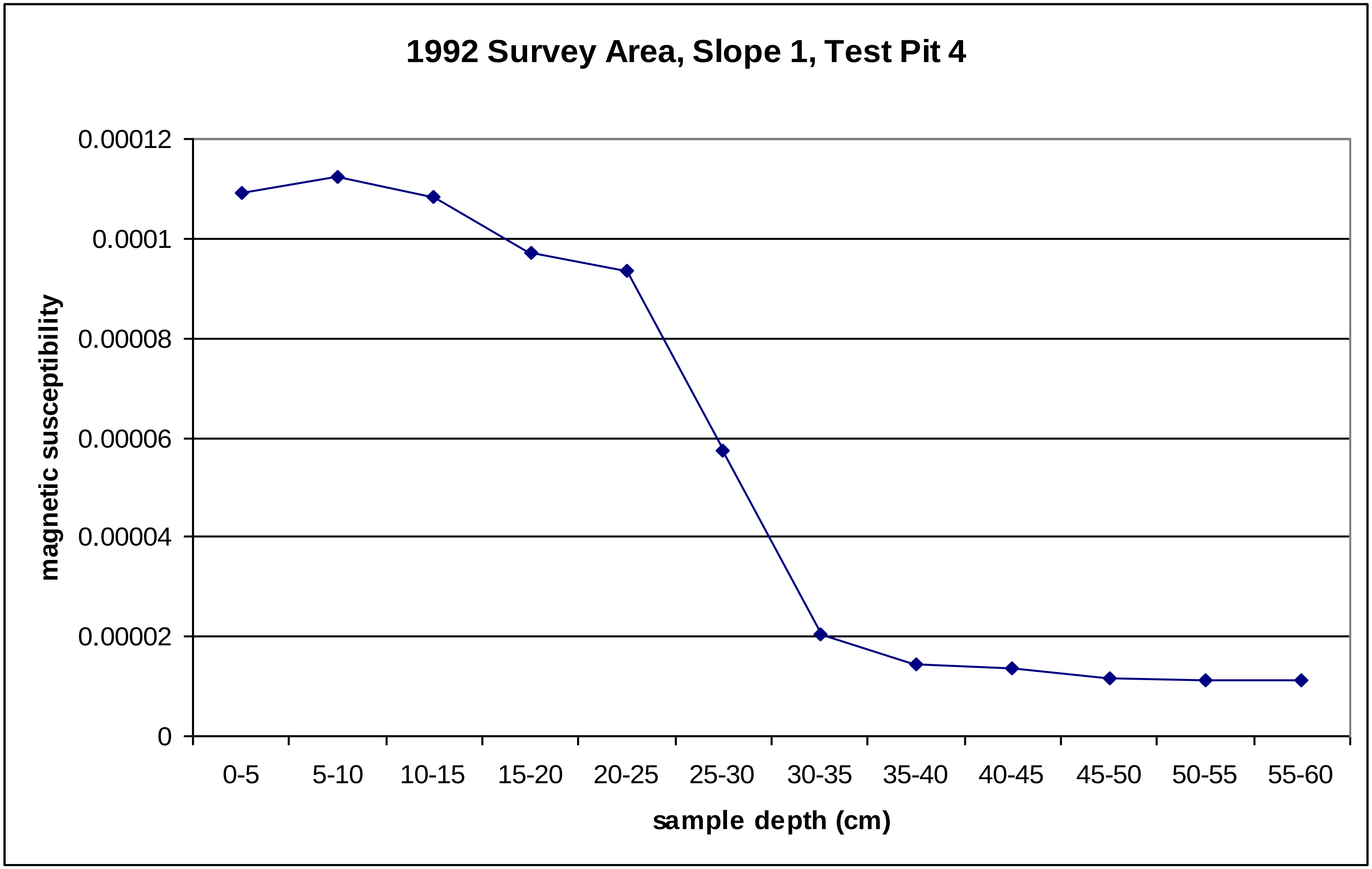

Figure A1 - 18: Magnetic susceptibility by depth, 1992 survey area, slope 1, soil test pit 4

1992 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 5

Date: July 5, 2005
Location: Toe of slope, hill west of Queimada
Coordinates: 29S 606135E, 4162412N Slope: 5* Aspect: E, 84*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 21	ABp	2.5 Y 6/3	moderate, coarse – very coarse granular	20/ sa-a, 2-15mm (majority <5mm)	loam	few, distinct ped face	clear, smooth	Plow zone. Clearly in an area of accumulation at the base of the slope, low point on the landscape.
21 – 42	(ABb)> Bt	2.5 Y 7/2	moderate, medium, subangular blocky	15-20/ sa-sr, 2-10mm	clay loam	common, distinct ped face	clear, smooth	Lower boundary is a stone line.
42 – 84	2AB> Bt2	10 YR 7/2	moderate, medium, subangular blocky	15-20/ sa-sr, 2-8mm	silty clay loam	common to many, distinct, ped face	abrupt irregular (bedrock)	Textural change and stone line at upper boundary, probably an old ground surface. Redoximorphic features are present (mottling and some gleying), they increase with depth. Old soil characteristics (horizons) have been overprinted. Clay increases with depth, grades to silty clay at base; boundary is obscured by moisture. Rooftile fragment at 45 cm.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: Aside from the yellow color, the ABp horizon is essentially the same as observed on the rest of the slope; the color may be due to inputs from the small fluvial system as opposed to just the slope, and it may be altered by increased water in this location. The subjacent horizon has characteristics of both a B horizon and a buried A horizon, indicating a cumulic soil. Structure and clay films are moderately developed, but the increase in fine sediments and water at this low point on the landscape implies rapid pedogenesis; these may be relatively recent deposits with some inherited soil characteristics. The stone line at the base of the Bt horizon suggests past erosion and a lag deposit. The basal unit again has characteristics of both a B horizon and a buried soil. Horizonation related to the deposit's previous position at the ground surface (if any) has been obscured by soil welding and by groundwater, which clearly is modifying the deposit significantly. Time dependent pedogenic characteristics are moderately expressed in the lowest horizon. The age of the unit is somewhat ambiguous, as it might have been deeply buried in the past (inhibiting soil formation) and it is in a geomorphic position where soil development should be relatively rapid. A rooftile fragment at 45 cm suggests that the unit was exposed at the surface during or after the Islamic period. It is possible that the stone line represents erosion and the ground surface during the Islamic period, and that the roof tile fragment was introduced into the uppermost 3cm of the lowest unit by trampling, plowing or other post-depositional processes. The multi-aliquot OSL date for the underlying sediments probably overestimates their age due to partial bleaching, as has been seen in every multi-aliquot sample retested with single grain analyses. It provides a maximum age for the deposit, perhaps reflecting millennia of relatively slow accumulation at the base of hillslopes prior to major hillslope erosion during the Islamic period. The surface of the bedrock does not appear weathered and there are no imbricated clasts at the base of the exposure, suggesting that soils were not completely removed from this location in the past for any significant length of time; as implied by the OSL date, the deepest stratum probably antedates the Islamic period. The magnetic susceptibility data are bimodal, with peaks at 15 – 20 cm and 35 – 40 cm, implying at least two periods of deposition and pedogenesis and consistent with the suggestion that the

stone line at the base of the (ABb)>Bt horizon was at the surface during the Islamic period. Overall, the stratigraphy is consistent with a period of erosion in the past that left only the lowest stratum intact, followed by renewed deposition and soil formation. The degree of soil development in the superjacent horizons is consistent with the erosion having occurred during the Islamic period, but is far from definitive given the problems of a cumulic profile, soil welding and groundwater effects. The uppermost unit clearly is a recent deposit with inherited soil characteristics.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

OSL Data:

Sample	**Depth/ Stratum**	**Optical Age (+/- 1 σ)**	**Measurement Type**	**Lab Number**
OSA S1 STP5 "upper"	48 – 62 cm/ upper 2AB>Bt2	4420 +/- 480 [2420 B.C.E.]	multiple aliquot	UNL-1283
OSA S1 STP5 "lower"	62 – 76 cm/ middle 2AB>Bt2	sample not analyzed		

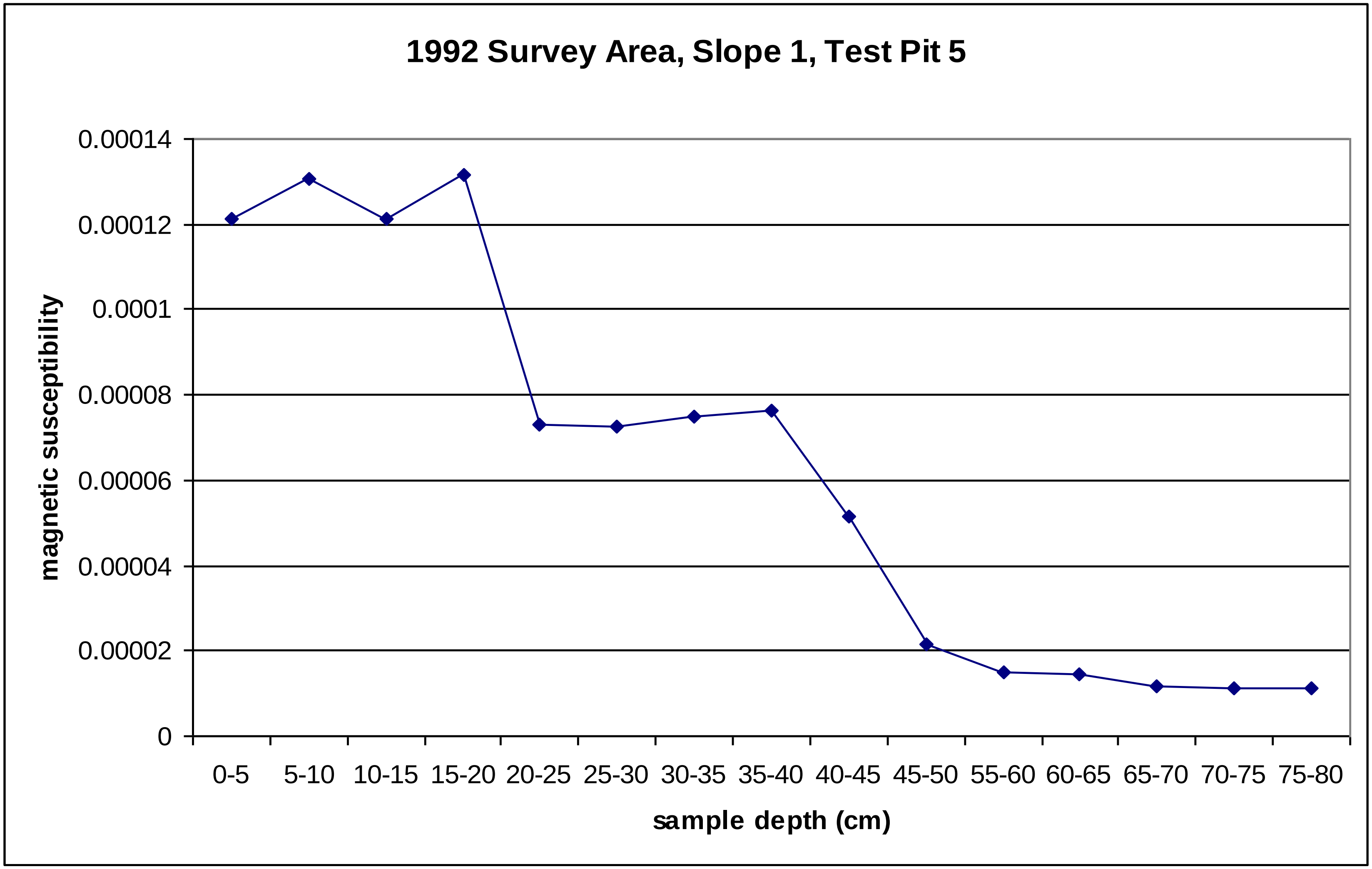

Figure A1 - 19: Magnetic susceptibility by depth, 1992 survey area, slope 1, soil test pit 5

1992 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 1

Date: July 6, 2005
Location: Summit of hill south of Góis
Coordinates: 29S 606227E, 4156065N Slope: 3* Aspect: N, 354*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 25	ABp	2.5 Y 6/4	moderate, medium subangular blocky	30/ a-sa, 2-30mm	loam	few, faint ped face	abrupt, irregular (bedrock)	Clay films more distinct lower in profile. Roof tiles *in situ* at 15 cm. Texture may grade to sandy loam. Rocky surface.
25 +	C/R							

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The sediments have been mixed by plowing/ disking for wheat cultivation. The structure and, to a lesser extent, clay films suggest that the deposit has been moderately altered by pedogenic processes. The sediments appear to be the same in the crevasses in the bedrock. Together with the presence of roof tile fragments (most likely derived from the nearby Islamic period site) *in situ* at a depth of 15 cm, this suggests that soils were eroded from this part of the hillslope in the past, some time during or after the Islamic period. It is, however, not possible to determine whether the few observed fragments are intrusive, and the slight increase in clay films lower in the profile may indicate that a few (<10) cm of ancient soils were preserved and that these were mixed with later deposits by plowing/ disking and bioturbation. In either case, additional sediments have been emplaced by bedrock weathering and aeolian inputs since the past erosion, and these have been altered by a moderate degree of pedogenesis. The rocky lag deposit at the surface indicates recent and ongoing erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 2

Date: July 6, 2005
Location: Shoulder of hill south of Góis
Coordinates: 29S 606229E, 4156083N Slope: 14* Aspect: N, 3*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 4/16	ABp	2.5 Y 6/4	moderate, medium subangular blocky	40/ sa-sr, 2-30mm	loam	few, faint ped face	abrupt, irregular (bedrock)	The surface is rocky. Roof tile fragments are present at the surface and throughout the profile.
4/16 +	C/R							Depth of deposits is variable.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The ABp horizon is similar to that observed in STP 1, with a slight increase in gravel and decrease in thickness implying more erosion at this point on the slope. The greater erosion is probably due to the steeper slope angle and increased water moving across the surface because of run-on from higher on the slope. Structure and clay films again indicate a moderately well-developed soil. The presence of artifacts throughout the profile, very likely derived from the Islamic period site nearby, suggests that soils were completely removed from this location by erosion during or after that period. Extant sediments must have been deposited since that time. The rocky surface appears to be a lag deposit, implying renewed erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 3

Date: July 6, 2005
Location: Backslope of hill south of Góis
Coordinates: 29S 606231E, 4156114N   Slope: 19*   Aspect: N, 7*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	2.5 Y 6/3	moderate, medium subangular blocky	40-50/ sa-sr, 2-30mm	loam	few, faint ped face	clear, smooth	The surface is very rocky. The area has not been plowed in several years – the lower boundary is no longer abrupt.
14 – 25	Bt	2.5 Y 6/4	moderate, medium subangular blocky	30/ sr-sa, 2-15mm	loam	common, distinct ped face	gradual, smooth	Texture grades to clay loam. Clay films suggest clay is pedogenic.
25 – 34	Bt2	10 YR 6/4	strong, fine, angular blocky	50/ a-r, 2-30mm	clay loam	common, prominent ped face	abrupt, irregular (bedrock)	The soil continues unaltered into the interstices in the bedrock.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva). This pit is located in a concave section of the slope, a depositional zone.

Interpretation: The plowed sediments at the surface are similar to those higher on the slope, with a gravelly lag deposit again indicating recent and ongoing erosion. The bimodal peaks in magnetic susceptibility at the surface and at 20 – 25 cm suggest both ongoing erosion and that the plow zone incorporates older B horizon materials from this location and/ or higher on the slope. The subjacent Bt horizon is probably similar to B horizons higher on the slope that have been incorporated into the plow zone and are no longer present/ recognizable. The structure and clay films indicate a significant period of pedogenesis, on the order of multiple centuries to a millennium. It is likely that this stratum originated higher on the hillslope and was deposited when sediments were eroded from the summit and shoulder of the slope during or after the Islamic period. The gradual lower boundary and gradual increase in clay content with depth are probably due to soil welding as the color, structure and clay films of the Bt2 horizon indicate significantly greater antiquity for this deposit, on the order of multiple millennia. The high gravel content and rounding of clasts, however, suggest that a significant amount of this basal deposit might have been removed by erosion prior to the deposition of the overlying sediments.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

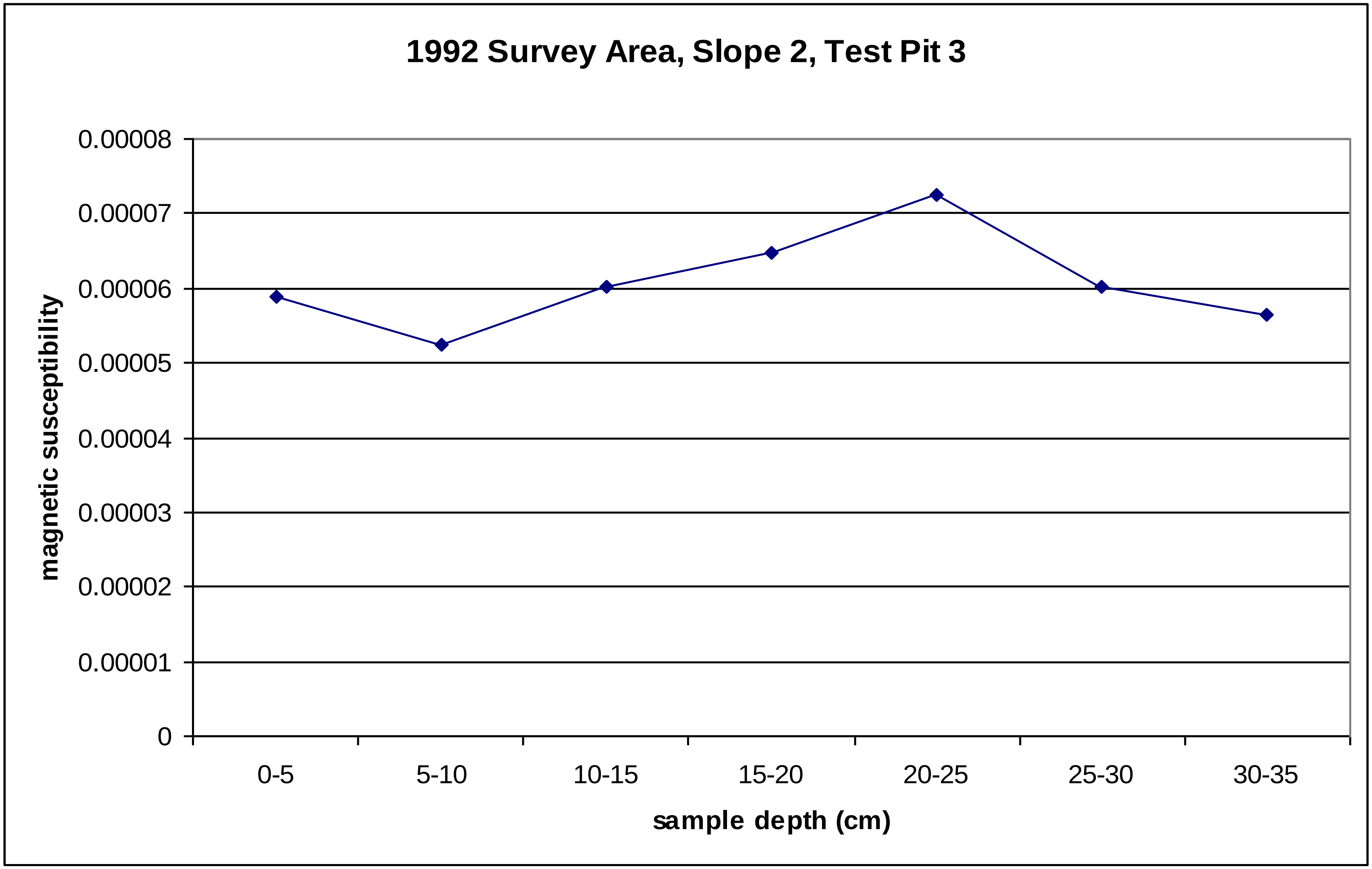

Figure A1 - 20: Magnetic susceptibility by depth, 1992 survey area, slope 2, soil test pit 3

1992 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 4

Date: July 7, 2005
Location: Foot of slope of hill south of Góis
Coordinates: 29S 606230E, 4156133N   Slope: 5*   Aspect: NNE, 16*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 19	ABp	2.5 Y 6/3	weak, medium, subangular blocky	30/ sr-sa, 2-20mm	loam	few, faint ped face	clear, wavy	The surface is rocky. Sediments have a slightly porous appearance. Unit appears to be slightly darkened, possibly by organic inputs.
19 – 56	Bt	2.5 Y 7/3	moderate, medium, subangular blocky	30/ sa-r, 2-20mm	loam	few, distinct ped face	clear, smooth	Clasts larger than 20mm are present but not common. The lower boundary is defined by a weak stone line, possibly a former surface. Artifacts are common throughout this stratum, suggesting deposition during or since the Islamic period. Sediments appear porous. Higher clay content than ABp.
56 – 78	Bt2	2.5 Y 7/3	moderate, medium, subangular blocky	40/ sa-r, 2-30mm	loam	few, distinct ped face	clear, smooth	Clasts larger than 30mm are present but not common. Few artifacts are present. Porous appearance similar to overlying. Clay content similar to overlying.
78 - 107	Btb>Bt3	2.5 Y 6/4	strong, medium subangular blocky	30/ sa-sr, 2-15mm	clay loam	common distinct – prominent ped face	abrupt, irregular (bedrock)	Clasts larger than 15mm are present; large gravels increase relative to overlying. No artifacts observed – may antedate occupation. Some mottling indicates groundwater. Sediments continue into interstices in bedrock.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva). This pit is located on a small alluvial fan that is currently incised ~40cm along the northern margin.

Interpretation: The plowed sediments are similar to those elsewhere on the slope, with rocks at the surface indicating recent and ongoing erosion. The slightly weaker expression of structure may indicate that the A horizon was initially thicker in this area such that fewer B horizon sediments were mixed in by plowing. This impression is supported by the magnetic susceptibility data. The structure and clay films of the subjacent Bt and Bt2 horizons indicate a moderate degree of pedogenesis, and artifacts are present throughout. The two units are almost identical, with the exception of fewer artifacts and more gravel in the lower. The relatively weak clay films imply that these units were deposited recently, perhaps due to plowing of the slopes above. The structure, on the other hand, suggests a longer period of stability and is consistent with deposition during or immediately after the Islamic period. It is possible that the upper unit was deposited recently, that the lower is significantly older, and that the stone line represents recent erosion that truncated a deeper soil. The fact that the two units are nearly identical, however, implies that two episodes of deposition separated by a short period of time is a more likely explanation. With the current data, it is not possible to determine with certainty whether the Bt and Bt2 horizon sediments were deposited recently, with pedogenic characteristics being inherited, or deposited during or immediately after the Islamic period. The artifacts throughout the two units provide some support to the contention that they were deposited during the Islamic period. In addition, the magnetic susceptibility data suggest that the Bt and Bt2 horizons formed in deposits of a similar age and origin, and comparisons to other soils on the slope provide support for deposition during or shortly after the Islamic period. The lack of artifacts in the basal deposit implies that it was in place prior to the Islamic period. If the superjacent deposits are recent, horizonation within the deepest unit must have been

masked by plowing or upper horizons were removed by erosion prior to deposition of the Bt2 unit. The decrease in magnetic susceptibility is consistent with erosion of upper horizons, but the lack of a lag deposit suggests that this is unlikely. Similarly, there is no evidence for plowing of the upper portion of the unit. It is simpler to posit that the Bt and Bt2 deposits were emplaced during the Islamic period, and original horizonation in the basal unit has been masked by soil welding and the effects of groundwater. Mottling in the lowest unit shows that it is seasonally saturated by groundwater.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

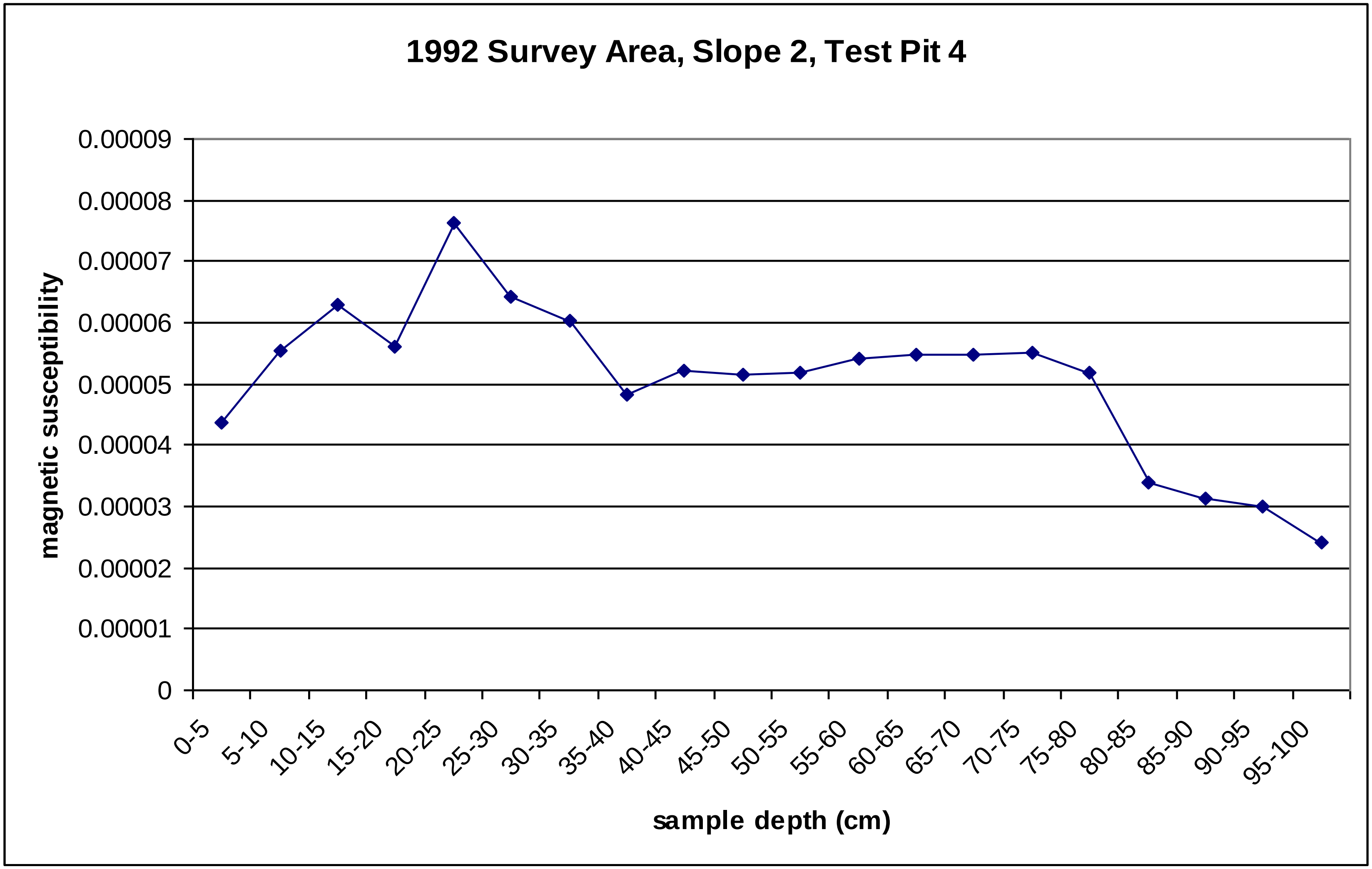

Figure A1 - 21: Magnetic susceptibility by depth, 1992 survey area, slope 2, soil test pit 4

1992 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 5

Date: July 7, 2005
Location: Toe of slope, hill south of Góis
Coordinates: 29S 606245E, 4156157N Slope: 3* Aspect: NNE, 18*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	ABp	2.5 Y 6/3	moderate, medium granular	40/ sa-r, 2-20mm	loam	few, faint ped face	clear, wavy	Majority of clasts are subrounded. Fewer rocks at the surface than higher on the slope; area of accumulation of materials eroded from the slope. Redder/ browner than subjacent, probably due to organics.
15 – 67	Bt	2.5 Y 7/3	moderate, fine, subangular blocky	40/ sa-r, 2-10mm	clay loam	few to common, distinct ped face	clear, smooth	Majority of clasts are subrounded. Texture grades to loam.
67 – 87	(Btb?)> Bt2	2.5 Y 7/3	moderate, medium, subangular blocky	40/ sr, 2-10mm	loam	few, faint ped face	clear, smooth	Texture grades to clay loam. Upper boundary is a weak stone line, possibly a former erosional surface. Some mottling is present, a few artifacts are present.
87 – 112	(2Btb?) >Bt3	2.5 Y 7/2	strong, medium subangular blocky	40-50/ a-sa, 2-15mm	clay loam	few, distinct ped face	not observed	Texture grades to loam. Clasts larger than 15mm are present but not common. Very rocky, mottled; unit is decomposing bedrock.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva). This pit is located on a small alluvial fan that is currently incised ~40cm along the northern margin.

Interpretation: The stratigraphy exposed in this pit is similar to STP 4, with a plow zone over two Bt horizons the age of which is difficult to determine, and a basal unit that appears to be considerably older. The relative lack of a gravelly lag deposit at the surface and the low magnetic susceptibility in the upper few cm indicate that erosion is less severe at the base of the slope. The structure of the two Bt horizons immediately subjacent to the ABp is moderately expressed, while the clay films are relatively weak, and as in STP 4 the two are separated by an indistinct stone line. Artifacts are present in those two horizons and are common to a depth of 75 cm. The magnetic susceptibility data, artifacts and pedogenic characteristics are consistent with these being older deposits, emplaced by hillslope erosion during or after the Islamic period and subsequently exposed at the surface for an extended period of time. The deepest observed unit contains no artifacts and probably antedates the Islamic occupation. Ped structure indicates strong soil formation, but the clay films are relatively poorly developed, perhaps because it has been deeply buried. The makeup and orientation of clasts clearly show that the unit is composed of bedrock that is decomposing *in situ*; excavations were stopped at 112 cm below the modern ground surface without encountering more solid bedrock.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

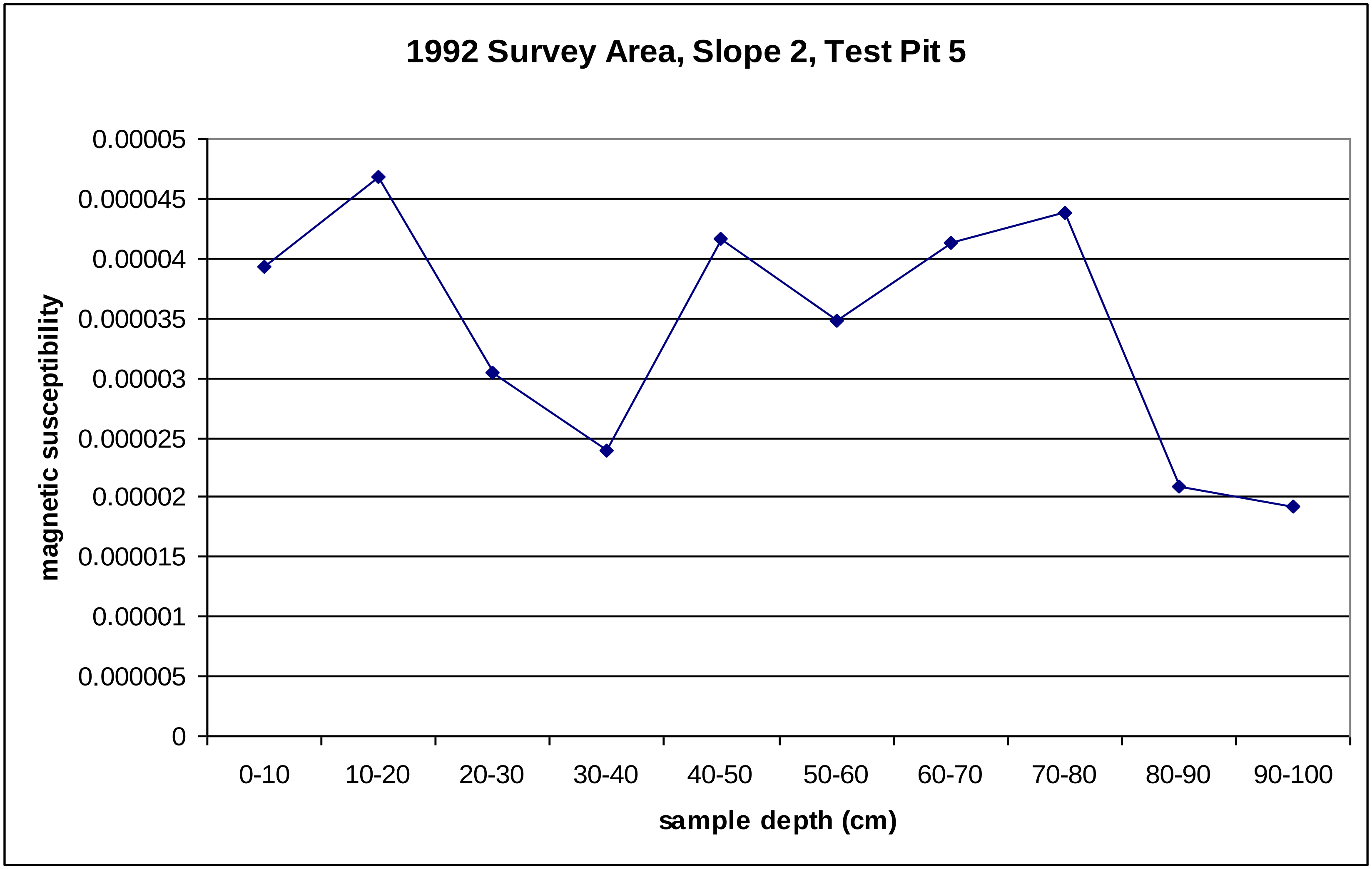

Figure A1 - 22: Magnetic susceptibility by depth, 1992 survey area, slope 2, soil test pit 5

1992 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 1

Date: July 12, 2005
Location: Summit of hill west of Pereiras
Coordinates: 29S 603067E, 4158203N Slope: 1* Aspect: NNE, 26*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 11	ABp	2.5 Y 6/3	weak, medium granular	40-50/ a-sa, 2-30mm	loam	none	abrupt, wavy	Sediments appear to be slightly darkened by organic material.
11 – 16	Bt	10 YR 6/4	moderate, medium subangular blocky	40-50/ a-sa, 2-30mm	loam	few, distinct ped face	abrupt, irregular (bedrock)	Depth to bedrock is highly variable, mostly less than 16cm; Bt horizon may not be preserved everywhere. Material continues into interstices in bedrock. Slightly more clay than overlying.

Notes: Area was disked this year after harvest.

Interpretation: Sediments at the surface have been mixed by plowing and disking for wheat cultivation; pedogenic characteristics are weakly expressed. The subjacent Bt horizon is preserved in areas of thicker deposits and in interstices in the bedrock. The color, structure and clay film morphology reflect moderate pedogenesis, and comparison with other soils in the study area suggests a period of soil formation on the order of a millennium. That deposits in the interstices in the bedrock do not exhibit stronger pedogenesis suggests that all loose sediments were removed from this area in the past. The data are consistent with the past episode of erosion having occurred during the Islamic period.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 2

Date: July 12, 2005
Location: Shoulder of hill west of Pereiras
Coordinates: 29S 603085E, 4158213N Slope: 12* Aspect: ENE, 57*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	2.5 Y 6/3	weak, medium granular	50/ a-sa, 2-30mm	loam	none	abrupt, wavy	Sediments appear to be slightly darkened by organic material. Gravels to 30mm are common, larger clasts are present.
10 – 18	Bt	10 YR 6/4	moderate, medium subangular blocky	40/ a-sa, 2-30mm	loam	common faint to distinct ped face	abrupt, irregular (bedrock)	Depth of deposits is variable; Bt is probably not preserved everywhere. Material continues into interstices in bedrock. Slightly more clay than overlying.

Notes: Area was disked this year after harvest.

Interpretation: The stratigraphy is essentially the same as in STP 1. Clay films are slightly more strongly expressed in the Bt horizon, probably reflecting increased water and fine sediment inputs into the solum from run-on at this lower point on the slope.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 3

Date: July 12, 2005
Location: Backslope of hill west of Pereiras
Coordinates: 29S 603124E, 4158245N Slope: 20* Aspect: ENE, 58*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 12	ABp	2.5 Y 6/3	moderate, coarse granular	50/ a-sa, 2-70mm	loam	none	abrupt, wavy	Sediments appear slightly darkened by organic material.
12 – 28	Bt	10 YR 6/4	moderate, medium subangular blocky	60/ a-sa, 2-60mm	clay loam	few, faint - distinct ped face	abrupt, irregular (bedrock)	Material continues into interstices in bedrock. Depth of bedrock is highly variable, as shallow as 11 cm. This is an anomalously deep pocket.
Notes: Area was disked this year after harvest.								
Interpretation: The pedostratigraphy is essentially the same as STPs 1 and 2, aside from a slight increase in clay and gravel in the Bt horizon. The magnetic susceptibility data show peaks at the surface and at 10-15cm. This suggests *in situ* soil development for the Bt horizon, that the plow zone incorporates materials that were initially part of a B horizon and that there is ongoing erosion at the surface.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

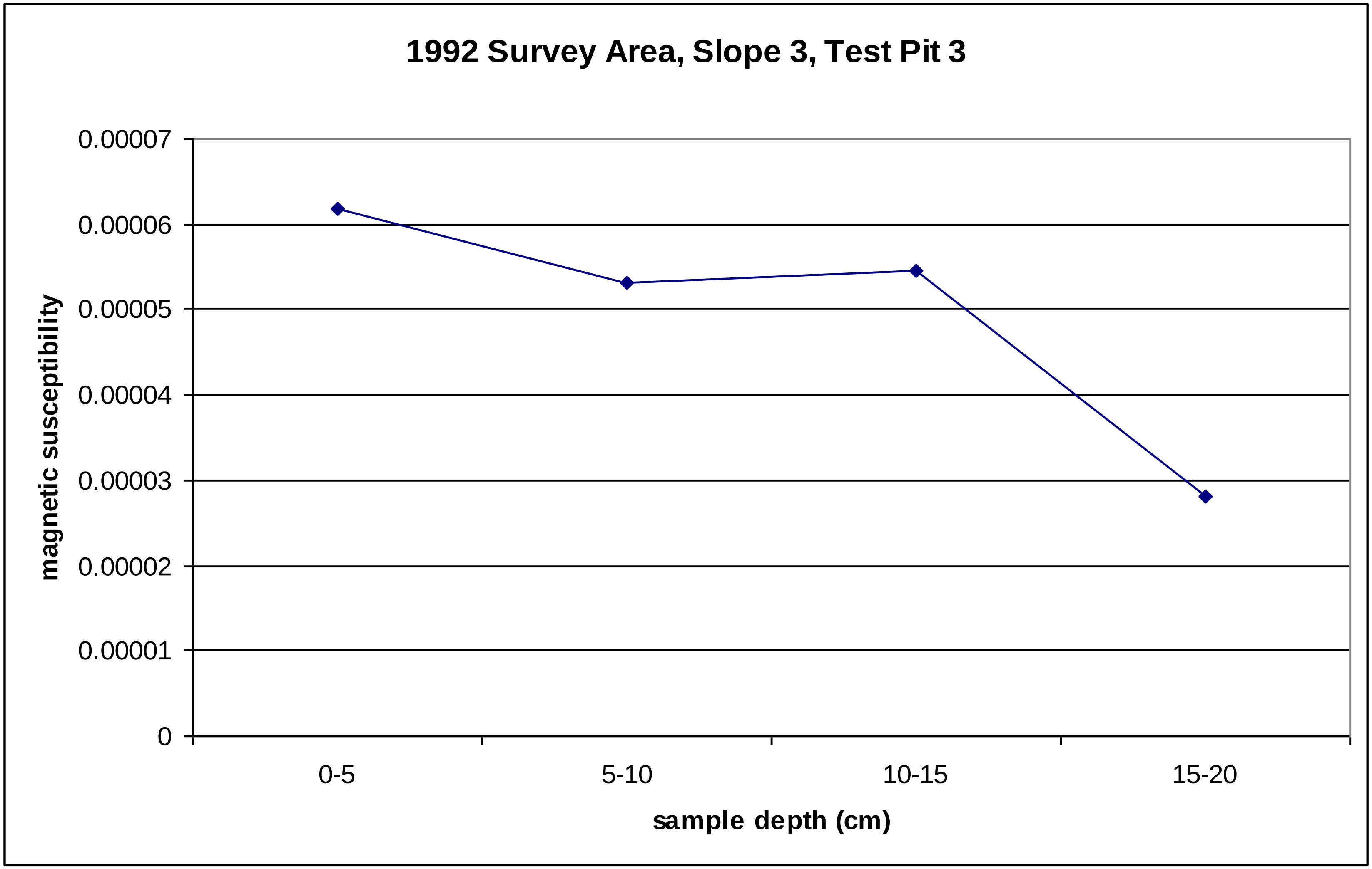

Figure A1 - 23: Magnetic susceptibility by depth, 1992 survey area, slope 3, soil test pit 3

1992 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 4

Date: July 12, 2005
Location: Foot of slope of hill west of Pereiras
Coordinates: 29S 603185E, 4158284N Slope: 11* Aspect: ENE, 65*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 11	ABp	2.5 Y 6/3	weak, medium, granular	60/ a-sa, 2-60mm	sandy loam	none	abrupt, irregular (bedrock)	Sediments appear slightly darkened by organic material. Larger clasts (>6cm) are common. The bedrock appears to have been planed off by plowing/ disking. There may be deeper sediments preserved elsewhere on the footslope.

Notes: Area was disked this year after harvest.

Interpretation: The Ap horizon is similar to that observed elsewhere on the slope. The increase in sand sized particles may be due to mechanized agriculture in that disks and plows are obviously breaking up the bedrock, most likely producing particles of many size classes that are incorporated into the sediments. It is likely that B horizon materials are preserved elsewhere on the footslope, at least in interstices in the bedrock. The lack of appreciable deposition is likely due to slope geometry (relatively straight) and the proximity of an ephemeral stream channel that probably carries mobilized sediment away from the base of the slope.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

1992 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 5

Date: July 12, 2005
Location: Toe of slope, hill west of Pereiras
Coordinates: 29S 603199E, 4158309N Slope: 3* Aspect: ESE, 114*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 16	ABp	2.5 Y 6/2	moderate, medium - coarse granular	40/ a-sr, 2-30mm	loam	none	abrupt, wavy	Sediments appear very slightly darkened by organic material.
16 – 80	Bt	2.5 Y 6/2	moderate, medium, subangular blocky	15-20/ sa-r, 2-10mm	clay loam	common, faint ped face	abrupt, irregular (bedrock)	Large krotovina are present. Mottling is also present.

Notes: Area was disked this year after harvest. Profile exposed by arroyo at base of slope.

Interpretation: The Ap horizon is essentially the same as that seen on other hillslopes in the area. The color and clay film morphology of the Bt horizon are similar to the observed characteristics of the Ap horizon higher on the slope. Taken together with its thickness and the lack of differentiation within it, this suggests that the Bt horizon is cumulic and that it is composed of sediments deposited at the base of the hillslope by recent erosion (i.e., 20th Century). The lack of older preserved sediments is probably due to the presence of an incised stream system at the base of the slope that presumably eroded older sediments and continues to flush mobilized sediments into the ribeira. Bedrock is visible at the base of the channel in most of the nearby area. The magnetic susceptibility data show peaks at the surface, at 15 – 20 cm and at 30 – 35 cm. While these data may be affected by seasonal saturation by groundwater, they suggest ongoing erosion and the accumulation of pedogenic clays at the base of the plow zone. The deepest peak may be inherited, it could be related to *in situ* development of a weak B horizon, or it may correspond to the lower limits of a previous plow zone. This profile presents evidence for recent hillslope erosion and deposition at the base of the hillslope. No preserved sediments in this location appear to have been in place for more than approximately the past century.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

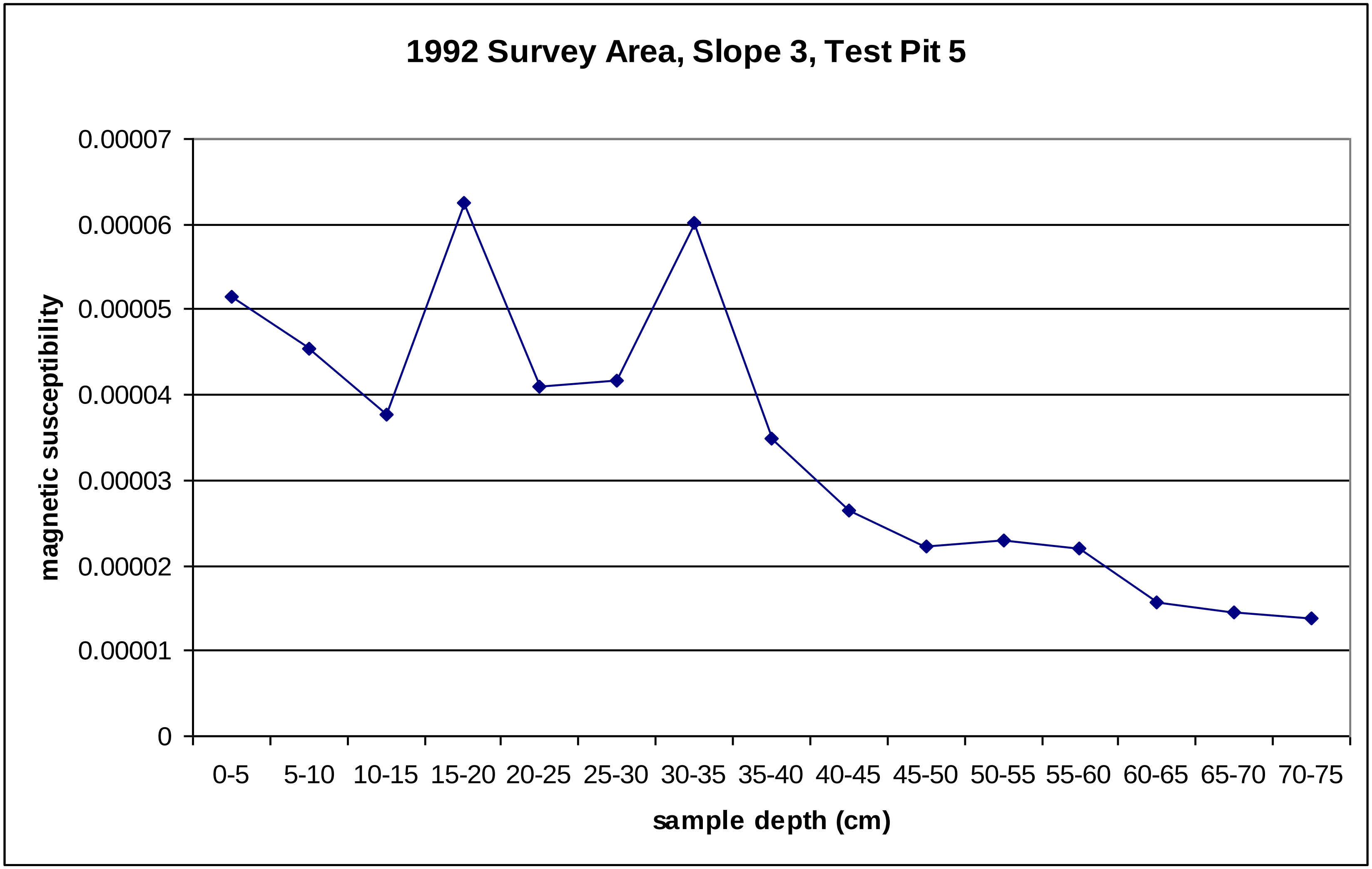

Figure A1 - 24: Magnetic susceptibility by depth, 1992 survey area, slope 3, soil test pit 5

2004-05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 1

Date: July 8, 2005
Location: Summit of hill west of Corte do Gafo Cima
Coordinates: 29S 613051E, 4175847N Slope: 1* Aspect: W, 268*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	7.5 YR 6/4	moderate, coarse granular	40/ a-sr, 2-20mm	sandy loam	few, faint ped face	abrupt, irregular (bedrock)	Texture may grade to loamy sand, high silt content. Small rocks (<20cm) common on the surface; plowing and recent erosion.
Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).								
Interpretation: The sediments in this location have been mechanically mixed by plowing and a gravelly lag deposit at the surface indicates ongoing erosion. Pedogenic characteristics are relatively weakly expressed, but the color and, to a lesser extent, structure and clay film morphology indicate incorporation of well-developed soils into the plowed deposit. Plowing and disking have planed off the surface of the bedrock in this location, so the lack of different sediments in the interstices in the bedrock is not particularly informative. The thickness of sediments and pedogenic characteristics are consistent with severe, recent erosion removing much of the A horizon, with current cultivation of the remnants mixed with the B horizon. This profile provides no evidence of erosion in the past.								

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 2

Date: July 8, 2005
Location: Shoulder of hill west of Corte do Gafo Cima
Coordinates: 29S 613028E, 4175848N Slope: 7* Aspect: W, 259*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	7.5 YR 6/4	moderate, medium subangular blocky to granular	40-50/ a-sa, 2-50mm	loam	common, faint ped face	clear, wavy	O horizon up to 1 cm thick is variably present at the surface. Texture grades to sandy loam with high silt content.
14 – 21	Bt	7.5 YR 6/4	strong, fine angular blocky	60-70/ a-sa, 2-20mm	clay loam	many, distinct ped face	abrupt, irregular (bedrock)	Thickness of this deposit is highly variable, from a few to > 10cm. Material continues into the interstices in the bedrock. It is slightly lighter in color and more reddish than the overlying.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The ABp horizon is basically the same as in STP 1, although the slightly stronger expression of clay films may indicate incorporation of a greater quantity of well-developed soil. The structure, color and clay film morphology of the subjacent Bt deposit indicate a period of pedogenesis on the order of multiple millennia; this is one of the most strongly developed soils encountered in the study area. Similarities in color and texture between the horizons as well as the generally flat magnetic susceptibility curve imply a similar age and genesis for the deposits. The lack of a buried stone line or buried soil horizons suggests that this area was not affected by severe erosion or redeposition in the past. While it is possible that past erosion removed overlying materials, there is no evidence for severe erosion during the Islamic period or at any time before recent cultivation.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

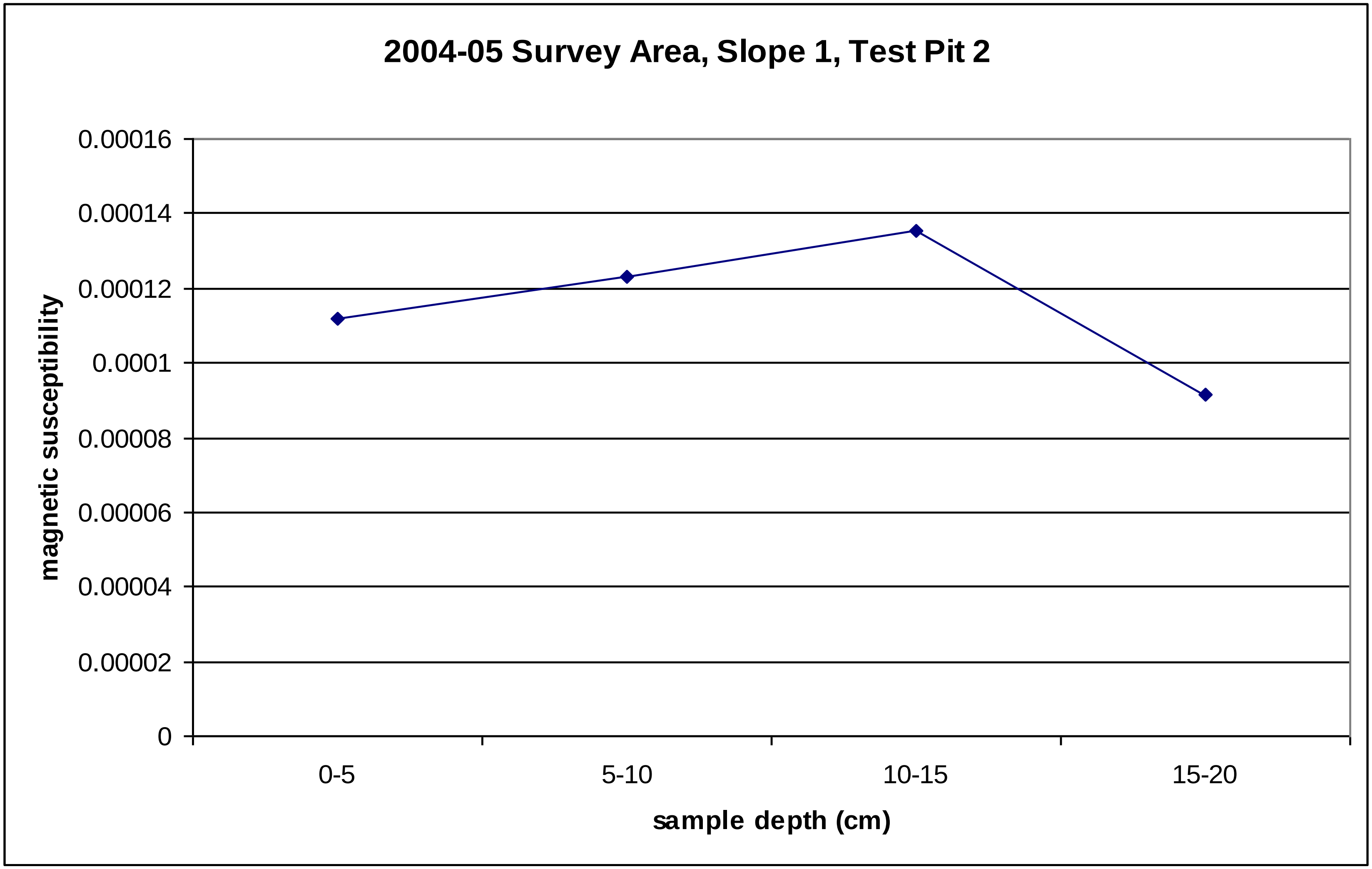

Figure A1 - 25: Magnetic susceptibility by depth, 2004-05 survey area, slope 1, soil test pit 2

2004-05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 3

Date: July 8, 2005
Location: Backslope of hill west of Corte do Gafo Cima
Coordinates: 29S 612992E, 4175844N Slope: 19* Aspect: WSW, 248*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 13	ABp	10 YR 6/4	moderate, coarse granular	30/ a-sa, 2-20mm	loam	common, faint ped face	abrupt, smooth	A thin O horizon (~1cm) is present. ABp is slightly darkened by admixture of organic materials. Fewer rocks at the surface than higher on the slope.
13 – 17	Bt	10 YR 6/4	moderate, medium subangular blocky	15-20/ a-sr, 2-15mm	loam	common, faint & few distinct ped face	clear, smooth	More clay than overlying.
17 – 26	Bt2	2.5 Y 6/4	moderate, medium subangular blocky	10-15/ a-sa, 2-10mm	clay loam	common faint ped face, common distinct pore	gradual, smooth	Peds have a marbled appearance, gray and reddish brown.
26 – 38	C>Bt3	2.5 Y 7/4	moderate, medium angular blocky	50/ a, 2-20mm	clay loam	common, distinct ped face	abrupt, irregular (bedrock)	Some mottling is visible. This is weathering bedrock, parent material, but illuvial pedogenic clay is present.
38 +	R							Schist weathering *in situ*. Upper surface is angular clasts, lined up parallel to bedding in the bedrock, held in place by weathered material. Not exposed at surface within past millennia.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva). Test pit is at the edge of an area of convergent flow.

Interpretation: The color and structure of the ABp horizon indicate slightly weaker soil formation than in analogous horizons higher on the slope. The weaker expression of pedogenic characteristics may be due to recent deposition in this location as erosion removed surface materials from points higher on the slope. The lack of a gravelly lag deposit at the surface, as was present in test pits 1 and 2, also suggests deposition in this location and erosion higher on the slope. The structure and clay film morphology of the subjacent Bt horizon suggest moderate soil formation. The color and especially the lower boundary, however, imply that the origin of this deposit is the same as the ABp horizon, specifically that it is probably a mix of *in situ* soil and materials emplaced recently due to plowing and the ensuing erosion higher on the hillslope. The pedogenic characteristics are likely at least partially inherited. The color of the subjacent Bt2 horizon and the peak in magnetic susceptibility at 20 – 25 cm suggests that it has been in place significantly longer than the superjacent deposits. Pedogenic characteristics are moderately expressed, implying a period of soil formation on the order of a millennium. The gradual lower boundary and similarities in clasts, color and texture, on the other hand, suggest that it is genetically related to the underlying deposit. The Bt3 deposit at the base of the exposure is clearly *in situ* weathered bedrock with a moderate degree of pedogenic alteration, mostly consisting of the presence of illuvial clays. Characteristics of the bedrock suggest that it has not been exposed at the surface within recent millennia. The age of the deposit is therefore somewhat ambiguous, but it is most likely related to bedrock weathering throughout the Holocene. The lack of stronger expression of pedogenic characteristics is probably related to geomorphic position. Soil textural characteristics

presumably have favored the movement of water down slope as opposed to downwards through the soil profile, retarding pedogenesis. In addition, the lower horizons may have been deeply buried in the past. Although the data are not conclusive, the simplest explanation is that the two strata nearest the surface reflect recent movement of sediments on the hillslope while the deeper horizons are significantly older, reflecting landscape stability and pedogenesis for millennia. There is no clear evidence for erosion during the Islamic period.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

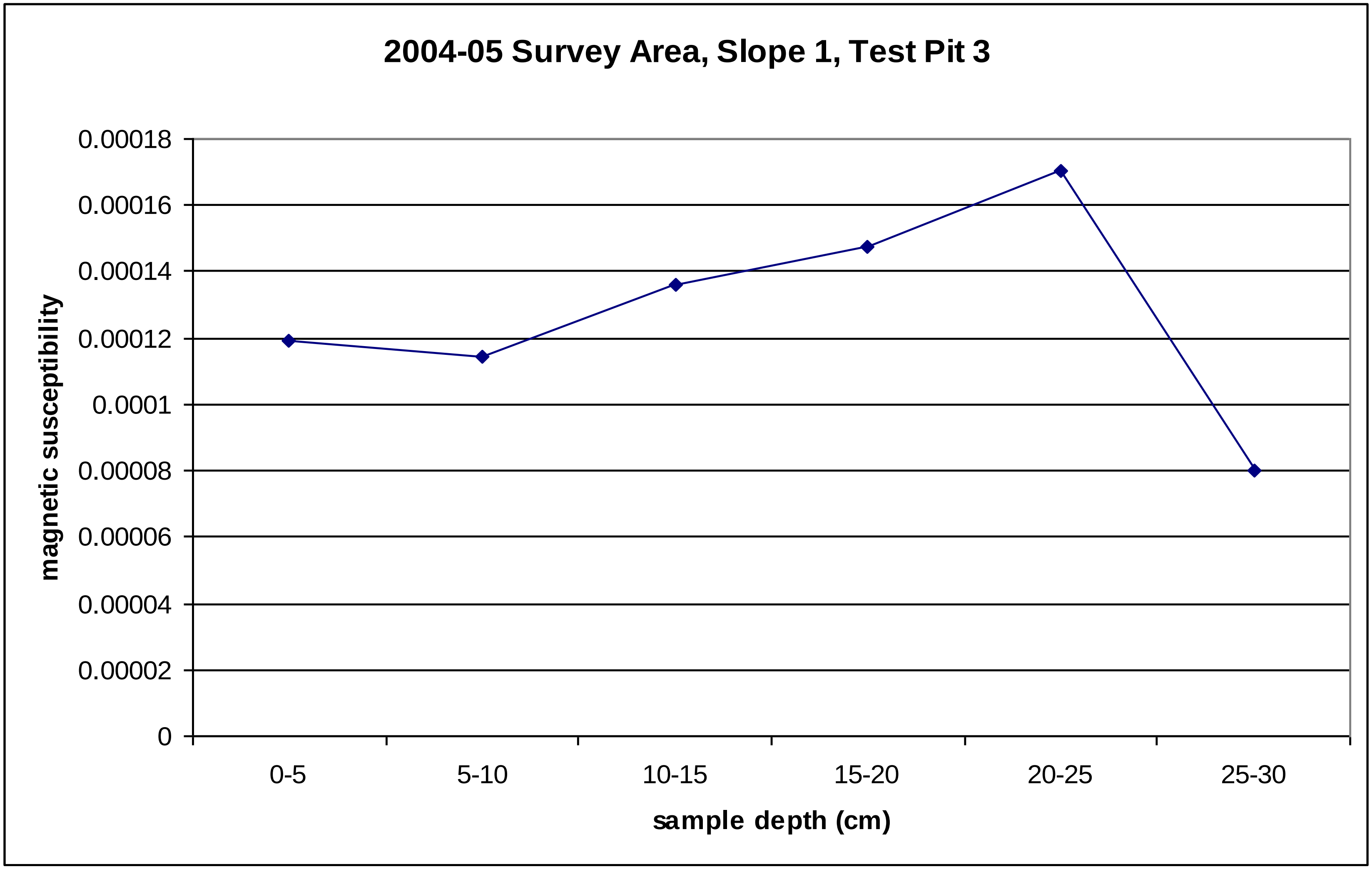

Figure A1 - 26: Magnetic susceptibility by depth, 2004-05 survey area, slope 1, soil test pit 3

2004-05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 4

Date: July 8, 2005
Location: Foot of slope of hill west of Corte do Gafo Cima
Coordinates: 29S 612944E, 4175839N   Slope: 6*   Aspect: WSW, 252*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	ABp	10 YR 6/4	moderate, coarse, granular	40/ a-sa, 2-25mm	loam	few, faint ped face	clear, wavy	The surface is furrowed perpendicular to the slope to minimize erosion.
15 – 31	Bt	10 YR 6/4	moderate, medium subangular blocky	25/ a-sr, 2-10mm	clay loam	few, faint ped face, common, distinct pore	clear, smooth	Larger angular clasts are quartz. Texture may grade to loam.
31 – 66	Bt2	2.5 Y 6/3	moderate, medium angular blocky	40/ a-sa, 2-15mm	loam	few, distinct ped face	gradual, smooth	Larger angular clasts are quartz. Very weak stone line is visible at the lower boundary, probably not a former surface. Texture may grade to clay loam.
66 – 105	C>Bt3	2.5 Y 7/4	strong, fine angular blocky	60/ a, 2-20mm	sandy clay	many, prominent ped face	not observed	Clearly decomposing bedrock. Schist and quartz gravels present. Has not been exposed at surface.

Notes: Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The pedostratigraphy is similar to that in STP 3. The ABp horizon exhibits weak soil development and is probably composed of *in situ* deposits mixed with sediments that originated higher on the slope. The color and lower boundary of the subjacent Bt horizon indicate a similar origin, suggesting that some pedogenic characteristics may be inherited. Peaks in magnetic susceptibility at 20 – 25 cm and at 5 – 10 cm imply that the Bt horizon incorporates a relatively well-developed *in situ* soil and that erosion continues on the slope. The timing of deposition of the underlying Bt2 horizon is problematic, with pedogenic characteristics indicating a moderate degree of soil development and the color, magnetic susceptibility data, and lower boundary suggesting that it is genetically related to the C>Bt3 horizon. It is possible that it reflects hillslope erosion during the Islamic period and that the boundary characteristics are due to soil welding, but this hypothesis does not explain why the color of the deposit would be so similar to that of the relatively unaltered parent material. A simpler explanation is that it is significantly older and that the expression of structure and clay films has been retarded by deep burial or because clays in the superjacent strata inhibited the movement of water downwards through the solum. The basal deposit is clearly decomposing bedrock that has remained in place for millennia, with clay film morphology and structure strongly expressed.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

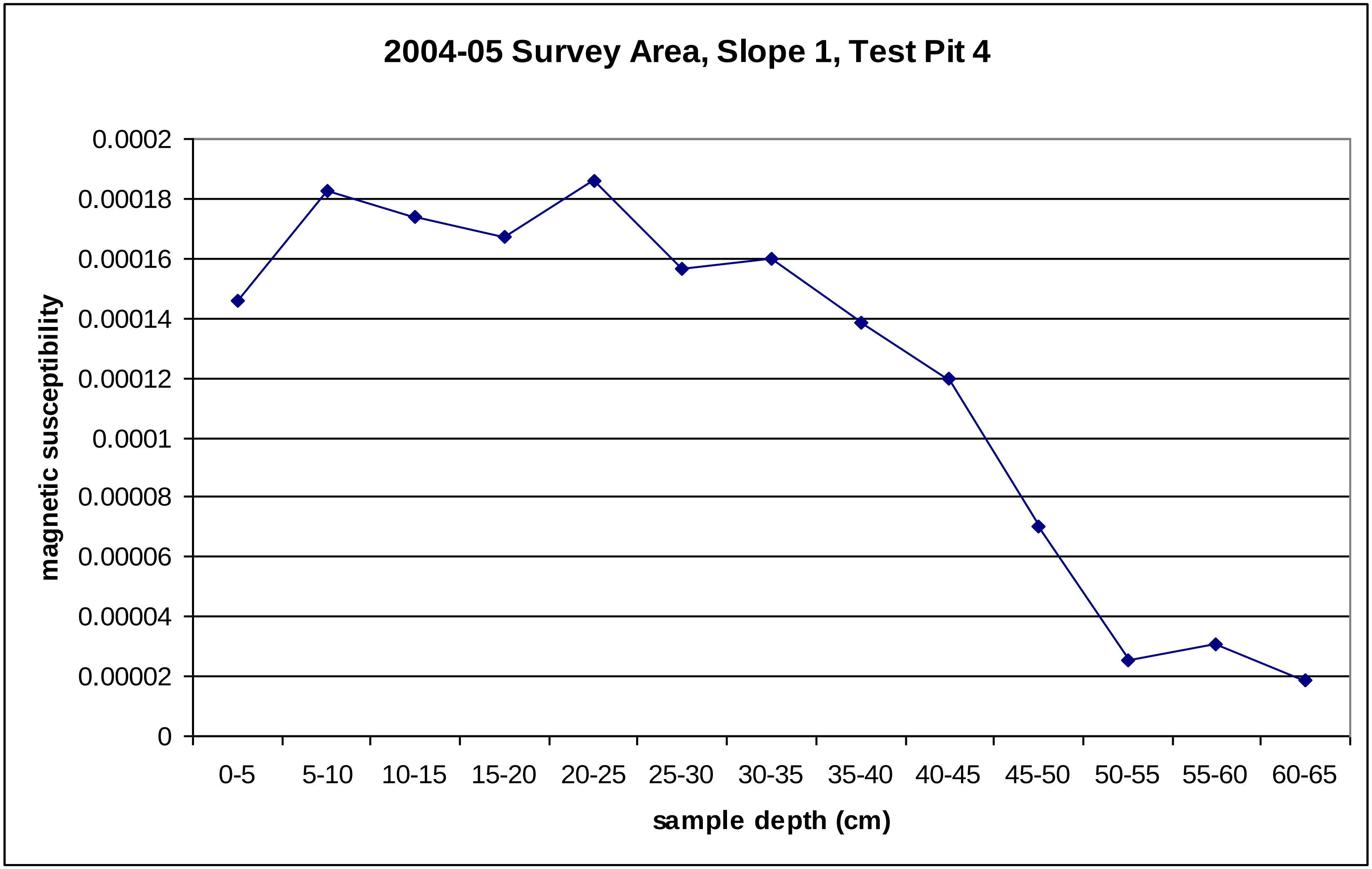

Figure A1 - 27: Magnetic susceptibility by depth, 2004-05 survey area, slope 1, soil test pit 4

2004-05 Survey Area Hillslope Soils: Slope 1, Soil Test Pit 5

Date: July 8, 2005
Location: Toe of slope, hill west of Corte do Gafo Cima
Coordinates: 29S 612923E, 4175810N Slope: 2* Aspect: S, 191*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 5	A	10 YR 5/3	weak, medium granular	<2/ a-r, 2-5mm	silt	none	clear, smooth	High organic content.
5 – 22	Ab>Bt	10 YR 6/4	moderate, coarse, subangular blocky	3-5/ r-sa, 2-8mm	loamy sand	very few, faint ped face and pore	abrupt, smooth	Weak clay films, structure may be inherited.
22 – 34	C	10 YR 5/3	moderate, medium granular	40/ a-r, 2-20mm	sand	none	abrupt, wavy	Rounded rooftile fragment at 25cm.
34 – 48	Btb	10 YR 6/4	moderate, coarse subangular blocky	5/ r-sa, 2-10mm	loamy sand	few, faint ped face and pore	clear, smooth	Some mottling is present.
48 – 90	2C>2Bt	2.5 Y 6/4	moderate, medium subangular blocky and granular	40-50/ sa-sr, 2-20mm	loamy sand	few, faint pore	abrupt, smooth	Rounded sherd present at 75 cm, type produced through mid 20th Century. Granular structure is most pronounced in lowest ~10cm, groundwater? Very little pedogenic clay, structure may be inherited.
90 – 110	3C	2.5 Y 6/3	strong, medium angular blocky	70/ a-sa, 2-20mm	sandy clay	common, distinct pore	clear, wavy (bedrock)	Lower boundary grades into decomposing bedrock. Rock line at upper boundary indicates former channel bedload, including angular quartz cobbles. Deposits are gleyed and mottled. Appears to be a mix of *in situ* decomposing bedrock with fluvial deposits. Sand fraction is decomposing bedrock. Slightly moist.

Notes: Profile in arroyo at base of slope. Area is not currently cultivated, but has been cultivated recently (no esteva).

Interpretation: The sediments exposed in this soil test pit are recent fluvial deposits over *in situ* parent material. Pedogenic characteristics are generally weakly expressed, as is common in cumulic floodplain soils. Physical characteristics of the thin A horizon (i.e., lack of clay films and clear lower boundary) indicate recent deposition and inherited color and structure. The subjacent horizon shows slightly stronger structure, suggesting some period of exposure at the surface, but again the abrupt lower boundary and weak clay films indicate that the structure may be inherited and that deposition was recent. The texture and lack of clay films in the C horizon suggests that it was deposited and buried rapidly. The subjacent Btb horizon exhibits weak soil development, suggesting exposure at the floodplain surface for a period of time as long as a few decades prior to burial. The color of the 2C>2Bt horizon suggests that it incorporates a large quantity of parent material similar to the basal stratum, implying that the structure may be inherited. Weak clay film morphology reflects very little exposure at the surface prior to burial. The abrupt lower boundary shows that the material has been redeposited, and the rock line at that elevation is a bedload deposit

indicating the presence of an incised channel. A sherd at 75cm is of a type that was produced as late as the mid-20th Century. Rounding suggests that the sherd moved through the fluvial system for a period of time at least on the order of years. Although single artifacts are not conclusive chronological markers, the sherd implies initial channel formation in the early to mid-20th Century, followed by filling prior to the formation of the current channel. The structure of the deepest stratum indicates that it has been in place for millennia, and it grades downward into decomposing bedrock. In sum, the strata exposed in the bank of the arroyo reflect a long period of landscape stability followed by channel formation during the 20th Century, at the same time as widespread changes in land use. Subsequently, the channel filled and sediments were deposited on the floodplain prior to the formation of the deeper, through-flowing modern channel. The repeated cycles of deposition and channel formation in one location are consistent with complex response models of fluvial systems.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 1

Date: July 11, 2005
Location: Summit of hill west of Cachopos
Coordinates: 29S 615719E, 4181883N Slope: 2* Aspect: NE, 44*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	5 YR 6/6	weak, medium granular	60/ a-sa, 2-50mm	sandy clay	common, distinct ped face; many prominent coatings	abrupt, wavy	The “soil” is essentially disked bedrock. The bedrock weathers to clay, the texture is due to a mixing of weathered bedrock with fragments created by disking. The sediments are somewhat darkened by organic material.
14 +	Bt/ R	5 YR 5/6	weak, medium granular	70/ a, 2-50mm	sandy clay	many prominent coatings	not observed	Stratum consists of weathered bedrock between sheets of schist. The bedrock is highly friable, crumbly.

Notes: Area has been cultivated recently (no esteva).

Interpretation: The sediments in this location have been mixed and, to some degree, created by mechanical breaking of bedrock. Although soil horizonation is not preserved, clay film morphology indicates that the surface sediments incorporate remnants of the B horizon of a well-developed soil. The sediments continue basically unaltered into the weathering bedrock. The pattern suggests that overlying soil horizons that once were present have been removed by recent, extreme erosion. Currently, cultivation takes place in weathered bedrock mixed with some remnants of the former soil.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 2

Date: July 11, 2005
Location: Shoulder of hill west of Cachopos
Coordinates: 29S 615734E, 4181892N Slope: 9* Aspect: NE, 43*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 16	ABp	7.5 YR 6/4	weak, medium granular	60/ a-sa, 2-50mm	sandy clay	common, distinct ped face; many prominent coatings	abrupt, wavy	Sediments are slightly darkened by organic material. Texture is due to mechanical mixing of weathering products (clay) with bedrock fragments created by disking (sand).
16 +	Bt/ R	5 YR 6/6	strong, fine angular blocky	70/ a, 2-50mm	clay loam	many, prominent ped face and coatings	not observed	Stratum is weathered, decomposing bedrock with clay (both pedogenic and a weathering product) in the interstices.

Notes: Area has been cultivated recently (no esteva).

Interpretation: The ABp horizon is similar to that in test pit 1, consisting of a mixture of well-developed soil and mechanically crushed bedrock. The color differences suggest that a somewhat larger amount of the previous soil is mixed into the decomposing bedrock here, probably including materials eroded from higher positions on the slope. The color, structure and clay film morphology of the subjacent Bt/ R horizon indicate a very long period of pedogenesis, on the order of several millennia. Time dependent pedogenic characteristics are as well expressed as in any soil encountered in the study area. The data suggest a long period of landscape stability followed by significant recent erosion. There is no preserved evidence for an episode of significant erosion in the past.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 3

Date: July 11, 2005
Location: Backslope of hill west of Cachopos
Coordinates: 29S 615747E, 4181904N Slope: 15* Aspect: NNE, 33*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 22	ABp	7.5 YR 6/6	moderate, coarse granular	40-50/ a-sa, 2-30mm	silty clay loam	common, distinct ped face and prominent coatings	abrupt, wavy	Appears slightly darkened by organic material. Texture indicates inputs from higher on slope.
22 – 38	Bt	7.5 YR 6/8	moderate, fine subangular blocky	40/ a-sa, 2-30mm	sandy clay loam	common, distinct ped face	gradual, irregular	Orientation of clasts indicates bedrock weathering in place.
38 +	C/ R							Bedrock is highly weathered and friable. Boundary is difficult to determine.

Notes: Area has been cultivated recently (no esteva).

Interpretation: The thicker soils exposed in this test pit reflect inputs from higher on the slope but are otherwise similar to the strata exposed in test pits 1 and 2. Specifically, the texture of the ABp horizon indicates a higher proportion of silt sized particles than higher on the slope, suggesting that it incorporates at least some of the original A or B horizons. This implies both less erosion on this segment of the slope and deposition due to erosion higher on the slope, although ongoing erosion is clearly significant. The clay film morphology and structure reflect incorporation of a well-developed soil. The subjacent Bt horizon also includes a greater proportion of silt sized particles than higher on the slope, implying less disturbance and erosion in this location as erosion in many cases preferentially removes silt. (Sand is larger and heavier, and clay particles are difficult to entrain due to their extremely small size and platy shape.) The Bt horizon is moderately well developed, with somewhat weaker expression of time dependent pedogenic characteristics than the analogous horizon in STP 2. It clearly grades downward into decomposing bedrock, however, suggesting that it has developed in place for a very long period of time on the order of millennia. The magnetic susceptibility curve is relatively flat, with a peak at the surface and a second at 20 – 25 cm. This is consistent with ongoing erosion and mobility of surface sediments as well as the preferential accumulation of pedogenic clays at the base of the plow zone.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

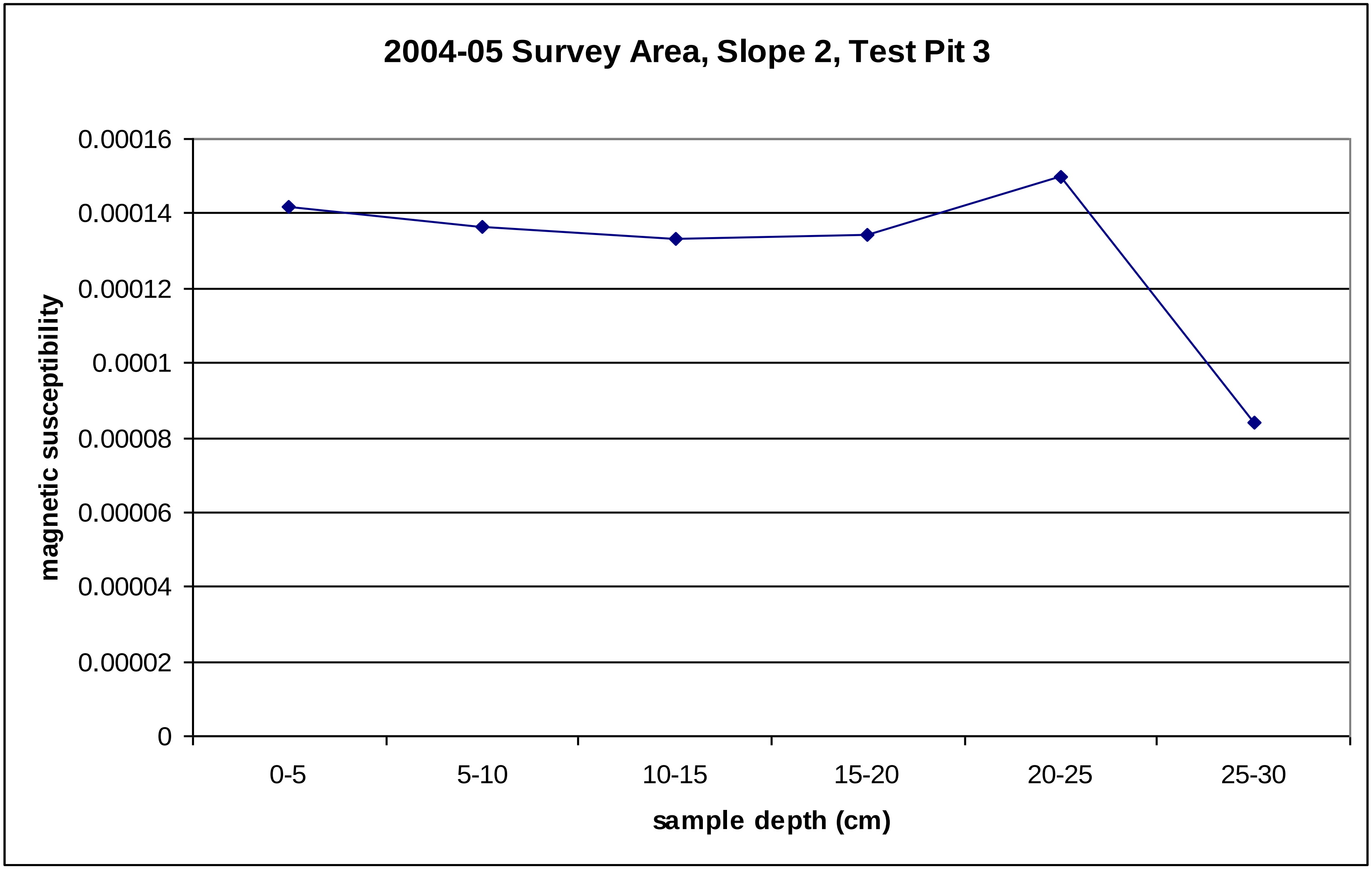

Figure A1 - 28: Magnetic susceptibility by depth, 2004-05 survey area, slope 2, soil test pit 3

2004-05 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 4

Date: July 11, 2005
Location: Foot of slope of hill west of Cachopos
Coordinates: 29S 615781E, 4181922N Slope: 10* Aspect: NE, 45*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 19	ABp	7.5 YR 6/6	moderate, coarse, granular	40/ sa-sr, 2-30mm	sandy clay loam	common, distinct ped face	abrupt, wavy	similar to higher points on slope
19 – 27	Bt	5 YR 5/8	moderate, medium subangular blocky	30/ a-sr, 2-20mm	silty clay loam	few, prominent ped face	gradual, smooth	Fewer large clasts present than in overlying stratum.
27 – 50	Bt2	5 YR 5/6	moderate, medium subangular blocky	35/ a-sr, 2-30mm	silty clay loam	common, distinct to prominent ped face	abrupt, smooth	Lower boundary indicates relatively recent deposition. Depth of stratum falls to the north, parallel with ground surface.
50 – 62	Bt3	7.5 YR 7/3	moderate, fine subangular blocky	40/ a-sr, 2-30mm	silty clay loam	common, distinct ped face	abrupt, smooth	Abundant, prominent mottling. Platy clasts are oriented horizontally, probably a former ground surface or effects of water. Gleying and mottling indicate a perched water table. Lower boundary indicates relatively recent deposition.
62 – 93	ABb	5 YR 6/4	strong, coarse angular blocky	5/ a, 2mm	silty clay	many, prominent ped face	gradual, smooth	prominent gleying and mottling
93 – 115	2Bt	10 YR 7/6	strong, medium angular blocky	2/ sa, 2mm	silty clay	many, distinct ped face	not observed	No lower boundary encountered. Prominent gleying and mottling, more black and less red than overlying, indicates reducing environment.

Notes: Area has been cultivated recently (no esteva).

Interpretation: The ABp horizon is similar to the plow zone in test pit 3, reflecting recent deposition. The clay film morphology probably is the result of well developed, clay rich soils being redeposited from the upper portions of the slope. The physical characteristics of the two subjacent horizons, Bt and Bt2, are similar to each other with the exception of an increase in clay films with depth. The lower boundary of the Bt2 horizon suggests recent deposition; the two strata likely were deposited when recent plowing mobilized soils on the adjacent hillslope. They both exhibit moderate soil formation, grading towards strong soil formation in the lower of the two, but the pedogenic characteristics were likely inherited as there is no major difference in texture that could account for the preservation of the lower boundary for any significant period of time. The magnetic susceptibility data are consistent with at least the upper 50 cm of deposits having been emplaced by multiple episodes of deposition separated by relatively short intervals of time. Mottling in the subjacent Bt3 horizon indicates frequent saturation with groundwater, explaining the falloff to nearly zero in magnetic susceptibility. Other characteristics, particularly the color, structure and abrupt lower boundary, suggest that this horizon also originated on the nearby slopes, was deposited recently, and was exposed at the surface for a relatively short period of time. Although original horizonation has apparently been obliterated in the underlying ABb horizon, the color, structure, and clay film

morphology indicate a period of pedogenesis on the order of multiple millennia. The relative lack of gravels also indicates that this stratum was in place during a period of landscape stability; this was the ground surface at the base of the slope prior to recent mobilization of surface sediments by plowing. The 2Bt horizon at the base of the exposure clearly has a similar origin and history, although the expression of time dependent pedogenic characteristics is slightly weaker, presumably due to the depth of burial. In sum, the strata record an extended period of landscape stability in the past followed by rapid, significant recent movement of sediments to the base of the slope. There is no preserved evidence for a previous cycle of erosion and deposition.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

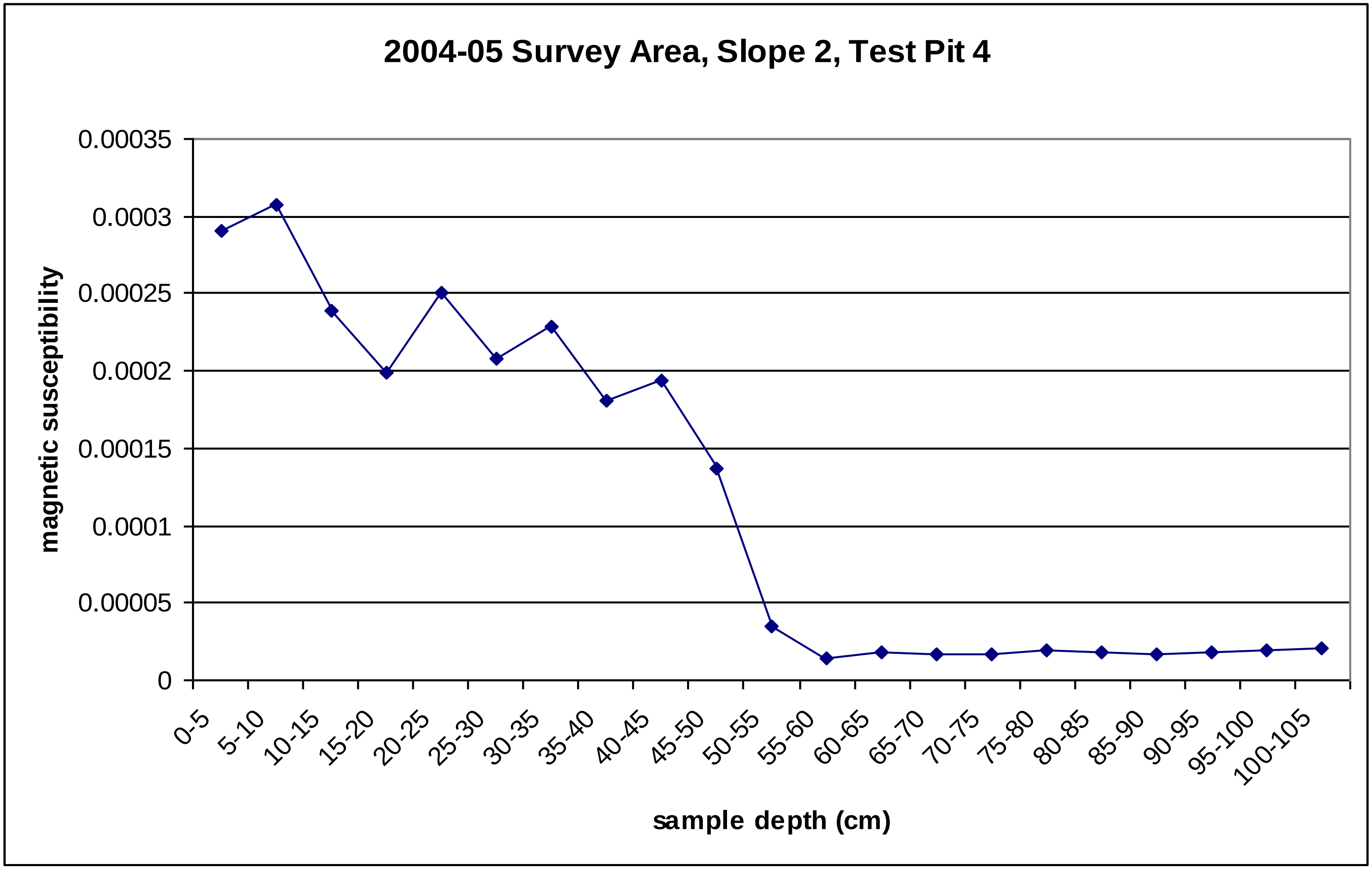

Figure A1 - 29: Magnetic susceptibility by depth, 2004-05 survey area, slope 2, soil test pit 4

2004-05 Survey Area Hillslope Soils: Slope 2, Soil Test Pit 5

Date: July 11, 2005
Location: Toe of slope, hill west of Cachopos
Coordinates: 29S 0615787E, 4181927N Slope: 4* Aspect: ESE, 120*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 17	ABp	7.5 YR 6/6	moderate, coarse granular	30/ sa-sr, 2-15mm	silty loam	few, distinct ped face	abrupt, wavy	Sediment appears slightly darkened by organic material.
17 – 26	Bt	7.5 YR 6/6	moderate, medium subangular blocky	30/ sa-sr, 2-20mm	clay loam	few, distinct ped face	gradual, smooth	Weak soil development similar to overlying, recent deposition.
26 – 58	Bt2	7.5 YR 6/4	moderate, medium subangular blocky	30-40/ sa-sr, 2-10mm	clay loam	few, distinct ped face	clear, smooth	Charcoal collected at 46 cm. Lower boundary slopes downward towards channel, parallel to ground surface.
58 – 87	Btb	10 YR 7/6	moderate to strong, medium subangular blocky	25/ a-sr, 2-10mm	silty clay loam	common, distinct ped face	abrupt, irregular (bedrock)	Some mottling is present. Stratum appears to be bedrock weathering in place. Overlying strata appear recent.

Notes: Located across a small incised channel from the hill on which soils were described. Area has been cultivated recently (no esteva).

Interpretation: The pedostratigraphy is simpler but generally similar to that in test pit 4, reflecting recent deposition over much older deposits. The physical characteristics of the ABp horizon are almost identical to those in test pits 4 and 3, reflecting recent deposition and some inherited characteristics. The clay film morphology of the subjacent Bt and Bt2 horizons is less strongly developed than in the analogous horizons at test pit 4, probably reflecting the presence of less water at this test pit because of its location on the other side of a small incised channel from the hillslope; presumably the incised channel captures the majority of slope runoff. (This test pit is located below a shorter slope segment, which would generate less runoff.) As in test pit 4 the Bt and Bt2 horizons are similar to each other and the clear lower boundary suggests recent deposition. The magnetic susceptibility data are consistent with at least two recent episodes of deposition separated by relatively short intervals of time. An ABb horizon analogous to that in test pit 4 is not preserved in this location, but the Btb stratum is almost identical to the C>2Bt horizon in test pit 4 with the exception of a higher gravel content. This is consistent with the ABb horizon having been removed by erosion prior to deposition of the overlying sediments. The stratum at the base appears to consist of decomposing bedrock, and pedogenic characteristics suggest a period of stability and soil formation on the order of multiple millennia. As in the other test pits on this slope, there is no preserved evidence of a previous episode of hillslope erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

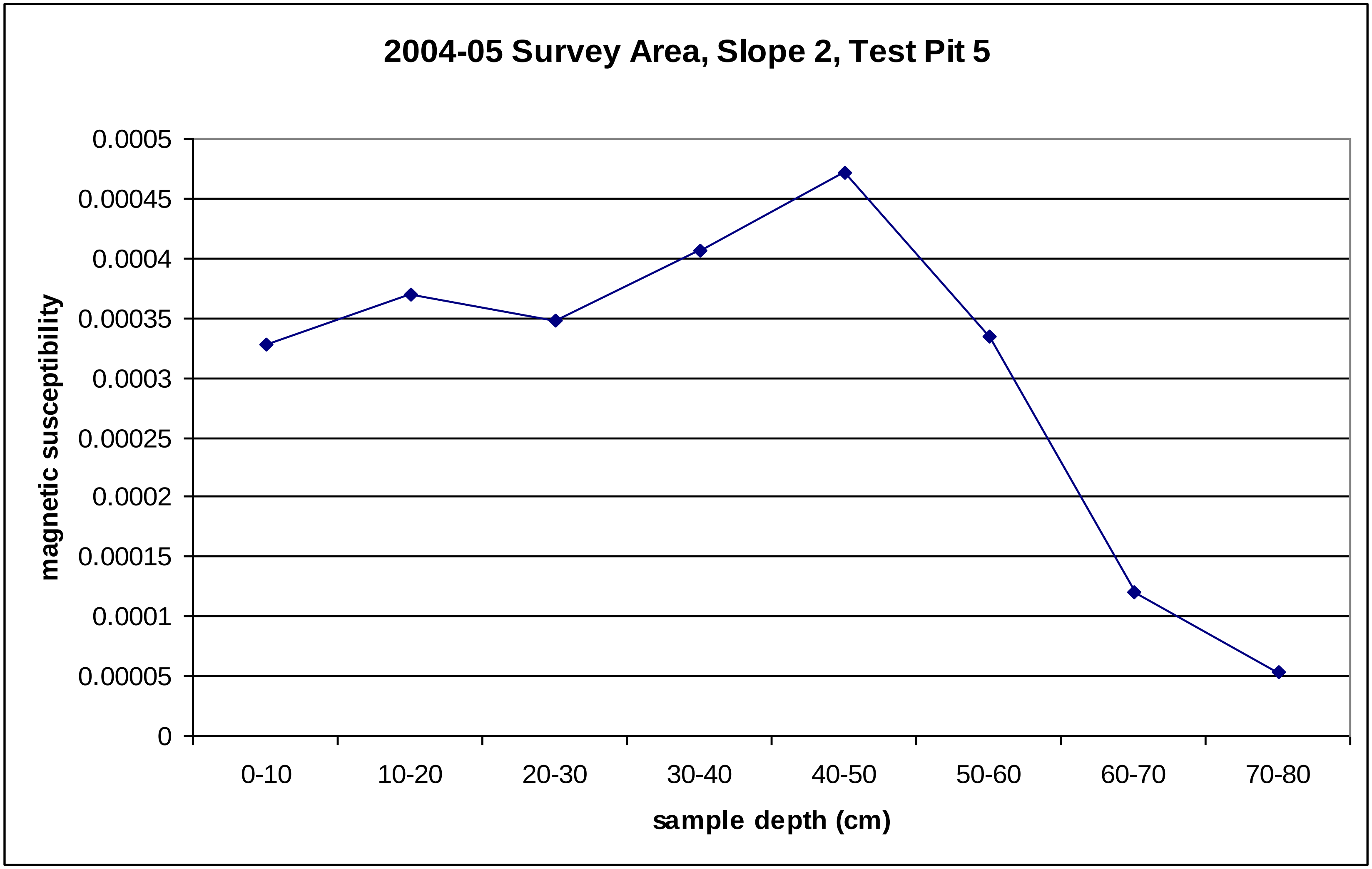

Figure A1 - 30: Magnetic susceptibility by depth, 2004-05 survey area, slope 2, soil test pit 5

2004-05 Survey Area Hillslope Soils: Slope3, Soil Test Pit 1

Date: June 13, 2007
Location: Summit of hill north of Corte do Gafo Baixo
Coordinates: 29S 615769E, 4176696N   Slope: flat   Aspect: Hill slopes south

Depth (cm)	**Soil Horizon**	**Munsell Color***	**Structure ** **	**% Gravel (est.)/ rounding, size**	**Texture Class**	**Clay Films*** **	**Lower Boundary**	**Comments/ Notes**
0 – 9	ABp	10 YR 6/4	moderate medium – coarse granular	30/ a – sa, 2 – 26mm	loam	common, distinct ped face	abrupt, irregular	Very little organic material at the surface, abundant gravels. Gravels and clay films suggest this is an exhumed B horizon. Lower boundary follows bedrock. Sand fraction is crushed bedrock.
9 + (base 13)	Bt/ R	10 YR 5/4	moderate, medium, subangular blocky	20/ a, 2 – 10mm	clay loam	common, prominent ped face		Described sediments in interstices in bedrock. Shape of peds affected by bedrock. Much less sand-sized fraction than overlying.

Notes: The area has not been plowed for several years. Esteva stands ~1.5 m tall.

Interpretation: The sediments exposed in this location reflect significant recent erosion. The abundance of gravels at the surface and in the plow zone implies a lag deposit, and clay film morphology shows that the surface deposit incorporates the remnants of a well-developed argillic B horizon. The sediments continue into the interstices in bedrock without changing radically. The clay film morphology and structure indicate a well-developed soil, implying landscape stability in the past for a period on the order of millennia. The upper horizons of that soil largely have been removed by recent erosion and people currently cultivate sediments created by mechanically mixing the B horizon with crushed bedrock. There is no evidence for an episode of significant erosion in the past.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 2

Date: June 13, 2007
Location: Shoulder of hill north of Corte do Gafo Baixo
Coordinates: 29S 615772E, 4176677N Slope: 8* Aspect: S, 193*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 7	ABp	10 YR 6/4	moderate, medium – coarse subangular blocky	30/ a – sa, 2 – 12mm	sandy loam	common, distinct ped face	abrupt, irregular	Very little organic material at the surface, abundant gravels. Lower boundary follows bedrock. Very gritty, lots of sand-sized particles, probably crushed bedrock. Clay films suggest B horizon.
7 + (base 9)	Bt/ R	7.5 YR 6/6	moderate, medium subangular blocky	20/ a, 2 – 10mm	clay loam	common, distinct ped face		Sediments in interstices in bedrock. Color suggests strong weathering – possibly near the surface for a very long period of time.

Notes: The area has not been plowed for several years. Esteva stands ~1.5 m tall.

Interpretation: The pedostratigraphy exposed in this pit is essentially the same as that in STP 1. The decreased thickness of the surface deposit and the sandier texture suggest stronger erosion here, very likely due to the slope angle and geomorphic position. Similarly, the slightly weaker expression of clay films in the subjacent Bt horizon very likely reflects decreased water inputs due to runoff. Interestingly, the color of that horizon and the appearance of the bedrock suggest very strong weathering; soils in this geomorphic position were probably never as deep as on other parts of the slope, exposing the bedrock to greater weathering over very long periods of time.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 3

Date: June 13, 2007
Location: Backslope, hill north of Corte do Gafo Baixo
Coordinates: 29S 615770E, 4176657N Slope: 12* Aspect: S, 190*

Depth (cm)	**Soil Horizon**	**Munsell Color***	**Structure ** **	**% Gravel (est.)/ rounding, size**	**Texture Class**	**Clay Films*** **	**Lower Boundary**	**Comments/ Notes**
0 – 8	ABp	10 YR 6/4	moderate, medium – coarse granular	40/ a – sa, 2 – 22mm	sandy loam	common, distinct ped face	abrupt, irregular	Very little organic material and abundant gravels at the surface. Lower boundary follows bedrock.
8 + (base 11)	Bt/ R	10 YR 6/4	moderate, fine subangular blocky	40/ a, 2 – 20mm	sandy loam	many, distinct ped face		Sediments in interstices in bedrock. Shape of peds is determined by bedrock. Slightly redder than overlying.

Notes: No esteva, but the area has not been plowed recently.

Interpretation: As in the pits higher on the slope, the sediments exposed here indicate significant recent erosion. The clay films in the surface deposit show that it incorporates a large quantity of a well-developed argillic horizon. The sediments in the interstices in the bedrock are similar in terms of color, texture, and gravel content and exhibit stronger clay film morphology; the similarities imply that the surface deposit retains almost none of the original A horizon. The sandy texture of deposits is probably related to geomorphic position on the backslope, the slope segment most prone to erosion due to slope angle and movement of water across the surface. The very strong expression of clay films in the argillic horizon shows landscape stability on the order of millennia prior to recent, severe erosion. There is no preserved evidence for a previous episode of significant erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 4

Date: June 25, 2007
Location: Foot of slope, hill north of Corte do Gafo Baixo
Coordinates: 29S 615772E, 4176623N Slope: 9* Aspect: SSW, 204*

Depth (cm)	**Soil Horizon**	**Munsell Color***	**Structure ****	**% Gravel (est.)/ rounding, size**	**Texture Class**	**Clay Films*****	**Lower Boundary**	**Comments/ Notes**
0 – 11	ABp	10 YR 6/4	moderate, coarse granular	40/ sa – sr, 2 – 25mm	loam	common, distinct ped face	abrupt, irregular	Very thin layer of organic material at the surface (<5 mm). Lower boundary follows bedrock. Gravels are local bedrock, detached by plowing.
11 + (base 15)	Bt/ R	10 YR 7/4	weak, coarse granular	60/ a, 2 – 30mm	clay loam	many, distinct ped face		Sediments in interstices in bedrock. Shape of peds is determined by bedrock.

Notes: No esteva, but the area has not been plowed recently.

Interpretation: The pedostratigraphy here is essentially the same as higher on the slope. Clay films in the plow zone show that the surface deposit is comprised primarily of an exhumed argillic B horizon. The sediments continue basically unaltered into the interstices in the bedrock, where the strong clay film morphology suggests that the surface was probably stable for millennia prior to the recent erosion. The finer texture of the sediments relative to pits higher on the slope reflects geomorphic position, as fine particles removed from higher positions have been deposited at the base of the slope.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 3, Soil Test Pit 5

Date: June 25, 2007
Location: Toe of slope, hill north of Corte do Gafo Baixo
Coordinates: 29S 615765E, 4176607N Slope: 3* Aspect: SSW, 213*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 15	ABp	10 YR 6/4	moderate, coarse granular	40/ a – sr, 2 – 35mm	loam	common, distinct ped face	abrupt, irregular	Texture may grade to sandy loam. Very thin layer of organic material at the surface (< 5mm). Lower boundary follows bedrock.
15 + (base 25)	Bt/ R	2.5 Y 7/4	moderate, medium, granular	30/ a, 2 – 30mm	clay loam	many, distinct ped face		Sediments in interstices in bedrock. Gravel % varied dramatically with location, 30% is at very low end.

Notes: No esteva, but the area has not been plowed recently.

Interpretation: The sediments exposed in this pit again are similar to those exposed higher on the slope, with surface deposits composed primarily of an exhumed argillic B horizon and sediments continuing essentially unchanged into the interstices in bedrock. The slightly different color of the Bt horizon here probably reflects increased water inputs due to position at the base of the slope. The lack of deeper deposits at the base of the slope is probably because a gentle slope continues to the ephemeral stream. Presumably, the fluvial system has carried away sediments that were eroded from higher on the slope. The lack of appreciable changes in magnetic susceptibility with depth corroborates the impression that these sediments all are of a similar age and that they have only recently been exhumed; there is no noticeable increase in the signal at the surface that would indicate that any large quantity of an A horizon is preserved or that significant pedogenesis has occurred since the removal of the A horizon by erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

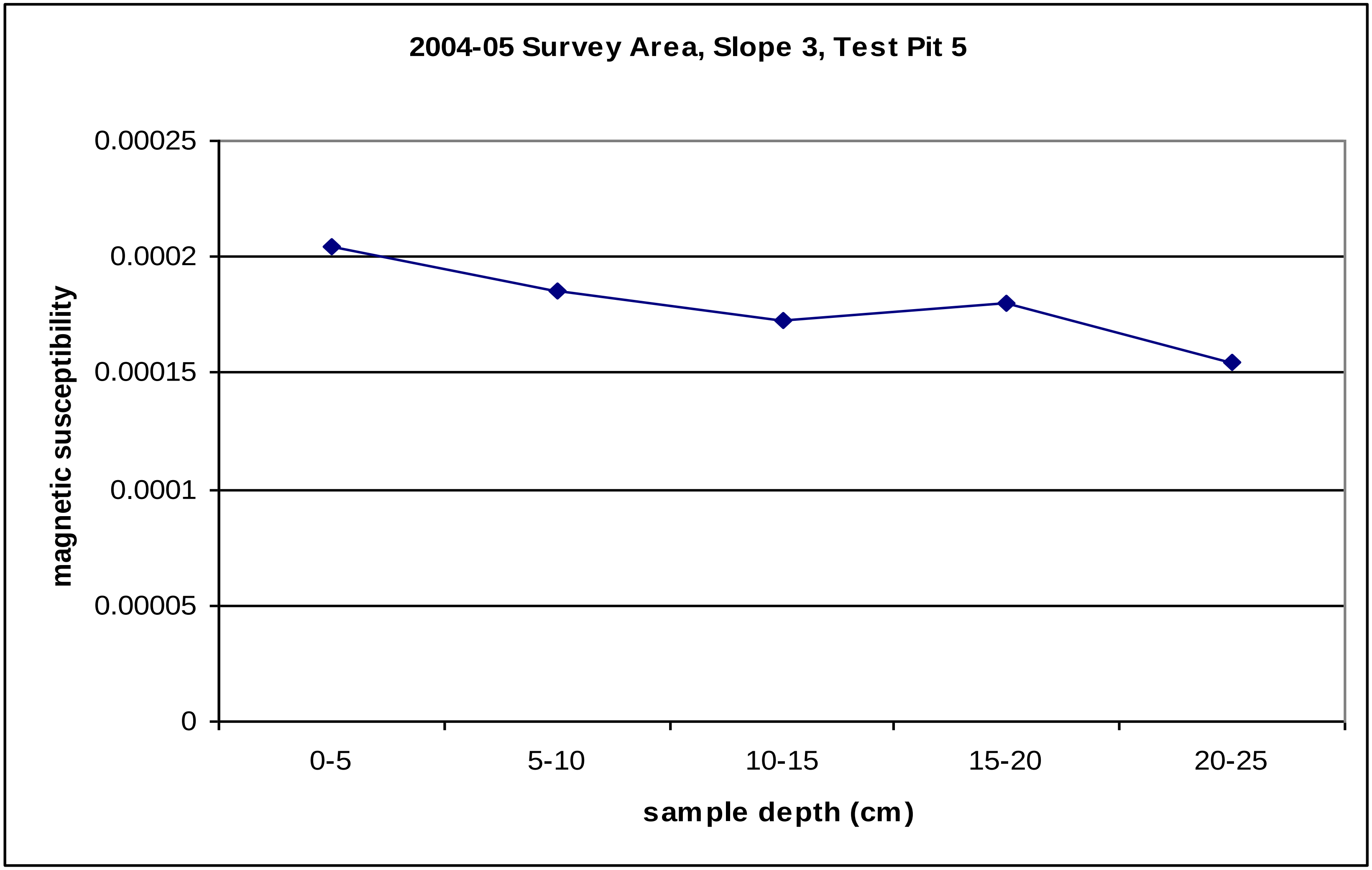

Figure A1 - 31: Magnetic susceptibility by depth, 2004-05 survey area, slope 3, soil test pit 5

2004-05 Survey Area Hillslope Soils: Slope 4, Soil Test Pit 1

Date: June 11, 2007
Location: Summit of hill north of Corte do Gafo Baixo
Coordinates: 29S 615773E, 4176387N Slope: flat Aspect: hill faces north

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 9	ABp	10 YR 5/3 – 6/4	moderate, medium granular	40/ a – sa, 2 – 14mm	sandy loam	many, distinct ped face	abrupt, irregular	Artifacts (rooftile fragments) are present in the upper 2-3 cm. Thin layer of organic material, abundant rootlets. Lower boundary is bedrock. Clay films suggest exposed B horizon. Sand fraction and gravels are crushed bedrock.
9 + (base 12)	Bt/ R	10 YR 6/4	weak, medium granular	40/ a, 2 – 12mm	clay loam	many, distinct ped face		Sediments in interstices in bedrock. Esteva roots are present in the cracks. Not radically different from overlying – lots of Bt incorporated into ABp.

Notes: Esteva ~1.5 m tall, this area has not been plowed for several years.

Interpretation: The soils exposed in this profile reflect severe recent erosion. Clay film morphology suggests that the plowed sediments consist predominantly of an exhumed B horizon. They are similar to the sediments contained in the interstices in the bedrock, with an increase in clay film morphology and finer texture of the latter suggesting a well-developed B horizon that formed on a relatively stable landscape over the course of multiple millennia. The presence of artifacts only in the upper few cm of sediments suggests that the bedrock was not exhumed by severe erosion in the past. There is no preserved evidence of a previous cycle of severe erosion.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 4, Soil Test Pit 2

Date: June 12, 2007

Location: Shoulder of hill north of Corte do Gafo Baixo

Coordinates: 29S 615769E, 4176391N Slope: 10* Aspect: N, 348*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	10 YR 5/3 – 6/4	moderate, medium granular	40/ a – sa, 2 – 12mm	loam	common, distinct ped face	abrupt, irregular	Lower boundary follows uneven bedrock. Thin layer (<1 cm) of organic material and moss at the surface. Rooftile fragment at 5 cm. Clay films suggest plowing B horizon. Sand fraction is crushed bedrock.
10 + (base 18)	Bt/ R	10 YR 6/4	weak, fine granular	60/ a, 2 – 14mm	clay loam	common, distinct ped face		Sediments in interstices in bedrock. Similar to overlying – lots of Bt incorporated into ABp.

Notes: Esteva ~1 m tall, this area has not been plowed for several years.

Interpretation: The sediments exposed in this test pit are similar to those exposed in STP 1. The plowed deposits appear to consist primarily of a B horizon exhumed by recent erosion. The basal deposit exhibits strong pedogenic alteration, consistent with millennia of landscape stability prior to the recent erosion. Artifacts are present in the plow zone, but not in contact with or in the interstices in the bedrock, suggesting that erosion in the past did not exhume the bedrock. There is no preserved evidence of a previous cycle of severe erosion.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 4, Soil Test Pit 3

Date: June 12, 2007

Location: Backslope of hill north of Corte do Gafo Baixo

Coordinates: 29S 615766E, 4176405N Slope: 17* Aspect: N, 350*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 12	ABp	10 YR 6/4	moderate, medium granular	30/ sa, 2 – 45mm	sandy loam	common, distinct ped face	abrupt, irregular	Lower boundary follows fractured bedrock. Thin layer (<1 cm) of organic material and moss at the surface. Clay films suggest plowing B horizon. Sand fraction is crushed bedrock.
12 + (base 27)	Bt/ R	10 YR 6/4	moderate, medium granular and platy	50/ a, 2 – 35mm	clay loam	common, distinct ped face		Sediments in interstices in bedrock. Platy structure is due to sediments being between sheets of bedrock. Color is redder than overlying due to localized outcrop of red schist bedrock, red when wet. Sand fraction is crushed bedrock.

Notes: No esteva is present in the immediate vicinity. Grasses and other small shrubs are common. Area does not appear to have been plowed recently.

Interpretation: This profile is similar to that exposed in STPs 1 and 2. The plowed deposits appear to consist primarily of a B horizon exhumed by recent erosion. The basal deposit exhibits strong pedogenic alteration, consistent with millennia of landscape stability prior to the recent erosion. There is no preserved evidence of a previous cycle of severe erosion.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 4, Soil Test Pit 4

Date: June 12, 2007
Location: Foot of slope of hill north of Corte do Gafo Baixo
Coordinates: 29S 615751E, 4176425N Slope: 12* Aspect: N, 18*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 21	ABp	10 YR 6/4	moderate, coarse granular	30/ sa - sr, 2 – 35mm	loam	common, distinct ped face	abrupt, irregular	Depth suggests cumulic horizon. Lower boundary follows fractured bedrock. Thin layer (<1 cm) of organic material and moss at the surface. Sand fraction is crushed bedrock; less “sand” than higher on the slope. Rooftile fragment at 8 cm.
21 + (base 30)	Bt/ R	10 YR 6/4	moderate, fine subangular blocky	30/ a - sa, 2 – 25mm	clay loam	common, distinct ped face		Sediments in interstices in bedrock. Structure is more strongly expressed than higher on the slope, probably due to higher clay content. Still slightly moist from winter precipitation. Bedrock not plowed, thicker zone of weathering, less rocky.

Notes: Grassy area with esteva nearby. Area does not appear to have been plowed recently.

Interpretation: This profile is broadly similar to those exposed higher on the slope. The surface horizon is significantly thicker than higher on the slope, but has the same color and clay film morphology and similar texture and structure, suggesting a similar age and origin. It is composed predominantly of an exhumed B horizon and the low magnetic susceptibility readings show that it has not been exposed at the surface for a long period of time. The thickness suggests either that erosion has not been as severe in this geomorphic position or that this is a cumulic horizon, incorporating materials that originated higher on the slope. The somewhat lower magnetic susceptibility in the uppermost 15 cm provides some evidence that this is a cumulic horizon that incorporates materials from higher on the slope that were more deeply buried in the past. In addition, similarities to plowed deposits higher on the slope show that the A horizon has been removed here, as it has higher on the slope, also favoring the second interpretation. The depth of the plow zone is probably not beyond the maximum depth that can be turned by the plowing/ disking equipment commonly used in the area. If it were, the fact that the lower boundary remains abrupt suggests that all of the plowing reflected in these preserved sediments has occurred recently, within the past few decades. The relatively flat magnetic susceptibility curve is consistent with the A horizon having been completely and recently removed from all portions of the slope. As seen higher on the slope, artifacts are present in the plow zone but not below or in contact with bedrock, suggesting that the bedrock was not exhumed during the occupation of the site at the summit of the slope. The sediments in the interstices in the bedrock also reflect strong pedogenic characteristics, implying a long period of landscape stability on the order of millennia.

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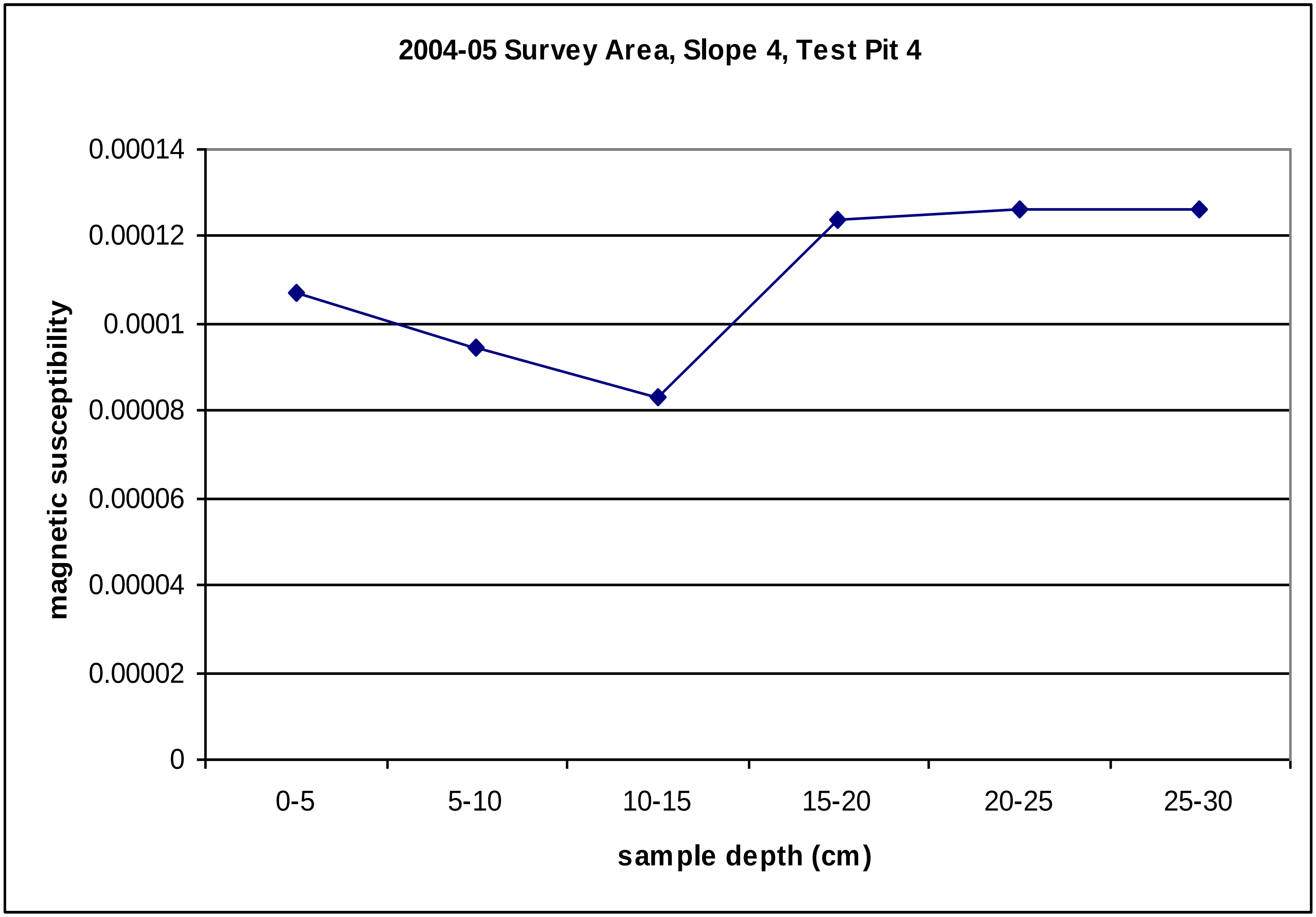

Figure A1 - 32: Magnetic susceptibility by depth, 2004-05 survey area, slope 4, soil test pit 4

2004-05 Survey Area Hillslope Soils: Slope 4, Soil Test Pit 5

Date: June 13, 2007
Location: Toe of slope of hill north of Corte do Gafo Baixo
Coordinates: 29S 615761E, 4176442N Slope: 4* Aspect: NE, 42*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	10 YR 6/4	moderate, medium, subangular blocky	30/ a - sr, 2 – 25mm	loam	common, distinct ped face	clear, wavy	Larger clasts present, to >20 cm. Rooftile fragments at 8 and 9 cm. Thin layer (<1 cm) of moss and organic material at the surface. Slight concentration of clasts at the lower boundary. Clasts angular, randomly oriented. Much less "sand" (crushed bedrock) than higher on the slope.
14 + (base 80)	Btg	10 YR 6/6	strong, coarse subangular blocky	30/ a - sr, 2 – 30mm	clay loam	many, prominent ped face		Red mottling and slight gleying, mottles 20 – 30% in upper portion, increasing gradually to >60% below 50 cm. Still slightly moist. No artifacts despite careful inspection. Stopped at 80 cm without encountering bedrock. Clasts angular and randomly oriented – initial deposition by mass movement? Small clasts more rounded, possibly indicating weathering. Much less "sand" than higher on the slope.

Notes: Base of slope, but continues to slope gently towards ribeira ~100 m north. Grass and annuals present, area does not appear to have been plowed for several years.

Interpretation: The sediments exposed in this profile are similar to those present higher on the slope. This test pit is, however, particularly revealing in that evidence for a past cycle of erosion is more likely to be preserved here than in any other geomorphic position; the stratigraphy reflects only recent erosion. The plowed sediments are essentially the same as higher on the slope, consisting primarily of an exhumed B horizon. The slightly stronger expression of structure is probably due to increased water inputs because of runoff from higher on the slope. Artifacts again are present in the plow zone, showing that they can be transported this distance from the site at the summit of the hill. Importantly, they are not present in the subjacent Btg horizon, suggesting that it has remained buried during and since the Islamic period. The low magnetic susceptibility at the surface and the increase below 10 cm is consistent with recent deposition in this location of B horizon sediments eroded from higher on the slope. The structure and clay film morphology of the Btg horizon are as strongly expressed as any encountered in this study, and the magnetic susceptibility is somewhat higher to a depth of 30 cm, suggesting a very long period of landscape stability and pedogenesis prior to the recent erosion. Mottling indicates seasonal saturation with groundwater. The random orientation and lack of size sorting of clasts suggests that initial deposition may have been by a mass movement. Given the degree of pedogenic alteration, the initial deposition may have been caused by significant climate changes during the Pleistocene – Holocene transition.

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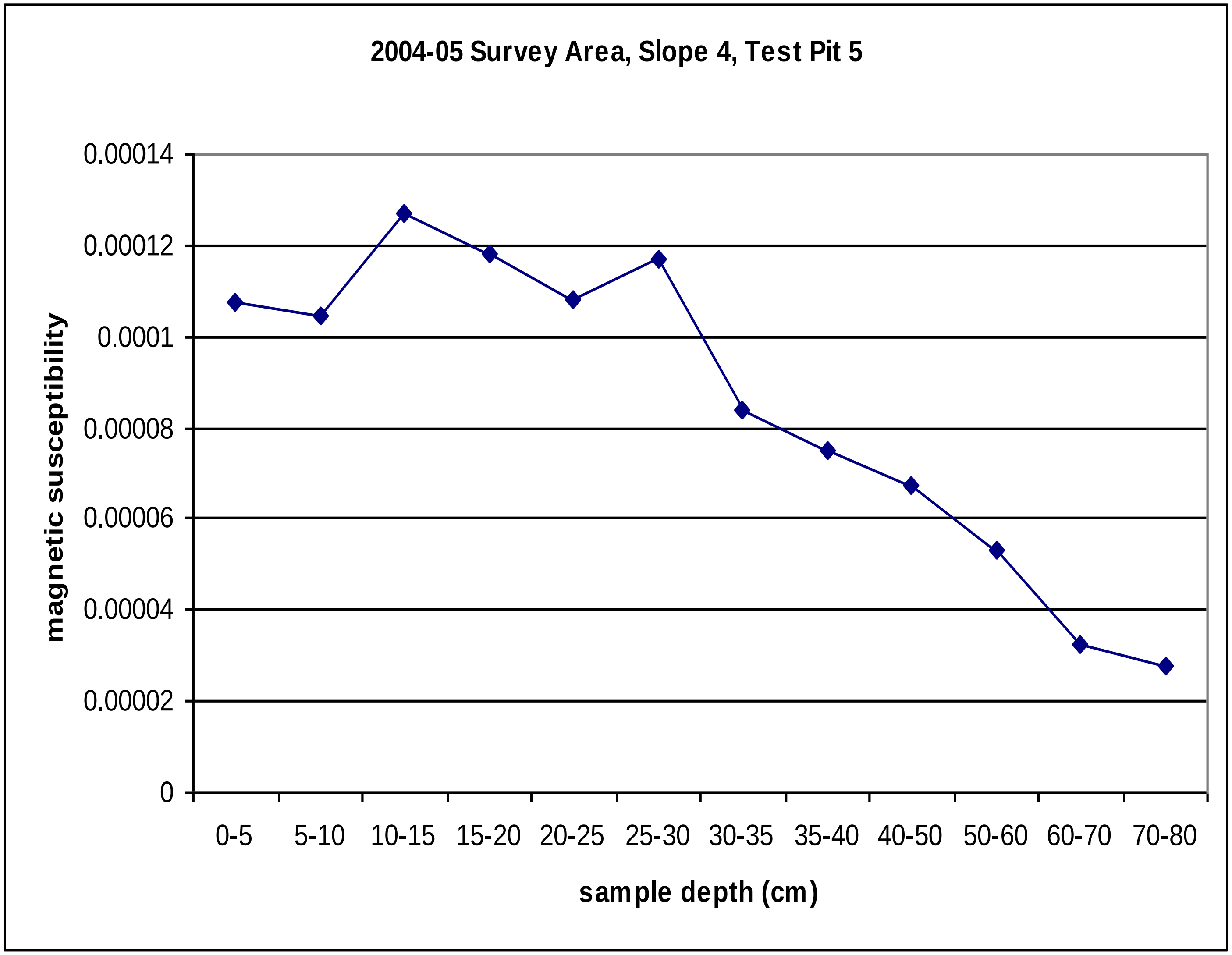

Figure A1 - 33: Magnetic susceptibility by depth, 2004-05 survey area, slope 4, soil test pit 5

2004-05 Survey Area Hillslope Soils: Slope 5, Soil Test Pit 1

Date: June 14, 2007
Location: Summit of hill south of Corte do Gafo Cima
Coordinates: 29S 614662E, 4174296N Slope: flat Aspect: hill faces west

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 9	ABp	7.5 YR 6/4	moderate, coarse – very coarse granular	40/ a - sa, 2 – 35mm	sandy loam	common, distinct ped face	abrupt, irregular	Lower boundary follows bedrock. Very little organic material at the surface, but abundant rootlets. “Sand” fraction is crushed bedrock.
9 + (base 12)	Bt/ R	7.5 YR 6/6	moderate, medium granular	20/ a, 2 – 20mm	clay loam	few to common (~25%), distinct ped face		Described material in interstices in bedrock. Reddish color is probably due to some red schist in bedrock.

Notes: Grassy slope, not plowed this year.

Interpretation: The sediments exposed in this test pit reflect significant recent erosion. The presence of common, distinct ped face clay films in the surface horizon suggest that it incorporates large quantities of an exhumed B horizon. The abundance of gravels in the plow zone also implies erosion and a lag deposit. The sediments continue into the interstices in bedrock with few changes, although the differences in color and texture probably are due to remnants of an A horizon. The clay film morphology is slightly weaker in the subjacent deposit, just below the threshold for common, distinct ped face. The lack of stronger clay film morphology may be due in part to the abrupt boundary and texture differences between the plowed sediments and the subjacent deposit; water probably preferentially moves downslope along the textural boundary as opposed to downwards through the solum. If a similar textural boundary existed prior to plowing, this could have inhibited pedogenic alteration of the materials below the boundary. The lack of stronger pedogenic alteration of the basal deposit is consistent with deep burial prior to the recent erosion or with sediments having been removed from this position by erosion in the past. The stronger expression of clay films in the surface deposit, which has a coarser texture, supports the hypothesis of deep burial. There is no convincing evidence of erosion in the past, prior to recent plowing of the hillslopes

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** “co-br” designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 5, Soil Test Pit 2

Date: June 14, 2007
Location: Shoulder of hill south of Corte do Gafo Cima
Coordinates: 29S 614650E, 4174300N Slope: 9* Aspect: W, 284*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 8	ABp	7.5 YR 6/4	moderate, coarse granular	20/ a - sa, 2 – 12mm	loam	few, distinct ped face	abrupt, irregular	Lower boundary follows bedrock. Very little organic material at the surface, but abundant rootlets.
8 + (base 15)	Bt/ R	7.5 YR 6/6	moderate, medium granular	15/ a, 2 – 8mm	clay loam	common, distinct ped face		Described material in interstices in bedrock. Shape of peds is affected by bedrock.

Notes: Grassy slope, not plowed this year.

Interpretation: The soils exposed in this pit also reflect significant recent erosion. Clay films in the plowed sediments and similarities to subjacent deposits show that they incorporate a significant quantity of a relatively well developed B horizon. The differences in color and texture suggest that remnants of an A horizon are incorporated into the plow zone. The finer texture here than in STP 1 may imply less erosion in this location a few meters below the exposed, rounded summit of the hill. The deposits in the interstices in the bedrock exhibit moderate clay film morphology, consistent with at least a millennium of landscape stability and soil formation prior to the recent erosion. That the clay films aren't more strongly developed could be due to deeper burial in the past, but it is also consistent with sediments having been stripped from this location at some time in the past. By itself, this test pit does not provide sufficient evidence to differentiate between the two hypotheses.

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2004-05 Survey Area Hillslope Soils: Slope 5, Soil Test Pit 3

Date: June 14, 2007
Location: Backslope of hill south of Corte do Gafo Cima
Coordinates: 29S 614622E, 4174306N Slope: 17* Aspect: W, 287*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 10	ABp	7.5 YR 6/4	moderate, coarse granular	30/ a - sa, 2 – 30mm	loam	few, distinct ped face	abrupt, irregular	Lower boundary follows bedrock. Very little organic material at the surface. Darker brown organic-rich layer at 4cm – former surface, buried by erosion from last plowing?
10 + (base 15)	Bt/ R	7.5 YR 6/6	moderate, medium - coarse granular	40/ a, 2 – 40mm	clay loam	common, distinct ped face		Described material in interstices in bedrock.
Notes: Grassy slope, not plowed this year.								
Interpretation: Aside from an increase in gravel and a dark, organic-rich layer at a depth of 4 cm, the soils exposed in this pit are identical to those in STP 2 and can be interpreted in the same way. The increase in gravel is likely due to geomorphic position, as the shoulder of the slope (where STP 2 is located) has a much smaller area above it from which gravels can move onto it. That the sediments and gravels are actively moving down the slope is supported by the presence of the darker layer. It most likely represents a former surface that was buried by erosion that occurred after the last plowing of the slope.								

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2004-05 Survey Area Hillslope Soils: Slope 5, Soil Test Pit 4

Date: June 14, 2007
Location: Foot of slope of hill south of Corte do Gafo Cima
Coordinates: 29S 614589E, 4174310N   Slope: 11*   Aspect: WNW, 292*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 18	ABp	7.5 YR 6/4	moderate, coarse granular	40/ a - sr, 2 – 30mm	loam	common, distinct ped face	abrupt, smooth	Lower boundary is depth of plowing. Plow can easily churn decomposing bedrock. Color is browner than higher on slope – remnants of A horizon? Depth of unit suggests cumulic horizon. Larger clasts are subrounded – transport?
18 – 31	R>Bt	7.5 YR 6/8	moderate - strong, fine angular blocky	30/ a - r, 2 – 25mm	clay loam	many prominent ped face	clear, irregular	This unit is decomposed bedrock. Thin laminae of more resistant material are present, continuing down into solid bedrock at the same angle. Small clasts are rounded.
31 +	R							Not excavated. Material in interstices resembles overlying.

Notes: Grassy slope, not plowed this year.

Interpretation: The sediments exposed in this test pit reflect significant recent erosion on the hillslope. The plowed deposits are similar to those higher on the slope, with stronger clay film morphology probably related to increased inputs of water and fine sediments in this location at the base of the slope. The clay films show that the plow zone is composed largely of an exhumed B horizon, and the increased susceptibility but relatively flat profile in the uppermost 20 cm are consistent with this interpretation and may also reflect some degree of recent deposition of B horizon materials from higher on the slope. The slightly browner color suggests that the plowed deposits incorporate some remnants of an A horizon, much of which probably originated higher on the slope, and the weak peak in susceptibility at 5 – 10 cm is consistent with this interpretation although not conclusive. The greater depth of the plow zone relative to higher geomorphic positions also indicates accumulation of sediments. It is also due to the presence of a subjacent stratum of deeply weathered and decomposing bedrock that can easily be churned by plowing. The strongly expressed clay films in this Bt horizon indicate a period of landscape stability and pedogenesis on the order of millennia prior to the recent erosion, and the very weak susceptibility signal suggests that these deposits were much more deeply buried in the past. That it is composed of bedrock decomposing *in situ* shows that bedrock has not been exposed by erosion in this location for many millennia. There is no preserved evidence for an episode of erosion prior to recent plowing of the hillslopes in this area.

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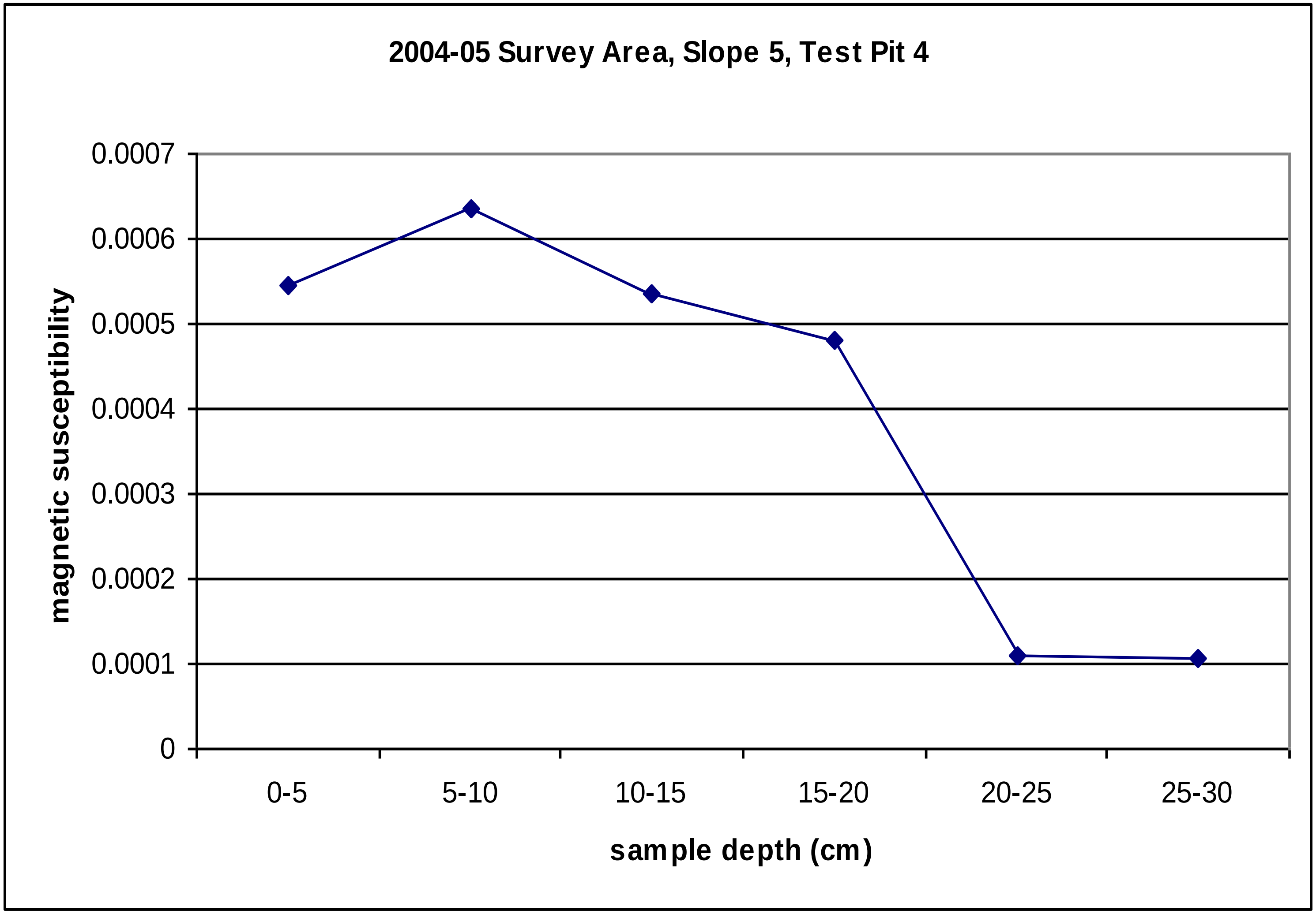

Figure A1 - 34: Magnetic susceptibility by depth, 2004-05 survey area, slope 5, soil test pit 4

2004-05 Survey Area Hillslope Soils: Slope 5, Soil Test Pit 5

Date: June 15, 2007

Location: Toe of slope, hill south of Corte do Gafo Cima

Coordinates: 29S 614565E, 4174319N   Slope: 5*   Aspect: NW, 316*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 12	ABp	10 YR 6/4	moderate, coarse granular	20/ sa - a, 2 – 30mm+	loam	few, distinct ped face	clear, wavy	Lower boundary is visible as a color change and appearance of mottling.
12 – 30	Bt	7.5 YR 5/6	strong, medium – coarse angular blocky	30/ a - sr, 2 – 60mm+	clay loam	many, prominent ped face	gradual, smooth	30 – 50% mottled, mottling increases with depth. Mottles ~5YR 4/4.
30 – 50	C>Bt2	10 YR 7/8	moderate, medium angular blocky	40/ sa – sr, 2 – 20mm	clay loam	many, distinct ped face	abrupt, irregular	Lower boundary defined by the presence of ~intact bedrock. Clasts do not appear to follow the orientation of bedrock; they are randomly oriented – very old mass movement? ~5% small (<1mm) red mottles, more yellow, oxygen reduced environment. Some angular clasts of quartz, schist. Lots of friable, "rusted" rock. Texture may grade to sandy clay.
50 + (base 53)	C/ R							Material described above continues into interstices in bedrock.

Notes: Grassy slope, not plowed this year. Soils washing off slopes did not accumulate along channel; sediments must have been carried away by fluvial system. The sediments are still slightly moist from rain.

Interpretation: This test pit exposes somewhat more complicated stratigraphy than others on the slope. The plowed sediments are slightly yellower than those higher on the slope, probably due to increased water at the base of the slope and the incorporation of a somewhat larger amount of A horizon material or material deposited by the nearby ephemeral stream system. The weaker expression of clay films and presence of less gravel also are consistent with the incorporation of more A horizon or stream-laid materials, and probably reflect these inputs as well as less erosion in this location due to the lower slope angle. The relatively low magnetic susceptibility of the surface deposits suggests either that these sediments were deposited by the stream and were eroded from deeper positions higher in the stream system or that the increased water inputs have diminished the signal. The relative abundance of water in this location is reflected in the clear lower boundary that is less distinct than the analogous abrupt boundary higher on the slope, as well as in the mottling in subjacent deposits. The clay film morphology in the Bt horizon indicates strong pedogenic alteration, implying millennia of soil formation prior to the recent erosion. The gradual lower boundary and relatively smooth drop-off in susceptibility with depth imply that the horizon is genetically related to the subjacent Bt2 horizon. Clay films in the Bt2 horizon are slightly less strongly expressed, most likely because of deeper burial in the past, again corroborated by the smooth diminution of the susceptibility signal. The random orientation and lack of size sorting of clasts suggests that these materials initially were deposited by a mass movement. The degree of soil development in this and the overlying horizons shows that the mass movement occurred millennia ago, perhaps because of climate shifts at the Pleistocene – Holocene boundary. Any differences that may have existed between the Bt2 sediments and materials in the interstices in the bedrock have since been obliterated by soil welding.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

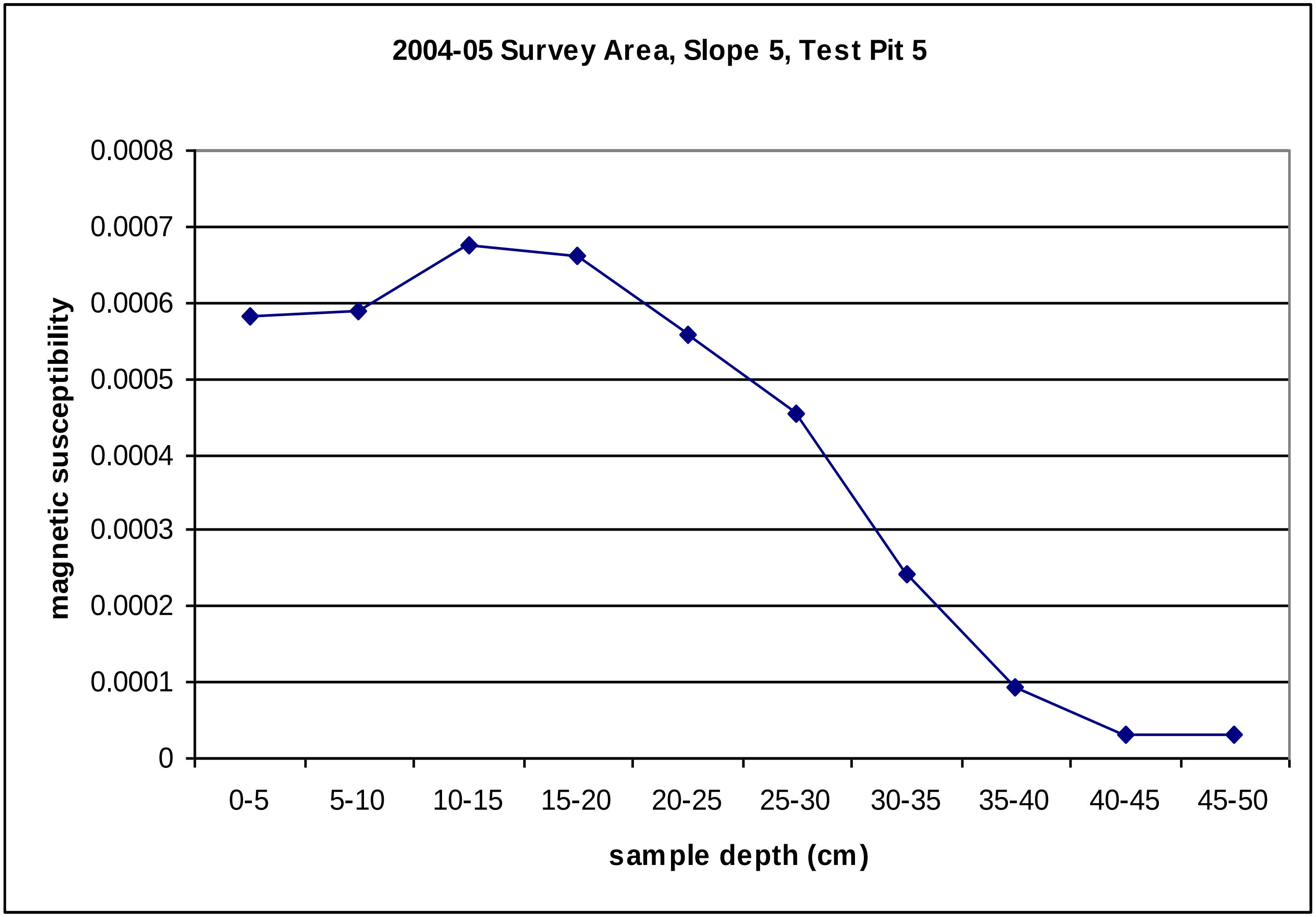

Figure A1 - 35: Magnetic susceptibility by depth, 2004-05 survey area, slope 5, soil test pit 5

2004-05 Survey Area Hillslope Soils: Slope 6, Soil Test Pit 1

Date: June 16, 2007
Location: Summit of hill southwest of Corte do Gafo Cima
Coordinates: 29S 612898E, 4173834N Slope: ~ flat Aspect: slope faces north

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 17	ABp	10 YR 6/4	moderate, medium to coarse granular	30/ sr - sa, 2 – 25mm	sandy loam	few, distinct ped face	abrupt, irregular	Lower boundary follows bedrock. Gravels increase below 12 cm, roots decrease. Thin (<1cm) layer of organics, moss at surface. Larger clasts are present, many at the surface.
17 + (base 22)	Bt/ R	7.5 YR 6/4	moderate, medium to fine granular	50/ sa - sr, 2 – 40mm	loam	common, distinct ped face		Described material in interstices in bedrock. Bedrock is mostly friable, but some more resistant, silicified beds are present – possible tool stone. Bedrock is much more "blocky" here, less tabular. Texture may grade to clay loam.

Notes: Broad, flat summit. Upper few cm of sediments are slightly moist from recent rain.

Interpretation: The soils exposed in this test pit reflect slightly less erosion in the recent past than those on other slopes in the 2004 – 05 survey area, but are otherwise broadly similar. The plowed deposits consist of a mixture of A and exhumed B horizon materials, as demonstrated by the color and clay film morphology. The thickness and weak clay film morphology imply that a relatively large amount of the A horizon was preserved here, perhaps in part due to the fact that this is a broad, flat summit. The subjacent deposits exhibit strong clay films, implying a very long period of pedogenesis prior to recent plowing. There is no evidence here for a past cycle of extreme erosion, and no indication that the bedrock was exposed in this location in the past.

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2004-05 Survey Area Hillslope Soils: Slope 6, Soil Test Pit 2

Date: June 16, 2007

Location: Shoulder of hill southwest of Corte do Gafo Cima

Coordinates: 29S 612904E, 4173834N Slope: 9* Aspect: NNE, 28*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	7.5 YR 6/4	moderate, coarse to v. coarse granular	40/ a - sa, 2 – 25mm	sandy loam	few, distinct ped face	abrupt, irregular	Thin (<1cm) layer of organics, moss at surface. Larger clasts are present, many at the surface. Lower boundary follows bedrock, boundary is clear in areas between blocks. Texture may grade to loam.
14 + (base 32)	Bt/ R	7.5 YR 5/4	moderate, medium subangular blocky	60/ sa, 2 – 40mm	loam	common, distinct ped face		Described material in interstices in bedrock. Ped shape is affected by bedrock. Sediments are slightly redder in deeper interstices.

Notes: Grassy slope, has not been plowed this year.

Interpretation: The sediments exposed in this location are similar to those in STP 1. The slightly redder, thinner plow zone indicates more erosion in this area and the preservation of a smaller amount of A horizon material. The subjacent Bt horizon again exhibits strong clay film morphology, indicating a protracted period of landscape stability and pedogenesis. There is no indication that bedrock has been exposed in this location in recent millennia, and no evidence is preserved of any previous episodes of erosion.

* colors given are for dry sediments unless otherwise noted

** structure designations after Birkeland 1999

*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

2004-05 Survey Area Hillslope Soils: Slope 6, Soil Test Pit 3

Date: June 16, 2007
Location: Backslope of hill southwest of Corte do Gafo Cima
Coordinates: 29S 612905E, 4173904N Slope: 15* Aspect: NNE, 30*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	10 YR 6/4	moderate, coarse to v. coarse granular	30/ a - sr, 2 – 40mm	sandy loam	few, distinct ped face	clear, wavy	Lower boundary is depth of plowing. Thin organic layer (<1cm) at surface. Rare red speckles, small pieces of decaying red bedrock. Larger gravels are angular quartz and siliceous material. Smaller gravels are rounded.
14 – 29	Bt	10 YR 6/6	moderate, medium to coarse subangular blocky	10/ sa - r, 2 – 10mm	loam	common, distinct ped face	gradual, smooth	5 – 10% small red "mottles" are probably the remains of red bedrock. The lower boundary is defined by dramatic increase in red. The stratum appears to be thoroughly decomposed bedrock. Rounded clasts are friable, can be crushed through screen.
29 – 40	Bt2	7.5 YR 6/6	strong, medium to coarse angular blocky	20/ sr, 2 – 15mm	silty clay	many, prominent ped face	clear, irregular	Gravels increase towards the base. The lower boundary is somewhat arbitrary, where digging through the bedrock becomes more difficult. The reddish color is due to red bedrock, some may be mottling. Clasts are friable.
40+ (base 48)	R							Bedrock is very friable, laminar, not like the blocky bedrock at the top of the hill.

Notes: Grassy slope, has not been plowed this year.

Interpretation: The sediments exposed in this location are surprisingly deep, again reflecting less erosion on this hillslope than on others in the 2004 – 05 survey area. The preservation of somewhat more intact soils in this location may be due to differences in land use practices. The hill is fenced and appears to have been used as a sheep enclosure during winter months. There are also the remains of what may be small terraces across the slope in several locations, although some of these may be natural outcrops of resistant bedrock or old animal enclosures. In any case, the terraces would make plowing down the slope impractical, helping to minimize erosion. The plowed deposit at the surface consists of mechanically mixed A and B horizon materials, with abundant gravels and the sandy texture suggestive of recent erosion. The weak clay films and color, however, indicate the presence of relatively large quantities of A horizon materials. This may be due, at least in part, to the presence of sediments that originated higher on the slope. The increase in magnetic susceptibility at 10 – 20 cm suggests recent deposition from higher on the slope with mobilized B horizon sediments covering an A horizon. It may also reflect downward movement of clays through mixed deposits to the base of the plow zone. The subjacent Bt horizon exhibits moderate to strong soil formation, suggesting a protracted period of landscape stability. The color suggests that it may incorporate some buried A horizon material, consistent with the suggestion that some of the plowed materials originated higher on the slope. The gradual lower boundary shows that it is genetically related to the Bt2 deposit, and observations of clast type and orientation suggest that both are primarily composed of bedrock that is decomposing *in situ*. The low magnetic susceptibility at the base of the Bt horizon is correlated with an increase in red color and redoximorphic features, suggesting that ground water has altered the signal. The structure and clay film morphology in the Bt2 horizon demonstrate strong pedogenic alteration, and show that the materials have been in place for millennia. Overall, the soils reflect millennia of landscape stability in the past, with no evidence that bedrock has been exposed in this location during the Holocene. More recently, plowing and grazing have caused moderate erosion, mobilizing surface deposits. These have been moving downhill and remnants of the A horizon are still present, at least in some locations.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

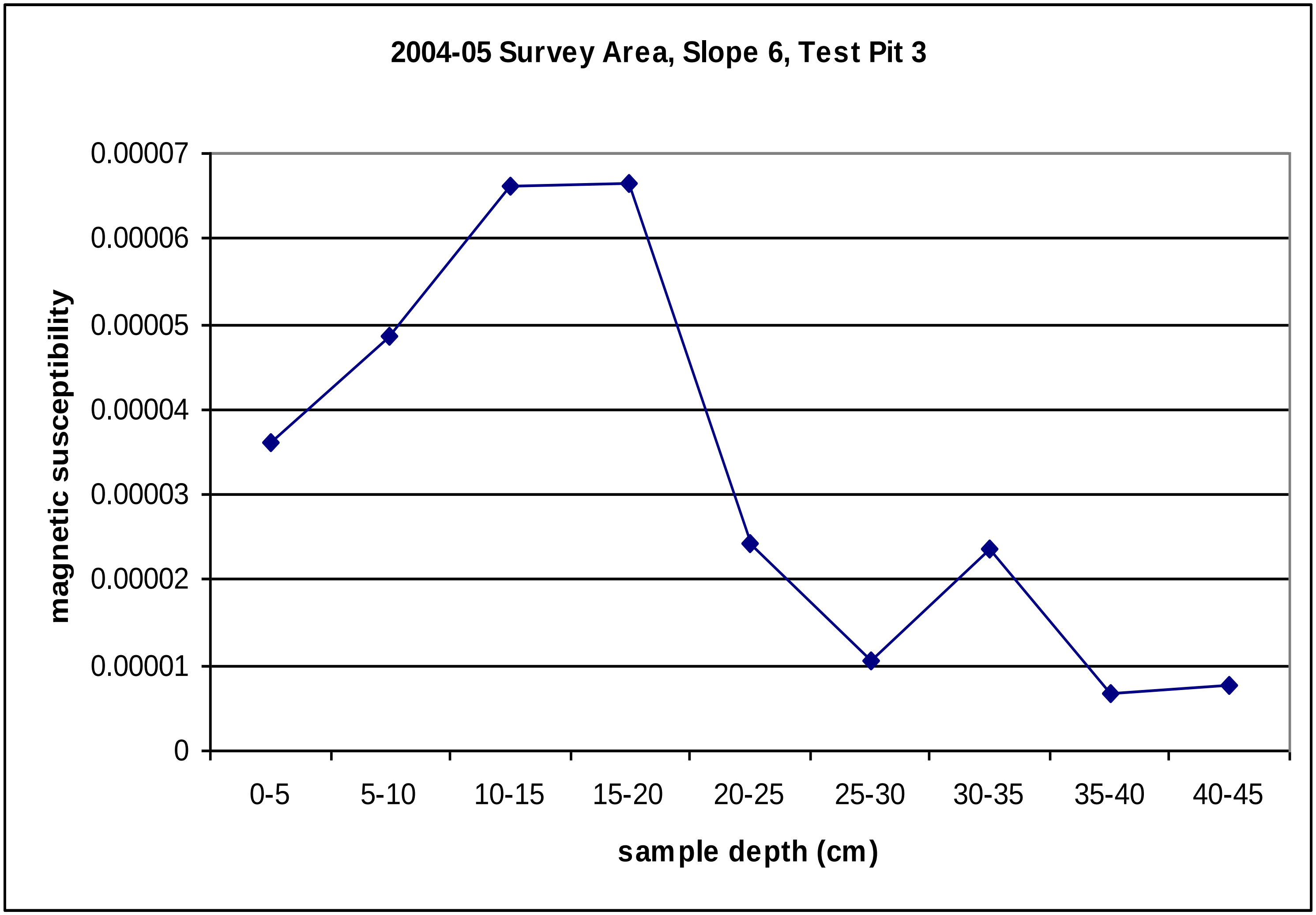

Figure A1 - 36: Magnetic susceptibility by depth, 2004-05 survey area, slope 6, soil test pit 3

2004-05 Survey Area Hillslope Soils: Slope 6, Soil Test Pit 4

Date: June 16, 2007
Location: Foot of slope, hill southwest of Corte do Gafo Cima
Coordinates: 29S 612928E, 4173959N Slope: 6* Aspect: NNE, 34*

Depth (cm)	Soil Horizon	Munsell Color*	Structure **	% Gravel (est.)/ rounding, size	Texture Class	Clay Films***	Lower Boundary	Comments/ Notes
0 – 14	ABp	10 YR 7/4	moderate, coarse granular	40/ a - r, 2 – 30mm	loam	few to common, distinct ped face	abrupt, irregular	Texture may grade to sandy loam. Lower boundary is transition to bedrock. Very thin layer of organic material (<.5cm) at the surface. Larger clasts are angular quartz, smaller are friable, weathered bedrock.
14 + (base 27)	Bt/ R	2.5 Y 7/4	moderate, medium angular blocky	50/ sa - sr, 2 – 30mm	clay loam	common, distinct ped face		Described material in interstices in bedrock. Shape of peds is determined by interstices in bedrock. Mostly similar to overlying. Clasts are friable bedrock, no quartz.
	R							Bedrock does not look like STP 3, not red. This is a different stratum, more blocky.

Notes: Grassy slope, has not been plowed this year.

Interpretation: The sediments exposed in this test pit are more typical of hillslope sediments throughout the 2004 – 05 survey area than those higher on the slope. This may be because the pit is located below the lithic alignments visible higher on the slope. The relatively strong expression of clay films in the plow zone shows that it consists primarily of an exhumed B horizon, and this is consistent with the relatively flat magnetic susceptibility curve with a weak peak at the surface. The presence of large quartz clasts at the surface also indicates erosion, as quartz clasts are not present in the bedrock at the base of the pit. The subjacent Bt horizon exhibits moderate to strong pedogenic alteration, suggesting a long period of landscape stability in the past. The difference in color from the surface deposit and the degree of pedogenesis are consistent with deeper burial in the past and inputs of water from higher on the slope, but the differences between the two deposits are not so great as to suggest that surface deposits were removed from this location at any time during the Holocene, and the lack of a significant change in susceptibility provides additional support for this interpretation. The sediments reflect significant recent erosion, but there is no preserved evidence for erosion in the past.

* colors given are for dry sediments unless otherwise noted
** structure designations after Birkeland 1999
*** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

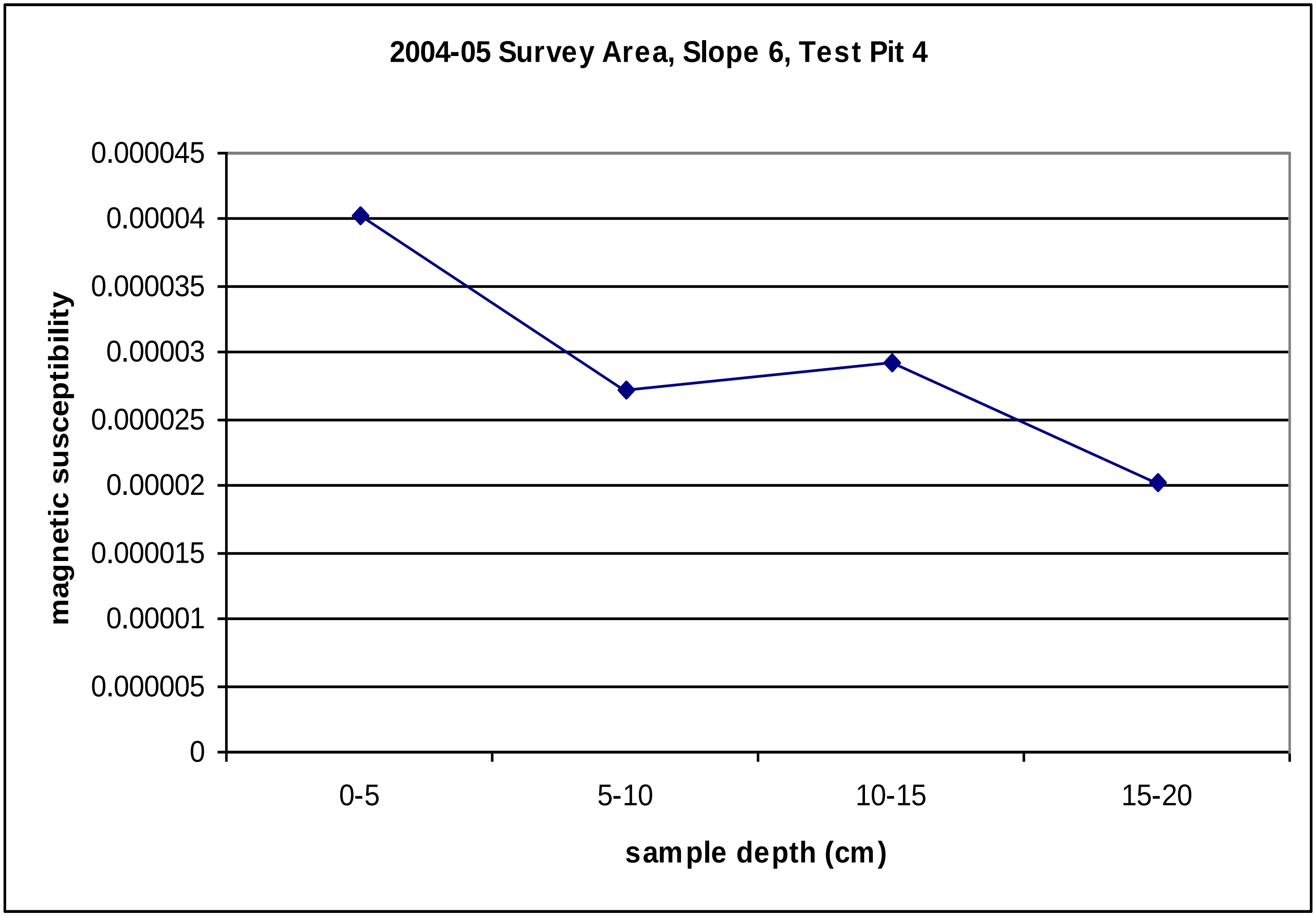

Figure A1 - 37: Magnetic susceptibility by depth, 2004-05 survey area, slope 6, soil test pit 4

2004-05 Survey Area Hillslope Soils: Slope 6, Soil Test Pit 5

Date: June 25, 2007
Location: Toe of slope, hill southwest of Corte do Gafo Cima
Coordinates: 29S 612934E, 4174008N Slope: 3* Aspect: NNE, 32*

Depth (cm)	**Soil Horizon**	**Munsell Color***	**Structure ** **	**% Gravel (est.)/ rounding, size**	**Texture Class**	**Clay Films*** **	**Lower Boundary**	**Comments/ Notes**
0 – 18	ABp	10 YR 7/4	moderate, medium granular	40/ sr, 2 – 10mm	loam	few, distinct ped face	clear, smooth	Texture may grade to sandy loam. Gravels include all local rock types, rounding indicates transport. ABp appears to be mixed slope deposits, thickness suggests cumulic. Some angular quartz is present, especially large clasts at surface and near base. Peds are variable in hardness. Thin (>1cm) layer of organics at the surface.
18 + (base 65)	Btb	10 YR 7/6	strong, coarse angular blocky	<5/ a, 2 – 7mm	clay	many, prominent ped face		Color is 10 YR 5/6 moist. Did not reach bedrock. Unit is homogeneous, possibly some increase in clay with depth. Weak stone line is present at the base of the plow zone. Clasts are rock types resistant to weathering, quartz and siliceous, or highly weathered schist, some as large as 20 cm. Clasts are in random orientation – old mass movement? The clay content and depth allow it to retain moisture. Few small, red mottles are present but barely noticeable. Identified as "barra" by Edgar – the material used to make pisé/ rammed earth walls.

Notes: Grassy slope, has not been plowed this year.

Interpretation: The sediments exposed in this location reflect only recent erosion. This is significant because this is the most likely geomorphic position in which evidence for past erosion should be preserved. The abundance of gravels in the plow zone suggests significant erosion, creating a lag deposit, as well as transport of clasts and presumably sediments from higher on the hill. The weak peak in magnetic susceptibility at 5 – 10 cm is consistent with some amount of recent deposition, but the pattern generally suggests that the majority of the sediments consist of an exhumed B horizon. The thickness of the plowed deposit reflects the effective depth of plowing and the ability of agricultural equipment to move and mix the subjacent materials. Clay film morphology suggests that the plowed deposits include B horizon materials, as well as minor remnants of an A horizon. The random orientation of clasts and the presence of multiple rock types in the basal unit suggest that this deposit originated as a mass movement. The very strong pedogenic alteration is consistent with soil formation over the course of many millennia, suggesting that initial deposition may have been related to climate shifts in the past, perhaps associated with the Pleistocene – Holocene transition.

The peak in magnetic susceptibility at 25 – 30 cm is puzzling as it is not correlated with any obvious changes in soil characteristics at that depth. An examination of the data reveals that the measurement is driven primarily by the readings on one aliquot (25 – 30 a) that was much lower than average in weight (only 2.9 g of sediment). Correcting for mass may have effectively multiplied a small error. With that reading removed, the other two aliquots at that depth create an average susceptibility measurement of only 0.0000339, only slightly higher than the superjacent and subjacent sample units. If this is a more accurate measurement, the minor increase may be due to the accumulation of clays just below the base of the plow zone. Alternatively, given the highly weathered nature of many clasts in the base unit and the range of lithic types present, it is possible that the aliquot included some quantity of a decomposing rock that contained relatively high quantities of magnetic minerals. While the data are insufficient to distinguish between these alternatives, the anomalous reading does not significantly alter the overall interpretation of the history of erosion and deposition in this location.

* colors given are for dry sediments unless otherwise noted ** structure designations after Birkeland 1999 *** "co-br" designates clay coatings on and/ or bridges between sand grains and clasts

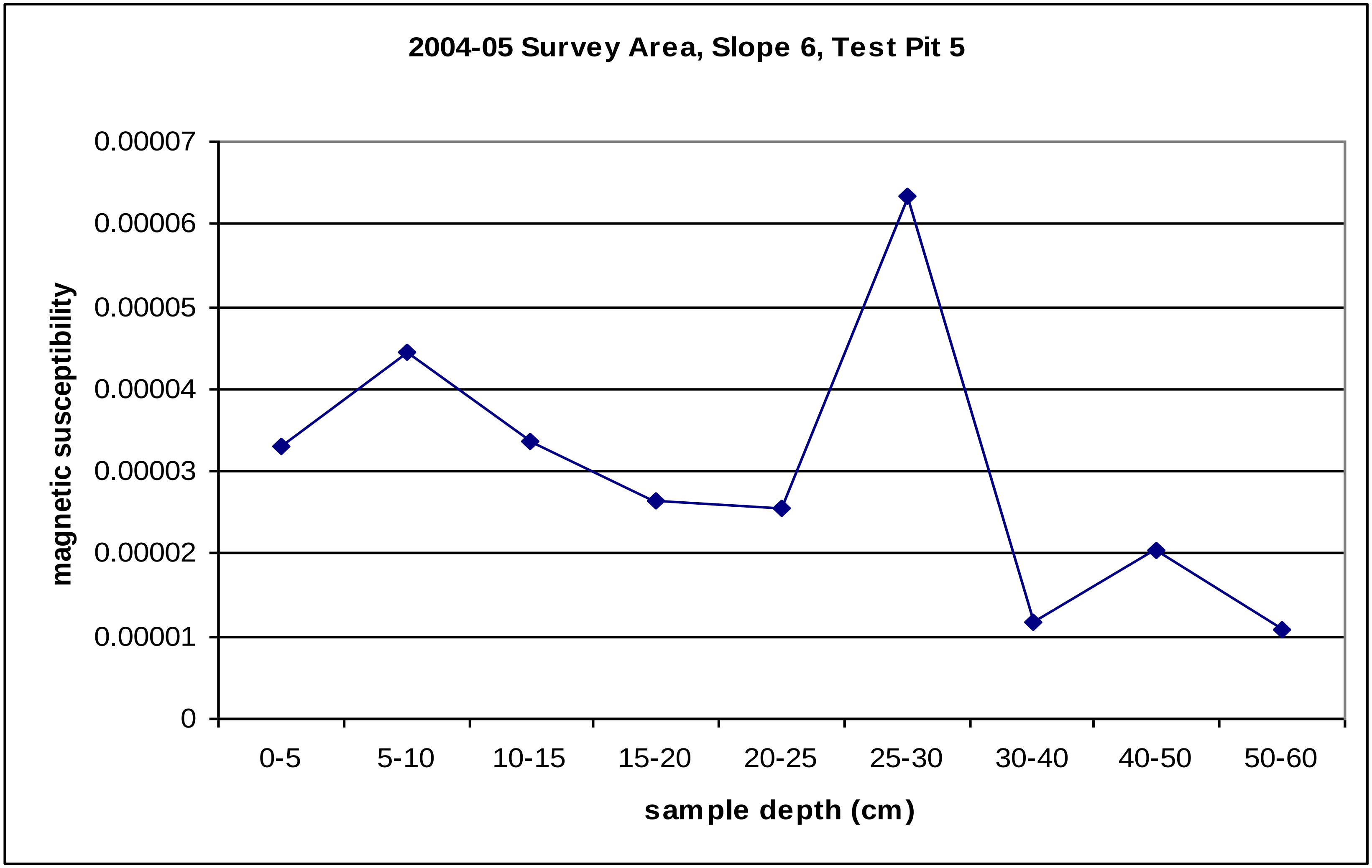

Figure A1 - 38: Magnetic susceptibility by depth, 2004-05 survey area, slope 6, soil test pit 5

APPENDIX 2: MAGNETIC SUSCEPTIBILITY DATA

This appendix presents the results of each individual magnetic susceptibility measurement. Every soil sample collected for susceptibility measurements was divided into three aliquots, and three measurements of the susceptibility of each aliquot were performed using an ASC Scientific MFK1-FA Kappabridge in the University of New Mexico Earth and Planetary Sciences Paleomagnetic and Rock Magnetic Lab. Each aliquot was weighed to the nearest 0.05 g using a standard three beam balance and the susceptibility was corrected for the mass of each aliquot. The resulting nine measurements of magnetic susceptibility per sample were averaged to produce the graphs presented in Appendix 1. In the rare cases where one aliquot had a significantly different susceptibility measurement from the other two (different by an order of magnitude or more) the outlier was removed before averaging. The tables are presented in the same order as the graphs in Appendix 1.

1992 Survey Area, Fluvial Study Unit 2

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	0.0001901	0.0001893	5.6	3.38036E-05	3.3941E-05
2		0.0001888				
3		0.000189				
4	05B	0.0001519	0.0001521	5.05	3.01188E-05	
5		0.0001521				
6		0.0001523				
7	05C	0.0002157	0.000216033	5.7	3.79006E-05	
8		0.0002169				
9		0.0002155				
10	510A	0.0002991	0.000299067	6	4.98444E-05	4.24255E-05
11		0.0002989				
12		0.0002992				
13	510B	0.0002855	0.0002861	6.4	4.47031E-05	
14		0.0002864				
15		0.0002864				
16	510C	0.000175	0.0001751	5.35	3.2729E-05	
17		0.0001751				
18		0.0001752				
19	1015A	0.0003162	0.000314633	5.65	5.56873E-05	5.02987E-05
20		0.0003138				
21		0.0003139				
22	1015B	0.000284	0.000283333	6.05	4.6832E-05	
23		0.0002829				
24		0.0002831				
25	1015C	0.000278	0.000278167	5.75	4.83768E-05	
26		0.0002783				
27		0.0002782				
28	1520A	0.000218	0.000218267	6.1	3.57814E-05	5.70618E-05
29		0.0002182				
30		0.0002186				
31	1520B	0.000248	0.0002463	7.4	3.32838E-05	
32		0.0002464				
33		0.0002445				
34	1520C	0.0006229	0.000622933	6.1	0.00010212	
35		0.000623				
36		0.0006229				
37	2025A	0.000127	0.000126867	5.9	2.15028E-05	2.59799E-05
38		0.0001268				
39		0.0001268				
40	2025B	0.000214	0.0002137	6.95	3.07482E-05	
41		0.0002138				
42		0.0002133				
43	2025C	0.000156	0.0001567	6.1	2.56885E-05	
44		0.000157				
45		0.0001571				
46	2530A	0.00007529	0.00007547	5.15	1.46544E-05	1.74427E-05
47		0.00007543				

48		0.00007569				
49	2530B	0.0001178	0.0001189	5.45	2.18165E-05	
50		0.000119				
51		0.0001199				
52	2530C	0.00008334	0.00008325	5.25	1.58571E-05	
53		0.0000832				
54		0.00008321				
55	3035A	0.00009542	0.0000949	6.05	1.5686E-05	1.55043E-05
56		0.00009467				
57		0.00009461				
58	3035B	0.0000926	9.25667E-05	5.65	1.63835E-05	
59		0.00009285				
60		0.00009225				
61	3035C	0.0000896	0.00008955	6.2	1.44435E-05	
62		0.00008962				
63		0.00008943				
64	3540A	0.0001201	0.000119867	7.45	1.60895E-05	1.34737E-05
65		0.0001196				
66		0.0001199				
67	3540B	0.00007252	0.00007277	5.95	1.22303E-05	
68		0.00007288				
69		0.00007291				
70	3540C	0.00006839	6.83733E-05	5.65	1.21015E-05	
71		0.00006839				
72		0.00006834				
73	4045A	0.00009384	9.37467E-05	5.95	1.57557E-05	1.79621E-05
74		0.00009371				
75		0.00009369				
76	4045B	0.0001202	0.000116	6.4	0.000018125	
77		0.0001141				
78		0.0001137				
79	4045C	0.0001179	0.000118033	5.9	2.00056E-05	
80		0.000118				
81		0.0001182				
82	4550A	0.00008421	0.00008379	6.5	1.28908E-05	1.34534E-05
83		0.00008351				
84		0.00008365				
85	4550B	0.00008388	0.00008338	6.3	1.32349E-05	
86		0.00008313				
87		0.00008313				
88	4550C	0.00008128	8.11367E-05	5.7	1.42345E-05	
89		0.00008126				
90		0.00008087				
91	5055A	0.00007358	7.23333E-05	5.65	1.28024E-05	1.35378E-05
92		0.00007195				
93		0.00007147				
94	5055B	0.00006502	6.52233E-05	5.25	1.24235E-05	
95		0.00006533				
96		0.00006532				
97	5055C	0.00008443	8.30933E-05	5.4	1.53877E-05	

98		0.00008368				
99		0.00008117				
100	5560A	0.00007066	7.06333E-05	5.9	1.19718E-05	1.22545E-05
101		0.0000706				
102		0.00007064				
103	5560B	0.00008278	8.27033E-05	6.75	1.22523E-05	
104		0.00008275				
105		0.00008258				
106	5560C	0.00007533	7.52367E-05	6	1.25394E-05	
107		0.00007522				
108		0.00007516				
109	6065A	0.00007606	0.00007611	5.25	1.44971E-05	1.5979E-05
110		0.00007612				
111		0.00007615				
112	6065B	0.0001042	0.0001039	6.9	1.5058E-05	
113		0.0001037				
114		0.0001038				
115	6065C	0.0001012	0.0001011	5.5	1.83818E-05	
116		0.0001011				
117		0.000101				
118	6570A	0.00006593	6.59067E-05	5.65	1.16649E-05	1.23159E-05
119		0.00006589				
120		0.0000659				
121	6570B	0.0000609	6.06633E-05	5	1.21327E-05	
122		0.00006052				
123		0.00006057				
124	6570C	0.00006501	6.50933E-05	4.95	1.31502E-05	
125		0.00006499				
126		0.00006528				
127	7075A	0.00006293	0.00006312	5.35	1.17981E-05	1.29864E-05
128		0.00006332				
129		0.00006311				
130	7075B	0.00008844	8.72067E-05	5.8	1.50356E-05	
131		0.0000865				
132		0.00008668				
133	7075C	0.00007263	7.27533E-05	6	1.21256E-05	
134		0.00007289				
135		0.00007274				
136	7580A	0.00007378	0.00007361	6.05	1.21669E-05	1.50206E-05
137		0.00007358				
138		0.00007347				
139	7580B	0.00009256	0.00009281	5.85	1.5865E-05	
140		0.00009288				
141		0.00009299				
142	7580C	0.00009885	9.87733E-05	5.8	1.70299E-05	
143		0.00009864				
144		0.00009883				

1992 Survey Area, Fluvial Study Unit 8

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	0.0001742	0.000174233	5.85	2.9783E-05	3.27051E-05
2		0.0001742				
3		0.0001743				
4	05B	0.0001778	0.000178133	5	3.5627E-05	
5		0.000178				
6		0.0001786				
7	05C	0.000588	0.000587667	5.5	0.00010685	
8		0.0005883				
9		0.0005867				
10	510A	0.000364	0.000362367	7.2	5.0329E-05	3.90006E-05
11		0.0003605				
12		0.0003626				
13	510B	0.000002528	2.52967E-06	6	4.2161E-07	
14		0.000002531				
15		0.00000253				
16	510C	0.0001603	0.000157733	5.7	2.7673E-05	
17		0.0001563				
18		0.0001566				
19	1015A	0.0001652	0.000165167	5.25	3.146E-05	3.10594E-05
20		0.0001658				
21		0.0001645				
22	1015B	0.0001566	0.000159133	4.6	3.4594E-05	
23		0.0001594				
24		0.0001614				
25	1015C	0.0001691	0.000168167	6.2	2.7124E-05	
26		0.0001681				
27		0.0001673				
28	1520A	0.0001922	0.000191967	5.65	3.3976E-05	5.03956E-05
29		0.000192				
30		0.0001917				
31	1520B	0.0005213	0.000520833	5.95	8.7535E-05	
32		0.0005212				
33		0.00052				
34	1520C	0.0001681	0.000167667	5.65	2.9676E-05	
35		0.000168				
36		0.0001669				
37	2025A	0.0001264	0.000127733	4.95	2.5805E-05	3.08531E-05
38		0.0001282				
39		0.0001286				
40	2025B	0.0001756	0.0001771	4.7	3.7681E-05	
41		0.0001766				
42		0.0001791				
43	2025C	0.0001645	0.000164267	5.65	2.9074E-05	
44		0.0001644				
45		0.0001639				
46	2530A	0.00009735	9.73467E-05	5.15	1.8902E-05	2.08795E-05
47		0.00009717				

48		0.00009752				
49	2530B	0.0001196	0.000119667	6.3	1.8995E-05	
50		0.0001198				
51		0.0001196				
52	2530C	0.0001429	0.0001435	5.8	2.4741E-05	
53		0.0001445				
54		0.0001431				
55	3035A	0.000101	0.000101067	5.6	1.8048E-05	2.06491E-05
56		0.0001011				
57		0.0001011				
58	3035B	0.0001229	0.0001228	6	2.0467E-05	
59		0.0001227				
60		0.0001228				
61	3035C	0.0001254	0.000125367	5.35	2.3433E-05	
62		0.0001261				
63		0.0001246				
64	3540A	0.00007123	7.12333E-05	4.4	1.6189E-05	1.74641E-05
65		0.00007134				
66		0.00007113				
67	3540B	0.00006689	6.67367E-05	4.15	1.6081E-05	
68		0.00006685				
69		0.00006647				
70	3540C	0.0001037	0.000104633	5.2	2.0122E-05	
71		0.0001055				
72		0.0001047				
73	4045A	0.0001223	0.0001229	5.45	2.255E-05	1.70456E-05
74		0.0001229				
75		0.0001235				
76	4045B	0.00006771	0.0000679	4.45	1.5258E-05	
77		0.00006802				
78		0.00006797				
79	4045C	0.00006407	6.39733E-05	4.8	1.3328E-05	
80		0.00006399				
81		0.00006386				
82	4550A	0.00006908	6.92867E-05	4.6	1.5062E-05	1.65195E-05
83		0.00006962				
84		0.00006916				
85	4550B	0.00008037	0.00008041	4.95	1.6244E-05	
86		0.00008054				
87		0.00008032				
88	4550C	0.00008516	8.57833E-05	4.7	1.8252E-05	
89		0.00008596				
90		0.00008623				
91	5055A	0.0000873	8.72767E-05	6.2	1.4077E-05	1.42545E-05
92		0.00008724				
93		0.00008729				
94	5055B	0.0000742	7.52067E-05	5.85	1.2856E-05	
95		0.000075				
96		0.00007642				
97	5055C	0.00008594	8.54867E-05	5.4	1.5831E-05	

98		0.00008548				
99		0.00008504				
100	5560A	0.00008548	8.51733E-05	5.7	1.4943E-05	1.65555E-05
101		0.00008496				
102		0.00008508				
103	5560B	0.0001023	0.000102167	4.9	2.085E-05	
104		0.0001021				
105		0.0001021				
106	5560C	0.00007466	7.49167E-05	5.4	1.3873E-05	
107		0.00007513				
108		0.00007496				
109	6065A	0.0001239	0.000123933	7.35	1.6862E-05	1.55442E-05
110		0.000124				
111		0.0001239				
112	6065B	0.00006983	7.01467E-05	4.85	1.4463E-05	
113		0.0000702				
114		0.00007041				
115	6065C	0.00006584	6.58233E-05	4.3	1.5308E-05	
116		0.00006422				
117		0.00006741				
118	6570A	0.00009802	9.81367E-05	5.75	1.7067E-05	1.63111E-05
119		0.0000982				
120		0.00009819				
121	6570B	0.00008463	0.00008471	5.45	1.5543E-05	
122		0.00008476				
123		0.00008474				
124	6570C	0.00006852	6.85567E-05	4.2	1.6323E-05	
125		0.00006861				
126		0.00006854				
127	7075A	0.0001042	0.0001044	5.7	1.8316E-05	1.82747E-05
128		0.0001046				
129		0.0001044				
130	7075B	0.0001053	0.000105267	5.8	1.8149E-05	
131		0.0001052				
132		0.0001053				
133	7075C	0.00009361	0.00009363	5.1	1.8359E-05	
134		0.00009364				
135		0.00009364				
136	7580A	0.0001236	0.000123733	6.15	2.0119E-05	1.9291E-05
137		0.0001238				
138		0.0001238				
139	7580B	0.00008181	8.18533E-05	4.5	1.819E-05	
140		0.0000819				
141		0.00008185				
142	7580C	0.00008911	8.90167E-05	4.55	1.9564E-05	
143		0.00008901				
144		0.00008893				

2004 – 05 Survey Area, Fluvial Study Unit 04 – 01

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	010A	6.86E-04	0.0006866	5.4	0.000127148	0.000137345
2		6.87E-04				
3		6.86E-04				
4	010B	7.44E-04	0.000744	4.5	0.000165333	
5		7.45E-04				
6		7.44E-04				
7	010C	7.05E-04	0.000705367	5.9	0.000119554	
8		7.06E-04				
9		7.05E-04				
10	1020A	6.32E-04	0.0006323	4.4	0.000143705	0.000133945
11		6.32E-04				
12		6.33E-04				
13	1020B	8.27E-04	0.000827233	6.4	0.000129255	
14		8.27E-04				
15		8.28E-04				
16	1020C	5.54E-04	0.000554167	4.3	0.000128876	
17		5.54E-04				
18		5.54E-04				
19	2030A	8.98E-04	0.000897833	5.6	0.000160327	0.000157247
20		8.98E-04				
21		8.98E-04				
22	2030B	7.48E-04	0.000747967	4.1	0.000182431	
23		7.48E-04				
24		7.48E-04				
25	2030C	7.61E-04	0.000761	5.9	0.000128983	
26		7.61E-04				
27		7.61E-04				
28	3040A	8.10E-04	0.000809533	4.8	0.000168653	0.0002232
29		8.10E-04				
30		8.10E-04				
31	3040B	1.75E-03	0.001747	6.7	0.000260746	
32		1.75E-03				
33		1.75E-03				
34	3040C	1.20E-03	0.001201	5	0.0002402	
35		1.20E-03				
36		1.20E-03				
37	4050A	1.29E-03	0.001287	6	0.0002145	0.000193144
38		1.29E-03				
39		1.29E-03				
40	4050B	9.19E-04	0.0009197	4.9	0.000187694	
41		9.20E-04				
42		9.20E-04				
43	4050C	9.39E-04	0.000939367	5.3	0.000177239	
44		9.40E-04				
45		9.39E-04				
46	5060A	9.15E-04	0.000915433	5.5	0.000166442	0.000179381
47		9.15E-04				

48		9.16E-04				
49	5060B	1.40E-03	0.001396	6.6	0.000211515	
50		1.40E-03				
51		1.40E-03				
52	5060C	9.45E-04	0.0009451	5.9	0.000160186	
53		9.46E-04				
54		9.45E-04				
55	6070A	9.39E-04	0.000939167	7.5	0.000125222	0.000119924
56		9.39E-04				
57		9.39E-04				
58	6070B	9.07E-04	0.0009077	5.7	0.000159246	
59		9.08E-04				
60		9.08E-04				
61	6070C	4.52E-04	0.000451833	6	7.53056E-05	
62		4.52E-04				
63		4.52E-04				
64	7080A	1.10E-04	0.00011	4.5	2.44444E-05	2.95435E-05
65		1.10E-04				
66		1.10E-04				
67	7080B	2.04E-04	0.0002041	6.4	3.18906E-05	
68		2.04E-04				
69		2.04E-04				
70	7080C	1.42E-04	0.0001421	4.4	3.22955E-05	
71		1.42E-04				
72		1.42E-04				
73	8090A	5.76E-04	0.0005766	6	0.0000961	0.000110584
74		5.77E-04				
75		5.77E-04				
76	8090B	4.69E-04	0.0004689	5.8	8.08448E-05	
77		4.69E-04				
78		4.69E-04				
79	8090C	8.51E-04	0.000851433	5.5	0.000154806	
80		8.52E-04				
81		8.51E-04				
82	90100A	3.13E-04	0.0003133	4.8	6.52708E-05	0.000111397
83		3.13E-04				
84		3.13E-04				
85	90100B	4.37E-04	0.0004362	5.3	8.23019E-05	
86		4.36E-04				
87		4.35E-04				
88	90100C	1.27E-03	0.001269	6.8	0.000186618	
89		1.27E-03				
90		1.27E-03				
91	100110A	4.66E-04	0.0004657	5.8	8.02931E-05	0.000101304
92		4.66E-04				
93		4.66E-04				
94	100110B	5.80E-04	0.0005801	6.4	9.06406E-05	
95		5.80E-04				
96		5.80E-04				
97	100110C	9.97E-04	0.000997333	7.5	0.000132978	

98	9.97E-04
99	9.98E-04

2004 – 05 Survey Area, Fluvial Study Unit 04 – 03

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	APA	1.20E-03	0.001199667	10	0.000119967	0.000111657
2		1.20E-03				
3		1.20E-03				
4	APB	1.06E-03	0.001057333	9.7	0.000109003	
5		1.06E-03				
6		1.06E-03				
7	APC	1.06E-03	0.00106	10	0.000106	
8		1.06E-03				
9		1.06E-03				
10	BTA	4.35E-04	0.0004347	9.5	4.57579E-05	4.47062E-05
11		4.35E-04				
12		4.35E-04				
13	BTB	3.45E-04	0.000344967	8.6	4.01124E-05	
14		3.45E-04				
15		3.45E-04				
16	BTC	4.53E-04	0.000453533	9.4	4.82482E-05	
17		4.54E-04				
18		4.54E-04				
19	CA	5.25E-05	5.25967E-05	9.3	5.65556E-06	7.52753E-06
20		5.26E-05				
21		5.27E-05				
22	CB	7.48E-05	0.00007477	8.1	9.23086E-06	
23		7.48E-05				
24		7.48E-05				
25	CC	6.70E-05	6.69567E-05	8.7	7.69617E-06	
26		6.70E-05				
27		6.69E-05				

Alcaria Longa, Soil Test Pit 1

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	105A	2.80E-04	0.0002802	8.2	3.4171E-05	3.08727E-05
2		2.80E-04				
3		2.81E-04				
4	105B	2.59E-04	0.000259433	8.1	3.2029E-05	
5		2.59E-04				
6		2.60E-04				
7	105C	2.38E-04	0.000237767	9	2.6419E-05	
8		2.38E-04				
9		2.38E-04				
10	158A	5.34E-04	0.0005334	9.2	5.7978E-05	4.96468E-05
11		5.33E-04				
12		5.33E-04				
13	158B	4.11E-04	0.0004106	9.5	4.3221E-05	
14		4.11E-04				
15		4.11E-04				
16	158C	4.49E-04	0.000448767	9.4	4.7741E-05	
17		4.49E-04				
18		4.49E-04				

Alcaria Longa, Soil Test Pit 2

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	205A	5.30E-04	0.000530233	8.8	6.02538E-05	5.39621E-05
2		5.30E-04				
3		5.30E-04				
4	205B	4.74E-04	0.000474967	8	5.93708E-05	
5		4.76E-04				
6		4.75E-04				
7	205C	3.34E-04	0.000333867	7.9	4.22616E-05	
8		3.34E-04				
9		3.34E-04				
10	2510A	4.10E-04	0.000409933	8.4	4.88016E-05	5.00643E-05
11		4.10E-04				
12		4.10E-04				
13	2510B	4.78E-04	0.000477467	9.1	5.24689E-05	
14		4.77E-04				
15		4.78E-04				
16	2510C	4.21E-04	0.000420733	8.6	4.89225E-05	
17		4.21E-04				
18		4.21E-04				
19	21015A	5.31E-04	0.000531633	7.7	6.90433E-05	7.6652E-05
20		5.32E-04				
21		5.32E-04				
22	21015B	6.62E-04	0.000661467	8.4	7.8746E-05	
23		6.61E-04				
24		6.62E-04				
25	21015C	7.73E-04	0.000772367	9.4	8.21667E-05	
26		7.72E-04				
27		7.72E-04				
28	21520A	1.20E-03	0.001195667	9.7	0.000123265	0.000125857
29		1.20E-03				
30		1.20E-03				
31	21520B	1.39E-03	0.001387	9.8	0.000141531	
32		1.39E-03				
33		1.39E-03				
34	21520C	9.70E-04	0.000969867	8.6	0.000112775	
35		9.70E-04				
36		9.70E-04				
37	22025A	1.81E-03	0.001809	9.4	0.000192447	0.000176732
38		1.81E-03				
39		1.81E-03				
40	22025B	2.12E-03	0.002119333	10	0.000211933	
41		2.12E-03				
42		2.12E-03				
43	22025C	9.56E-04	0.0009562	7.6	0.000125816	
44		9.56E-04				
45		9.57E-04				
46	22530A	8.72E-04	0.0008717	7.9	0.000110342	0.000132776
47		8.72E-04				

48		8.72E-04			
49	22530B	1.22E-03	0.001223667	7.9	0.000154895
50		1.22E-03			
51		1.22E-03			
52	22530C	1.29E-03	0.001291	9.7	0.000133093
53		1.29E-03			
54		1.29E-03			

Alcaria Longa, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.41E-04	0.000240767	9.4	2.56135E-05	2.8396E-05
2		2.41E-04				
3		2.40E-04				
4	05B	2.77E-04	0.000277967	7.6	3.65746E-05	
5		2.78E-04				
6		2.78E-04				
7	05C	2.07E-04	0.000207	9	0.000023	
8		2.07E-04				
9		2.07E-04				
10	510A	3.39E-04	0.000338933	10.5	3.22794E-05	3.10941E-05
11		3.39E-04				
12		3.39E-04				
13	510B	3.05E-04	0.000305633	9.4	3.25142E-05	
14		3.06E-04				
15		3.06E-04				
16	510C	2.56E-04	0.0002564	9	2.84889E-05	
17		2.56E-04				
18		2.57E-04				
19	1015A	4.02E-04	0.000401867	9.9	4.05926E-05	3.55585E-05
20		4.02E-04				
21		4.02E-04				
22	1015B	3.47E-04	0.0003474	10.3	3.37282E-05	
23		3.48E-04				
24		3.47E-04				
25	1015C	3.04E-04	0.000304133	9.4	3.23546E-05	
26		3.04E-04				
27		3.04E-04				
28	1520A	2.17E-04	0.0002165	9.8	2.20918E-05	2.29032E-05
29		2.17E-04				
30		2.17E-04				
31	1520B	2.15E-04	0.000215033	10	2.15033E-05	
32		2.15E-04				
33		2.15E-04				
34	1520C	2.56E-04	0.000256167	10.2	2.51144E-05	
35		2.56E-04				
36		2.56E-04				
37	2025A	9.39E-05	9.39733E-05	8.4	1.11873E-05	1.21035E-05
38		9.38E-05				
39		9.42E-05				
40	2025B	9.98E-05	9.96667E-05	8.5	1.17255E-05	
41		9.99E-05				
42		9.93E-05				
43	2025C	1.11E-04	0.0001112	8.3	1.33976E-05	
44		1.11E-04				
45		1.11E-04				

Alcaria Longa, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	1.20E-04	0.0001201	9.5	1.2642E-05	1.37832E-05
2		1.20E-04				
3		1.21E-04				
4	05B	1.31E-04	0.000130767	9.3	1.4061E-05	
5		1.31E-04				
6		1.31E-04				
7	05C	1.22E-04	0.000121567	8.3	1.4647E-05	
8		1.22E-04				
9		1.22E-04				
10	510A	1.57E-04	0.0001566	9.3	1.6839E-05	1.6836E-05
11		1.57E-04				
12		1.57E-04				
13	510B	1.39E-04	0.000139	8.9	1.5618E-05	
14		1.39E-04				
15		1.39E-04				
16	510C	1.88E-04	0.000187733	10.4	1.8051E-05	
17		1.88E-04				
18		1.88E-04				
19	1015A	1.23E-04	0.000123167	9.6	1.283E-05	1.47044E-05
20		1.23E-04				
21		1.23E-04				
22	1015B	1.37E-04	0.000136867	8.7	1.5732E-05	
23		1.37E-04				
24		1.37E-04				
25	1015C	1.66E-04	0.0001664	10.7	1.5551E-05	
26		1.67E-04				
27		1.66E-04				
28	1520A	1.43E-04	0.000143167	9.4	1.523E-05	1.46018E-05
29		1.43E-04				
30		1.43E-04				
31	1520B	1.32E-04	0.0001322	9.5	1.3916E-05	
32		1.32E-04				
33		1.32E-04				
34	1520C	1.30E-04	0.000130467	8.9	1.4659E-05	
35		1.31E-04				
36		1.31E-04				
37	2025A	1.10E-04	0.000109733	9.1	1.2059E-05	1.24157E-05
38		1.10E-04				
39		1.10E-04				
40	2025B	1.03E-04	0.000103267	8.4	1.2294E-05	
41		1.03E-04				
42		1.03E-04				
43	2025C	1.19E-04	0.000118633	9.2	1.2895E-05	
44		1.18E-04				
45		1.18E-04				

Alcaria Longa, Soil Test Pit 6

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05a	2.44E-04	0.0002425	7.5	3.2333E-05	2.81964E-05
2		2.43E-04				
3		2.40E-04				
4	05b	1.34E-04	0.000132633	6	2.2106E-05	
5		1.32E-04				
6		1.32E-04				
7	05c	1.54E-04	0.000153767	5.1	3.015E-05	
8		1.53E-04				
9		1.54E-04				
10	510a	1.44E-04	0.0001422	5.3	2.683E-05	2.80586E-05
11		1.40E-04				
12		1.43E-04				
13	510b	1.84E-04	0.000183867	5.6	3.2833E-05	
14		1.83E-04				
15		1.85E-04				
16	510c	1.33E-04	0.000132367	5.4	2.4512E-05	
17		1.30E-04				
18		1.34E-04				
19	1015a	1.12E-04	0.000111133	4.9	2.268E-05	2.30547E-05
20		1.10E-04				
21		1.11E-04				
22	1015b	1.63E-04	0.000161967	6.5	2.4918E-05	
23		1.61E-04				
24		1.62E-04				
25	1015c	1.65E-04	0.0001639	7.6	2.1566E-05	
26		1.63E-04				
27		1.63E-04				
28	1520a	1.28E-04	0.0001281	5.9	2.1712E-05	3.20958E-05
29		1.28E-04				
30		1.28E-04				
31	1520b	3.14E-04	0.000313733	6.6	4.7535E-05	
32		3.14E-04				
33		3.14E-04				
34	1520c	1.57E-04	0.000156833	5.8	2.704E-05	
35		1.57E-04				
36		1.57E-04				
37	2025a	8.45E-05	0.00008494	4.5	1.8876E-05	2.16296E-05
38		8.35E-05				
39		8.68E-05				
40	2025b	1.27E-04	0.000126167	5	2.5233E-05	
41		1.26E-04				
42		1.26E-04				
43	2025c	1.10E-04	0.000110133	5.3	2.078E-05	
44		1.11E-04				
45		1.10E-04				
46	2530a	5.10E-04	0.000510733	5.2	9.8218E-05	4.66754E-05
47		5.08E-04				

48		5.15E-04				
49	2530b	9.38E-05	9.29967E-05	5.1	1.8235E-05	
50		9.27E-05				
51		9.25E-05				
52	2530c	1.02E-04	0.000101367	4.3	2.3574E-05	
53		1.01E-04				
54		1.01E-04				
55	3035a	1.09E-04	0.000107333	5.2	2.0641E-05	1.86267E-05
56		1.06E-04				
57		1.07E-04				
58	3035b	8.94E-05	8.87767E-05	5	1.7755E-05	
59		8.85E-05				
60		8.85E-05				
61	3035c	8.65E-05	0.00008567	4.9	1.7484E-05	
62		8.65E-05				
63		8.40E-05				
64	3540a	9.38E-05	0.00009245	4.6	2.0098E-05	2.18051E-05
65		9.17E-05				
66		9.18E-05				
67	3540b	1.42E-04	0.0001413	5.1	2.7706E-05	
68		1.41E-04				
69		1.42E-04				
70	3540c	9.61E-05	9.51033E-05	5.4	1.7612E-05	
71		9.49E-05				
72		9.43E-05				
73	4045a	1.08E-04	0.000108	5.6	1.9286E-05	2.09853E-05
74		1.07E-04				
75		1.09E-04				
76	4045b	1.18E-04	0.000118433	4.5	2.6319E-05	
77		1.17E-04				
78		1.20E-04				
79	4045c	8.94E-05	8.84933E-05	5.1	1.7352E-05	
80		8.72E-05				
81		8.89E-05				
82	4550a	1.32E-04	0.0001307	4.9	2.6673E-05	2.4657E-05
83		1.31E-04				
84		1.29E-04				
85	4550b	1.30E-04	0.000128733	5.5	2.3406E-05	
86		1.27E-04				
87		1.29E-04				
88	4550c	1.03E-04	0.000102733	4.3	2.3891E-05	
89		1.02E-04				
90		1.04E-04				
91	5055a	1.24E-04	0.000123467	5.4	2.2864E-05	2.59078E-05
92		1.24E-04				
93		1.22E-04				
94	5055b	1.16E-04	0.000114333	3.7	3.0901E-05	
95		1.13E-04				
96		1.14E-04				
97	5055c	1.14E-04	0.000115	4.8	2.3958E-05	

98		1.17E-04				
99		1.13E-04				
100	5560a	1.30E-04	0.000129533	4.7	2.756E-05	2.83789E-05
101		1.29E-04				
102		1.30E-04				
103	5560b	1.43E-04	0.000142267	4.8	2.9639E-05	
104		1.42E-04				
105		1.42E-04				
106	5560c	1.35E-04	0.0001341	4.8	2.7938E-05	
107		1.33E-04				
108		1.34E-04				
109	6065a	2.18E-04	0.000217367	5.5	3.9521E-05	3.77008E-05
110		2.18E-04				
111		2.16E-04				
112	6065b	1.63E-04	0.0001628	4.5	3.6178E-05	
113		1.61E-04				
114		1.64E-04				
115	6065c	1.47E-04	0.000142133	3.8	3.7404E-05	
116		1.35E-04				
117		1.44E-04				
118	6570a	2.39E-04	0.000238067	5	4.7613E-05	5.03241E-05
119		2.38E-04				
120		2.37E-04				
121	6570b	2.98E-04	0.0002975	5.6	5.3125E-05	
122		2.99E-04				
123		2.96E-04				
124	6570c	2.38E-04	0.0002361	4.7	5.0234E-05	
125		2.35E-04				
126		2.36E-04				
127	100a	6.46E-04	0.0006468	6.4	0.00010106	9.05213E-05
128		6.48E-04				
129		6.47E-04				
130	100b	4.48E-04	0.000448	5.7	7.8596E-05	
131		4.48E-04				
132		4.48E-04				
133	100c	5.79E-04	0.000579	6.3	9.1905E-05	
134		5.79E-04				
135		5.79E-04				

Queimada, Soil Test Pit 1

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.51E-04	0.0002507	10	0.00002507	2.60485E-05
2		2.51E-04				
3		2.50E-04				
4	05B	2.08E-04	0.000208067	8.2	2.5374E-05	
5		2.08E-04				
6		2.08E-04				
7	05C	2.66E-04	0.000265933	9.6	2.7701E-05	
8		2.66E-04				
9		2.66E-04				
10	510A	2.38E-04	0.000237733	9.2	2.5841E-05	2.58716E-05
11		2.38E-04				
12		2.38E-04				
13	510B	2.47E-04	0.000247433	9.9	2.4993E-05	
14		2.47E-04				
15		2.48E-04				
16	510C	2.73E-04	0.000273167	10.2	2.6781E-05	
17		2.73E-04				
18		2.73E-04				
19	1015A	2.47E-04	0.000247333	9.9	2.4983E-05	2.43406E-05
20		2.47E-04				
21		2.47E-04				
22	1015B	2.81E-04	0.000281233	10.7	2.6283E-05	
23		2.81E-04				
24		2.81E-04				
25	1015C	1.72E-04	0.000171867	7.9	2.1755E-05	
26		1.72E-04				
27		1.72E-04				
28	1520A	3.03E-04	0.000303367	11.4	2.6611E-05	2.44683E-05
29		3.04E-04				
30		3.03E-04				
31	1520B	2.40E-04	0.0002399	9.9	2.4232E-05	
32		2.40E-04				
33		2.40E-04				
34	1520C	2.15E-04	0.000214333	9.5	2.2561E-05	
35		2.14E-04				
36		2.14E-04				

Queimada, Soil Test Pit 2

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.78E-04	0.000278467	8.9	3.12884E-05	3.18959E-05
2		2.77E-04				
3		2.80E-04				
4	05B	2.91E-04	0.000291233	8.8	3.30947E-05	
5		2.91E-04				
6		2.91E-04				
7	05C	3.28E-04	0.0003287	10.5	3.13048E-05	
8		3.29E-04				
9		3.29E-04				
10	510A	2.65E-04	0.000264767	9	2.94185E-05	3.24073E-05
11		2.65E-04				
12		2.65E-04				
13	510B	3.22E-04	0.0003216	10.1	3.18416E-05	
14		3.21E-04				
15		3.22E-04				
16	510C	3.78E-04	0.0003776	10.5	3.59619E-05	
17		3.77E-04				
18		3.77E-04				
19	1015A	7.81E-05	7.80767E-05	7.4	1.05509E-05	1.11713E-05
20		7.81E-05				
21		7.81E-05				
22	1015B	1.34E-04	0.0001338	9.7	1.37938E-05	
23		1.34E-04				
24		1.34E-04				
25	1015C	8.16E-05	8.16067E-05	8.9	9.16929E-06	
26		8.16E-05				
27		8.16E-05				

Queimada, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.37E-04	0.000236867	9.1	2.6029E-05	2.61596E-05
2		2.37E-04				
3		2.37E-04				
4	05B	2.12E-04	0.000211633	8.4	2.5194E-05	
5		2.12E-04				
6		2.12E-04				
7	05C	2.67E-04	0.0002671	9.8	2.7255E-05	
8		2.67E-04				
9		2.67E-04				
10	510A	2.12E-04	0.000211733	9.9	2.1387E-05	2.53867E-05
11		2.12E-04				
12		2.12E-04				
13	510B	3.42E-04	0.0003417	10.8	3.1639E-05	
14		3.42E-04				
15		3.42E-04				
16	510C	2.01E-04	0.000201267	8.7	2.3134E-05	
17		2.01E-04				
18		2.01E-04				
19	1012A	2.95E-04	0.000294533	10.3	2.8595E-05	2.38646E-05
20		2.95E-04				
21		2.95E-04				
22	1012B	2.12E-04	0.000212233	9.9	2.1438E-05	
23		2.12E-04				
24		2.13E-04				
25	1012C	2.30E-04	0.0002307	10.7	2.1561E-05	
26		2.32E-04				
27		2.31E-04				

Queimada, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.11E-04	0.0002106	7.4	2.8459E-05	3.3139E-05
2		2.11E-04				
3		2.11E-04				
4	05B	2.44E-04	0.000243667	6.8	3.5833E-05	
5		2.44E-04				
6		2.43E-04				
7	05C	2.57E-04	0.0002564	7.3	3.5123E-05	
8		2.56E-04				
9		2.56E-04				
10	510A	2.00E-04	0.000198533	7.4	2.6829E-05	3.141E-05
11		1.98E-04				
12		1.98E-04				
13	510B	2.15E-04	0.000214933	6.4	3.3583E-05	
14		2.15E-04				
15		2.15E-04				
16	510C	2.40E-04	0.0002401	7.1	3.3817E-05	
17		2.40E-04				
18		2.40E-04				
19	1015A	1.92E-04	0.0001922	6.5	2.9569E-05	3.5438E-05
20		1.92E-04				
21		1.92E-04				
22	1015B	3.46E-04	0.000345433	7	4.9348E-05	
23		3.46E-04				
24		3.45E-04				
25	1015C	1.98E-04	0.000197267	7.2	2.7398E-05	
26		1.97E-04				
27		1.97E-04				
28	1520A	3.09E-04	0.000309667	7.7	4.0216E-05	3.3054E-05
29		3.10E-04				
30		3.10E-04				
31	1520B	2.19E-04	0.000219167	7.2	3.044E-05	
32		2.19E-04				
33		2.19E-04				
34	1520C	2.11E-04	0.000210933	7.4	2.8505E-05	
35		2.11E-04				
36		2.11E-04				
37	2025A	2.18E-04	0.000217233	7.8	2.785E-05	2.6511E-05
38		2.17E-04				
39		2.17E-04				
40	2025B	1.82E-04	0.000181733	6.3	2.8847E-05	
41		1.81E-04				
42		1.81E-04				
43	2025C	1.65E-04	0.000165567	7.25	2.2837E-05	
44		1.66E-04				
45		1.66E-04				
49	2530A2	2.02E-04	0.000201967	7.4	2.7293E-05	2.9442E-05
50		2.02E-04				

51		2.02E-04				
52	2530B	1.72E-04	0.000171867	5.6	3.069E-05	
53		1.72E-04				
54		1.72E-04				
55	2530C	2.18E-04	0.000218467	7.2	3.0343E-05	
56		2.19E-04				
57		2.18E-04				
58	3035A	1.69E-04	0.0001687	7.6	2.2197E-05	2.8621E-05
59		1.69E-04				
60		1.68E-04				
61	3035B	2.26E-04	0.000226	6.2	3.6452E-05	
62		2.26E-04				
63		2.26E-04				
64	3035C	2.13E-04	0.000212267	7.8	2.7214E-05	
65		2.12E-04				
66		2.12E-04				
67	3540A	1.82E-04	0.000181867	7.5	2.4249E-05	3.0284E-05
68		1.82E-04				
69		1.82E-04				
70	3540B	1.67E-04	0.000167067	5.7	2.931E-05	
71		1.67E-04				
72		1.68E-04				
73	3540C	2.47E-04	0.000246133	6.6	3.7293E-05	
74		2.45E-04				
75		2.46E-04				
76	4045A	1.25E-04	0.000125167	5.9	2.1215E-05	2.6772E-05
77		1.25E-04				
78		1.25E-04				
79	4045B	2.41E-04	0.000240033	7.2	3.3338E-05	
80		2.40E-04				
81		2.40E-04				
82	4045C	1.75E-04	0.0001752	6.8	2.5765E-05	
83		1.75E-04				
84		1.75E-04				
88	4550B	9.99E-05	0.000100363	5.9	1.7011E-05	1.7723E-05
89		1.00E-04				
90		1.01E-04				
91	4550A2	1.12E-04	0.000111767	7.1	1.5742E-05	
92		1.12E-04				
93		1.12E-04				
94	4550C	1.33E-04	0.0001327	6.5	2.0415E-05	
95		1.33E-04				
96		1.33E-04				

Queimada, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	1.91E-04	0.000191233	5.8	3.29713E-05	4.02277E-05
2		1.91E-04				
3		1.92E-04				
4	05B	3.20E-04	0.000319	5.8	0.000055	
5		3.20E-04				
6		3.18E-04				
7	05C	2.42E-04	0.000242067	7.4	3.27117E-05	
8		2.42E-04				
9		2.43E-04				
10	510A	1.94E-04	0.000193733	7	2.76762E-05	4.40175E-05
11		1.94E-04				
12		1.94E-04				
13	510B	2.82E-04	0.000281967	6.2	4.54785E-05	
14		2.82E-04				
15		2.82E-04				
16	510C	2.89E-04	0.0002886	4.9	5.8898E-05	
17		2.89E-04				
18		2.89E-04				
19	1015A	2.39E-04	0.000239167	7.3	3.27626E-05	3.72442E-05
20		2.39E-04				
21		2.39E-04				
22	1015B	2.77E-04	0.000276867	7.8	3.54957E-05	
23		2.77E-04				
24		2.77E-04				
25	1015C	3.39E-04	0.0003391	7.8	4.34744E-05	
26		3.39E-04				
27		3.40E-04				
28	1520A	2.35E-04	0.0002349	6.5	3.61385E-05	3.7694E-05
29		2.35E-04				
30		2.35E-04				
31	1520B	2.23E-04	0.000223233	7.8	2.86197E-05	
32		2.23E-04				
33		2.23E-04				
34	1520C	3.38E-04	0.000338267	7	4.83238E-05	
35		3.38E-04				
36		3.38E-04				
37	2025A	1.42E-04	0.000142167	4.9	2.90136E-05	3.53761E-05
38		1.42E-04				
39		1.43E-04				
40	2025B	1.61E-04	0.0001617	5.3	3.05094E-05	
41		1.62E-04				
42		1.61E-04				
43	2025C	3.54E-04	0.0003542	7.6	4.66053E-05	
44		3.53E-04				
45		3.55E-04				
46	2530A	8.39E-05	8.39667E-05	3.8	2.20965E-05	2.15364E-05
47		8.39E-05				

48		8.40E-05				
49	2530B	1.24E-04	0.000123833	5.7	2.17251E-05	
50		1.24E-04				
51		1.24E-04				
52	2530C	8.94E-05	8.93867E-05	4.3	2.07876E-05	
53		8.94E-05				
54		8.94E-05				
55	3035A	1.26E-04	0.0001261	6	2.10167E-05	2.10763E-05
56		1.26E-04				
57		1.26E-04				
58	3035B	1.50E-04	0.000150633	6.5	2.31744E-05	
59		1.51E-04				
60		1.51E-04				
61	3035C	8.56E-05	0.00008567	4.5	1.90378E-05	
62		8.56E-05				
63		8.58E-05				
64	3540A	9.38E-05	9.37333E-05	5.4	1.7358E-05	2.51758E-05
65		9.37E-05				
66		9.37E-05				
67	3540B	1.49E-04	0.000149267	6.1	2.44699E-05	
68		1.49E-04				
69		1.49E-04				
70	3540C	2.06E-04	0.000205567	6.1	3.36995E-05	
71		2.05E-04				
72		2.05E-04				
73	4045A	1.20E-04	0.0001196	5.5	2.17455E-05	2.05876E-05
74		1.20E-04				
75		1.19E-04				
76	4045B	8.41E-05	0.00008395	4.5	1.86556E-05	
77		8.39E-05				
78		8.39E-05				
79	4045C	1.00E-04	0.0001004	4.7	2.13617E-05	
80		1.00E-04				
81		1.00E-04				
82	4550A	2.02E-04	0.000201467	5.7	3.5345E-05	2.68444E-05
83		2.02E-04				
84		2.01E-04				
85	4550B	1.44E-04	0.0001434	6.3	2.27619E-05	
86		1.43E-04				
87		1.43E-04				
88	4550C	1.37E-04	0.0001368	6.1	2.24262E-05	
89		1.37E-04				
90		1.37E-04				
91	5055A	2.90E-04	0.0002907	6.5	4.47231E-05	3.08273E-05
92		2.90E-04				
93		2.92E-04				
94	5055B	9.51E-05	9.53467E-05	4.5	2.11881E-05	
95		9.51E-05				
96		9.58E-05				
97	5055C	1.57E-04	0.000156767	5.9	2.65706E-05	

98		1.57E-04				
99		1.57E-04				
100	5560A	1.49E-04	0.000148633	5.8	2.56264E-05	2.96122E-05
101		1.49E-04				
102		1.49E-04				
103	5560B	1.25E-04	0.0001245	5	0.0000249	
104		1.25E-04				
105		1.25E-04				
106	5560C	1.65E-04	0.000164733	4.3	3.83101E-05	
107		1.65E-04				
108		1.65E-04				
109	6065A	1.18E-04	0.000118267	4.7	2.51631E-05	3.14078E-05
110		1.18E-04				
111		1.18E-04				
112	6065B	1.14E-04	0.0001144	5.5	0.0000208	
113		1.14E-04				
114		1.14E-04				
115	6065C	1.98E-04	0.000197867	4.1	4.82602E-05	
116		1.98E-04				
117		1.98E-04				
118	6570A	7.94E-05	7.86833E-05	4.2	1.87341E-05	3.21146E-05
119		7.79E-05				
120		7.87E-05				
121	6570B	9.70E-05	0.00009757	4.2	2.3231E-05	
122		9.76E-05				
123		9.82E-05				
124	6570C	2.39E-04	0.000239267	4.4	5.43788E-05	
125		2.39E-04				
126		2.39E-04				
127	7075A	8.63E-05	8.63933E-05	5.3	1.63006E-05	1.81892E-05
128		8.64E-05				
129		8.65E-05				
130	7075B	8.99E-05	8.98733E-05	5.2	1.72833E-05	
131		8.99E-05				
132		8.99E-05				
133	7075C	1.28E-04	0.000128	6.1	2.09836E-05	
134		1.28E-04				
135		1.28E-04				
136	7580A	6.42E-05	6.41533E-05	4.4	1.45803E-05	1.46453E-05
137		6.42E-05				
138		6.41E-05				
139	7580B	6.28E-05	0.00006277	5.5	1.14127E-05	
140		6.28E-05				
141		6.28E-05				
142	7580C	7.54E-05	0.00007536	4.2	1.79429E-05	
143		7.54E-05				
144		7.53E-05				
145	8085A	7.74E-05	7.73967E-05	6.1	1.2688E-05	1.34881E-05
146		7.74E-05				
147		7.74E-05				

148	8085B	4.53E-05	4.53067E-05	3.8	1.19228E-05	
149		4.53E-05				
150		4.53E-05				
151	8085C	5.23E-05	5.23167E-05	3.3	1.58535E-05	
152		5.24E-05				
153		5.23E-05				
154	8590A	7.00E-05	7.00333E-05	5.5	1.27333E-05	1.49013E-05
155		7.00E-05				
156		7.00E-05				
157	8590B	9.56E-05	0.00009498	4.6	2.06478E-05	
158		9.50E-05				
159		9.43E-05				
160	8590C	5.66E-05	5.66133E-05	5	1.13227E-05	
161		5.66E-05				
162		5.66E-05				
163	9095A	7.69E-05	7.69333E-05	5.3	1.45157E-05	1.3201E-05
164		7.70E-05				
165		7.69E-05				
166	9095B	7.83E-05	7.82833E-05	5.9	1.32684E-05	
167		7.83E-05				
168		7.83E-05				
169	9095C	6.03E-05	6.02767E-05	5.1	1.1819E-05	
170		6.03E-05				
171		6.03E-05				

Queimada, Site Soil

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.78E-04	0.0002767	8.5	3.2553E-05	3.37676E-05
2		2.76E-04				
3		2.76E-04				
4	05B	2.30E-04	0.000230033	8.2	2.8053E-05	
5		2.30E-04				
6		2.30E-04				
7	05C	3.58E-04	0.000358133	8.8	4.0697E-05	
8		3.58E-04				
9		3.58E-04				
10	510A	2.49E-04	0.000249133	7.9	3.1536E-05	3.20707E-05
11		2.50E-04				
12		2.49E-04				
13	510B	2.76E-04	0.000275367	8.9	3.094E-05	
14		2.76E-04				
15		2.75E-04				
16	510C	3.24E-04	0.000323867	9.6	3.3736E-05	
17		3.24E-04				
18		3.24E-04				
19	1015A	4.60E-04	0.000459267	9.2	4.992E-05	5.2966E-05
20		4.59E-04				
21		4.59E-04				
22	1015B	4.13E-04	0.000413267	9.1	4.5414E-05	
23		4.13E-04				
24		4.13E-04				
25	1015C	5.98E-04	0.0005975	9.4	6.3564E-05	
26		5.97E-04				
27		5.98E-04				
28	1520A	4.58E-04	0.000457533	9.6	4.766E-05	4.69808E-05
29		4.58E-04				
30		4.58E-04				
31	1520B	2.84E-04	0.0002844	8.6	3.307E-05	
32		2.84E-04				
33		2.85E-04				
34	1520C	4.99E-04	0.000499767	8.3	6.0213E-05	
35		4.99E-04				
36		5.01E-04				
37	2025A	4.94E-04	0.000494067	8.5	5.8125E-05	4.05871E-05
38		4.94E-04				
39		4.95E-04				
40	2025B	3.32E-04	0.000332067	9.2	3.6094E-05	
41		3.32E-04				
42		3.32E-04				
43	2025C	1.98E-04	0.0001983	7.2	2.7542E-05	
44		1.98E-04				
45		1.99E-04				
46	2530A	4.34E-04	0.000434267	9.9	4.3865E-05	4.55844E-05
47		4.34E-04				

48		4.35E-04				
49	2530B	4.15E-04	0.0004151	9.3	4.4634E-05	
50		4.15E-04				
51		4.15E-04				
52	2530C	4.82E-04	0.000482533	10	4.8253E-05	
53		4.82E-04				
54		4.83E-04				
55	3035A	3.83E-04	0.000383167	10.2	3.7565E-05	3.63399E-05
56		3.83E-04				
57		3.83E-04				
58	3035B	3.36E-04	0.000335567	9.4	3.5699E-05	
59		3.36E-04				
60		3.36E-04				
61	3035C	3.08E-04	0.0003075	8.6	3.5756E-05	
62		3.08E-04				
63		3.07E-04				
64	3540A	2.74E-04	0.000273833	9.1	3.0092E-05	3.60172E-05
65		2.74E-04				
66		2.74E-04				
67	3540B	3.09E-04	0.000308333	9.3	3.3154E-05	
68		3.08E-04				
69		3.08E-04				
70	3540C	4.07E-04	0.000407733	9.1	4.4806E-05	
71		4.08E-04				
72		4.09E-04				
73	4045A	4.26E-04	0.0004254	9.4	4.5255E-05	4.55657E-05
74		4.26E-04				
75		4.25E-04				
76	4045B	3.85E-04	0.000384567	8.8	4.3701E-05	
77		3.83E-04				
78		3.86E-04				
79	4045C	4.92E-04	0.000491733	10.3	4.7741E-05	
80		4.92E-04				
81		4.91E-04				
82	4550A	3.35E-04	0.000335367	9.8	3.4221E-05	3.44881E-05
83		3.36E-04				
84		3.35E-04				
85	4550B	4.81E-04	0.000480767	9.3	5.1695E-05	
86		4.80E-04				
87		4.81E-04				
88	4550C	1.53E-04	0.000152667	8.7	1.7548E-05	
89		1.53E-04				
90		1.53E-04				
91	5055A	1.72E-04	0.000171667	9	1.9074E-05	1.99378E-05
92		1.72E-04				
93		1.72E-04				
94	5055B	2.21E-04	0.0002209	9.4	0.0000235	
95		2.21E-04				
96		2.21E-04				
97	5055C	1.47E-04	0.000146533	8.5	1.7239E-05	

98	1.47E-04
99	1.47E-04

1992 Survey Area, Slope 1, Soil Test Pits 1 & 2 (combined)

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	4.22E-04	0.000418	5.1	8.1961E-05	8.37994E-05
2		4.13E-04				
3		4.19E-04				
4	05B	3.44E-04	0.000347933	4.4	7.9076E-05	
5		3.50E-04				
6		3.50E-04				
7	05C	4.25E-04	0.0004247	4.7	9.0362E-05	
8		4.25E-04				
9		4.25E-04				
10	510A	4.34E-04	0.0004335	5.7	7.6053E-05	8.10999E-05
11		4.34E-04				
12		4.33E-04				
13	510B	4.62E-04	0.0004615	5.9	7.822E-05	
14		4.62E-04				
15		4.61E-04				
16	510C	4.45E-04	0.000445133	5	8.9027E-05	
17		4.45E-04				
18		4.45E-04				
19	1015A	4.32E-04	0.000432233	5.1	8.4752E-05	8.22666E-05
20		4.32E-04				
21		4.32E-04				
22	1015B	4.15E-04	0.000414833	4.7	8.8262E-05	
23		4.15E-04				
24		4.15E-04				
25	1015C	5.16E-04	0.0005165	7	7.3786E-05	
26		5.17E-04				
27		5.17E-04				

1992 Survey Area, Slope 1, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	4.10E-04	0.0004098	4.5	9.1067E-05	9.2742E-05
2		4.09E-04				
3		4.10E-04				
4	05B	4.49E-04	0.0004487	5.2	8.6288E-05	
5		4.48E-04				
6		4.49E-04				
7	05C	5.24E-04	0.000524533	5.2	0.00010087	
8		5.24E-04				
9		5.25E-04				
10	510A	4.24E-04	0.000421833	4.1	0.00010289	0.00010591
11		4.24E-04				
12		4.17E-04				
13	510B	4.71E-04	0.0004706	4.7	0.00010013	
14		4.71E-04				
15		4.70E-04				
16	510C	5.85E-04	0.000585067	5.1	0.00011472	
17		5.85E-04				
18		5.85E-04				
19	1015A	5.25E-04	0.000525267	5	0.00010505	0.00010348
20		5.25E-04				
21		5.25E-04				
22	1015B	5.82E-04	0.0005823	5.8	0.0001004	
23		5.83E-04				
24		5.82E-04				
25	1015C	4.94E-04	0.000493467	4.7	0.00010499	
26		4.93E-04				
27		4.93E-04				

1992 Survey Area, Slope 1, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	4.10E-04	0.000411733	5	8.2347E-05	0.00010923
2		4.16E-04				
3		4.09E-04				
4	05B	4.95E-04	0.000495133	5.1	9.7085E-05	
5		4.95E-04				
6		4.95E-04				
7	05C	8.45E-04	0.000845	5.7	0.00014825	
8		8.45E-04				
9		8.45E-04				
10	510A	3.28E-04	0.000329833	4	8.2458E-05	0.00011236
11		3.28E-04				
12		3.33E-04				
13	510B	6.43E-04	0.000642067	4.9	0.00013103	
14		6.42E-04				
15		6.41E-04				
16	510C	5.19E-04	0.000519067	4.2	0.00012359	
17		5.19E-04				
18		5.19E-04				
19	1015A	5.83E-04	0.0005828	5.2	0.00011208	0.00010827
20		5.83E-04				
21		5.83E-04				
22	1015B	5.91E-04	0.0005908	5.5	0.00010742	
23		5.91E-04				
24		5.91E-04				
25	1015C	5.47E-04	0.000547633	5.2	0.00010531	
26		5.48E-04				
27		5.48E-04				
28	1520A	5.55E-04	0.000554867	5	0.00011097	9.7027E-05
29		5.55E-04				
30		5.55E-04				
31	1520B	5.19E-04	0.0005192	5.9	0.000088	
32		5.20E-04				
33		5.19E-04				
34	1520C	4.79E-04	0.000478967	5.2	9.2109E-05	
35		4.79E-04				
36		4.79E-04				
37	2025A	4.22E-04	0.000421833	5.1	8.2712E-05	9.348E-05
38		4.22E-04				
39		4.22E-04				
40	2025B	5.58E-04	0.000557967	6.5	8.5841E-05	
41		5.58E-04				
42		5.58E-04				
43	2025C	6.53E-04	0.000648933	5.8	0.00011189	
44		6.53E-04				
45		6.41E-04				
46	2530A	2.08E-04	0.000206633	3.8	5.4377E-05	5.7564E-05
47		2.06E-04				

48		2.06E-04				
49	2530B	2.45E-04	0.000244033	4.2	5.8103E-05	
50		2.44E-04				
51		2.44E-04				
52	2530C	3.67E-04	0.0003673	6.1	6.0213E-05	
53		3.67E-04				
54		3.67E-04				
55	3035A	1.40E-04	0.000139167	6.3	2.209E-05	2.0648E-05
56		1.39E-04				
57		1.39E-04				
58	3035B	1.03E-04	0.000102333	5	2.0467E-05	
59		1.02E-04				
60		1.03E-04				
61	3035C	9.79E-05	9.88733E-05	5.1	1.9387E-05	
62		9.93E-05				
63		9.94E-05				
64	3540A	4.37E-05	4.22533E-05	3	1.4084E-05	1.4363E-05
65		3.97E-05				
66		4.33E-05				
67	3540B	6.43E-05	6.51833E-05	4.4	1.4814E-05	
68		6.63E-05				
69		6.50E-05				
70	3540C	6.10E-05	0.00006102	4.3	1.4191E-05	
71		6.10E-05				
72		6.10E-05				
73	4045A	6.54E-05	6.54033E-05	4.9	1.3348E-05	1.3489E-05
74		6.53E-05				
75		6.55E-05				
76	4045B	8.22E-05	8.22133E-05	5.9	1.3934E-05	
77		8.23E-05				
78		8.22E-05				
79	4045C	6.46E-05	0.00006461	4.9	1.3186E-05	
80		6.46E-05				
81		6.47E-05				
82	4550A	6.32E-05	6.09733E-05	5.3	1.1504E-05	1.1484E-05
83		6.05E-05				
84		5.92E-05				
85	4550B	3.60E-05	3.45533E-05	3	1.1518E-05	
86		3.39E-05				
87		3.38E-05				
88	4550C	5.88E-05	5.71467E-05	5	1.1429E-05	
89		5.82E-05				
90		5.45E-05				
91	5055A	6.19E-05	6.10667E-05	5.6	1.0905E-05	1.111E-05
92		6.07E-05				
93		6.07E-05				
94	5055B	5.76E-05	0.00005603	4.9	1.1435E-05	
95		5.52E-05				
96		5.53E-05				
97	5055C	6.45E-05	6.37533E-05	5.8	1.0992E-05	

98		6.33E-05				
99		6.35E-05				
100	5560A	5.08E-05	5.05133E-05	4.4	1.148E-05	1.1089E-05
101		5.04E-05				
102		5.04E-05				
103	5560B	4.89E-05	0.00004852	4.4	1.1027E-05	
104		4.84E-05				
105		4.83E-05				
106	5560C	5.99E-05	6.02567E-05	5.6	1.076E-05	
107		6.04E-05				
108		6.05E-05				

1992 Survey Area, Slope 1, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	6.99E-04	0.000696867	5.2	0.00013401	0.00012105
2		6.96E-04				
3		6.96E-04				
4	05B	7.09E-04	0.000708967	6	0.00011816	
5		7.09E-04				
6		7.09E-04				
7	05C	4.99E-04	0.000499333	4.5	0.00011096	
8		5.00E-04				
9		5.00E-04				
10	510A	6.11E-04	0.000613833	4.9	0.00012527	0.0001306
11		6.12E-04				
12		6.19E-04				
13	510B	7.89E-04	0.000789233	5.3	0.00014891	
14		7.89E-04				
15		7.89E-04				
16	510C	6.60E-04	0.000658567	5.6	0.0001176	
17		6.56E-04				
18		6.60E-04				
19	1015A	6.50E-04	0.000650267	5	0.00013005	0.0001213
20		6.51E-04				
21		6.50E-04				
22	1015B	6.03E-04	0.000603467	5.2	0.00011605	
23		6.04E-04				
24		6.03E-04				
25	1015C	5.06E-04	0.000506567	4.3	0.00011781	
26		5.07E-04				
27		5.07E-04				
28	1520A	5.16E-04	0.0005154	4.7	0.00010966	0.00013177
29		5.15E-04				
30		5.16E-04				
31	1520B	6.40E-04	0.000635067	4.8	0.00013231	
32		6.39E-04				
33		6.27E-04				
34	1520C	8.27E-04	0.0008281	5.4	0.00015335	
35		8.31E-04				
36		8.27E-04				
37	2025A	4.71E-04	0.0004725	6.6	7.1591E-05	7.3239E-05
38		4.72E-04				
39		4.75E-04				
40	2025B	4.22E-04	0.000423067	5.3	7.9824E-05	
41		4.24E-04				
42		4.24E-04				
43	2025C	3.84E-04	0.0003825	5.6	6.8304E-05	
44		3.81E-04				
45		3.83E-04				
46	2530A	3.05E-04	0.000305133	5.2	5.8679E-05	7.2366E-05
47		3.05E-04				

48		3.05E-04				
49	2530B	4.51E-04	0.0004499	5.1	8.8216E-05	
50		4.52E-04				
51		4.46E-04				
52	2530C	3.37E-04	0.000336967	4.8	7.0201E-05	
53		3.37E-04				
54		3.37E-04				
55	3035A	3.38E-04	0.000337567	6	5.6261E-05	7.4938E-05
56		3.37E-04				
57		3.38E-04				
58	3035B	3.41E-04	0.0003423	5.4	6.3389E-05	
59		3.42E-04				
60		3.44E-04				
61	3035C	5.58E-04	0.000557367	5.3	0.00010516	
62		5.57E-04				
63		5.57E-04				
64	3540A	4.27E-04	0.000430433	5.3	8.1214E-05	7.6381E-05
65		4.33E-04				
66		4.31E-04				
67	3540B	4.32E-04	0.000430167	5.8	7.4167E-05	
68		4.29E-04				
69		4.29E-04				
70	3540C	4.35E-04	0.0004352	5.9	7.3763E-05	
71		4.37E-04				
72		4.33E-04				
73	4045A	2.12E-04	0.000212133	4.3	4.9333E-05	5.1607E-05
74		2.12E-04				
75		2.13E-04				
76	4045B	3.73E-04	0.0003733	5.9	6.3271E-05	
77		3.73E-04				
78		3.74E-04				
79	4045C	2.42E-04	0.000240633	5.7	4.2216E-05	
80		2.40E-04				
81		2.40E-04				
82	4550A	1.03E-04	0.000101733	3.9	2.6085E-05	2.1733E-05
83		1.01E-04				
84		1.01E-04				
85	4550B	1.26E-04	0.0001258	6	2.0967E-05	
86		1.24E-04				
87		1.27E-04				
88	4550C	8.77E-05	0.0000871	4.8	1.8146E-05	
89		8.66E-05				
90		8.70E-05				
91	5560A	7.58E-05	7.47133E-05	5.4	1.3836E-05	1.5E-05
92		7.37E-05				
93		7.47E-05				
94	5560B	7.52E-05	7.48467E-05	5.4	1.386E-05	
95		7.52E-05				
96		7.42E-05				
97	5560C	8.97E-05	8.99833E-05	5.2	1.7304E-05	

98		9.08E-05				
99		8.94E-05				
100	6065A	7.90E-05	7.78933E-05	5.3	1.4697E-05	1.4457E-05
101		7.74E-05				
102		7.73E-05				
103	6065B	1.01E-04	0.00010013	6.2	0.00001615	
104		1.00E-04				
105		9.90E-05				
106	6065C	7.97E-05	7.88967E-05	6.3	1.2523E-05	
107		7.84E-05				
108		7.87E-05				
109	6570A	5.54E-05	5.44067E-05	4.9	1.1103E-05	1.1936E-05
110		5.39E-05				
111		5.40E-05				
112	6570B	5.93E-05	6.00667E-05	5.2	1.1551E-05	
113		6.15E-05				
114		5.95E-05				
115	6570C	8.03E-05	8.02433E-05	6.1	1.3155E-05	
116		8.10E-05				
117		7.94E-05				
118	7075A	4.94E-05	4.88867E-05	4.2	1.164E-05	1.1321E-05
119		4.98E-05				
120		4.75E-05				
121	7075B	4.95E-05	4.88767E-05	4.6	1.0625E-05	
122		4.94E-05				
123		4.78E-05				
124	7075C	5.48E-05	0.00005381	4.6	1.1698E-05	
125		5.30E-05				
126		5.37E-05				
127	7580A	4.52E-05	0.00004498	4.3	1.046E-05	1.1266E-05
128		4.46E-05				
129		4.52E-05				
130	7580B	5.46E-05	0.0000557	4.4	1.2659E-05	
131		5.59E-05				
132		5.66E-05				
133	7580C	4.68E-05	4.59167E-05	4.3	1.0678E-05	
134		4.55E-05				
135		4.55E-05				

1992 Survey Area, Slope 2, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.31E-04	0.0002312	4.5	5.1378E-05	5.8904E-05
2		2.31E-04				
3		2.32E-04				
4	05B	2.12E-04	0.000211867	3.7	5.7261E-05	
5		2.11E-04				
6		2.13E-04				
7	05C	3.39E-04	0.000340367	5	6.8073E-05	
8		3.42E-04				
9		3.40E-04				
10	510A	2.77E-04	0.0002796	5.5	5.0836E-05	5.2328E-05
11		2.79E-04				
12		2.83E-04				
13	510B	2.95E-04	0.000295633	5.3	5.578E-05	
14		2.94E-04				
15		2.99E-04				
16	510C	3.32E-04	0.000332433	6.6	5.0369E-05	
17		3.33E-04				
18		3.33E-04				
19	1015A	3.42E-04	0.000341033	6.2	5.5005E-05	6.0158E-05
20		3.39E-04				
21		3.42E-04				
22	1015B	3.77E-04	0.000376767	6.8	5.5407E-05	
23		3.77E-04				
24		3.77E-04				
25	1015C	3.38E-04	0.0003363	4.8	7.0063E-05	
26		3.38E-04				
27		3.33E-04				
28	1520A	4.32E-04	0.000433467	7.8	5.5573E-05	6.468E-05
29		4.32E-04				
30		4.36E-04				
31	1520B	3.40E-04	0.000340267	6.3	5.4011E-05	
32		3.40E-04				
33		3.40E-04				
34	1520C	5.93E-04	0.0005912	7	8.4457E-05	
35		5.93E-04				
36		5.88E-04				
37	2025A	3.99E-04	0.0003992	5.9	6.7661E-05	7.2511E-05
38		3.99E-04				
39		3.99E-04				
40	2025B	5.37E-04	0.000536933	6.6	8.1354E-05	
41		5.37E-04				
42		5.37E-04				
43	2025C	3.70E-04	0.00037	5.4	6.8519E-05	
44		3.70E-04				
45		3.70E-04				
46	2530A	2.95E-04	0.0002903	4.5	6.4511E-05	6.0223E-05
47		2.88E-04				

48		2.89E-04				
49	2530B	3.80E-04	0.0003805	5.8	6.5603E-05	
50		3.80E-04				
51		3.81E-04				
52	2530C	2.14E-04	0.000212333	4.2	5.0556E-05	
53		2.11E-04				
54		2.12E-04				
55	3035A	2.64E-04	0.000263133	4.9	5.3701E-05	5.6442E-05
56		2.63E-04				
57		2.62E-04				
58	3035B	2.10E-04	0.000209867	3.8	5.5228E-05	
59		2.09E-04				
60		2.11E-04				
61	3035C	2.53E-04	0.000253667	4.2	6.0397E-05	
62		2.54E-04				
63		2.54E-04				

1992 Survey Area, Slope 2, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.36E-04	0.000236633	5.1	4.6399E-05	4.37719E-05
2		2.37E-04				
3		2.37E-04				
4	05B	2.46E-04	0.0002446	6.2	3.9452E-05	
5		2.48E-04				
6		2.40E-04				
7	05C	2.62E-04	0.0002637	5.8	4.5466E-05	
8		2.68E-04				
9		2.62E-04				
10	510A	4.56E-04	0.0004562	6.9	6.6116E-05	5.53967E-05
11		4.56E-04				
12		4.57E-04				
13	510B	2.87E-04	0.0002868	6.1	4.7016E-05	
14		2.87E-04				
15		2.86E-04				
16	510C	2.77E-04	0.0002759	5.2	5.3058E-05	
17		2.75E-04				
18		2.76E-04				
19	1015A	2.61E-04	0.000263133	5.9	4.4599E-05	6.29131E-05
20		2.60E-04				
21		2.69E-04				
22	1015B	4.34E-04	0.000432733	6.3	6.8688E-05	
23		4.32E-04				
24		4.32E-04				
25	1015C	5.06E-04	0.000505533	6.7	7.5453E-05	
26		5.05E-04				
27		5.06E-04				
28	1520A	2.40E-04	0.000239233	4.7	5.0901E-05	5.5958E-05
29		2.39E-04				
30		2.39E-04				
31	1520B	2.71E-04	0.0002736	4.6	5.9478E-05	
32		2.71E-04				
33		2.79E-04				
34	1520C	1.92E-04	0.000189733	3.3	5.7495E-05	
35		1.89E-04				
36		1.88E-04				
37	2025A	3.75E-04	0.000374633	6	6.2439E-05	7.63933E-05
38		3.74E-04				
39		3.75E-04				
40	2025B	5.25E-04	0.000525	4.7	0.0001117	
41		5.25E-04				
42		5.26E-04				
43	2025C	3.28E-04	0.000330233	6	5.5039E-05	
44		3.28E-04				
45		3.35E-04				
46	2530A	3.25E-04	0.000324933	4.9	6.6313E-05	6.42902E-05
47		3.25E-04				

48		3.25E-04				
49	2530B	3.10E-04	0.0003098	6.1	5.0787E-05	
50		3.10E-04				
51		3.10E-04				
52	2530C	4.84E-04	0.000484933	6.4	7.5771E-05	
53		4.83E-04				
54		4.88E-04				
55	3035A	3.76E-04	0.0003759	7	0.0000537	6.02322E-05
56		3.75E-04				
57		3.76E-04				
58	3035B	3.85E-04	0.000386367	6.6	5.854E-05	
59		3.84E-04				
60		3.90E-04				
61	3035C	3.93E-04	0.0003902	5.7	6.8456E-05	
62		3.93E-04				
63		3.84E-04				
64	3540A	2.65E-04	0.000264467	5.5	4.8085E-05	4.81224E-05
65		2.63E-04				
66		2.66E-04				
67	3540B	2.45E-04	0.000244433	5.3	4.6119E-05	
68		2.44E-04				
69		2.44E-04				
70	3540C	2.16E-04	0.0002157	4.3	5.0163E-05	
71		2.15E-04				
72		2.16E-04				
73	4045A	3.50E-04	0.000348667	6.7	5.204E-05	5.2312E-05
74		3.50E-04				
75		3.46E-04				
76	4045B	3.49E-04	0.000346767	7	4.9538E-05	
77		3.48E-04				
78		3.44E-04				
79	4045C	3.71E-04	0.0003709	6.7	5.5358E-05	
80		3.71E-04				
81		3.71E-04				
82	4550A	3.16E-04	0.000316367	5.5	5.7521E-05	5.13608E-05
83		3.16E-04				
84		3.17E-04				
85	4550B	3.44E-04	0.000346	7.3	4.7397E-05	
86		3.45E-04				
87		3.49E-04				
88	4550C	3.09E-04	0.000309733	6.3	4.9164E-05	
89		3.10E-04				
90		3.11E-04				
91	5055A	2.64E-04	0.0002658	6.3	4.219E-05	5.17026E-05
92		2.64E-04				
93		2.69E-04				
94	5055B	3.24E-04	0.000323933	5.1	6.3516E-05	
95		3.24E-04				
96		3.23E-04				
97	5055C	3.67E-04	0.000365567	7.4	4.9401E-05	

98		3.68E-04				
99		3.62E-04				
100	5560A	4.06E-04	0.000406967	6.9	5.8981E-05	5.39873E-05
101		4.06E-04				
102		4.09E-04				
103	5560B	2.28E-04	0.000226167	4.8	4.7118E-05	
104		2.25E-04				
105		2.26E-04				
106	5560C	3.13E-04	0.000312833	5.6	5.5863E-05	
107		3.13E-04				
108		3.12E-04				
109	6065A	2.34E-04	0.000232933	5.2	4.4795E-05	5.47136E-05
110		2.31E-04				
111		2.35E-04				
112	6065B	4.19E-04	0.000420533	7	6.0076E-05	
113		4.19E-04				
114		4.25E-04				
115	6065C	2.49E-04	0.000248933	4.2	5.927E-05	
116		2.49E-04				
117		2.48E-04				
118	6570A	4.25E-04	0.000420933	6.6	6.3778E-05	5.47061E-05
119		4.25E-04				
120		4.13E-04				
121	6570B	2.15E-04	0.0002134	4.5	4.7422E-05	
122		2.12E-04				
123		2.13E-04				
124	6570C	2.61E-04	0.0002593	4.9	5.2918E-05	
125		2.61E-04				
126		2.56E-04				
127	7075A	2.78E-04	0.0002781	6.3	4.4143E-05	5.49919E-05
128		2.78E-04				
129		2.78E-04				
130	7075B	3.15E-04	0.000314667	6.5	4.841E-05	
131		3.15E-04				
132		3.15E-04				
133	7075C	4.06E-04	0.000405567	5.6	7.2423E-05	
134		4.06E-04				
135		4.05E-04				
136	7580A	2.12E-04	0.000209167	4.9	4.2687E-05	5.18982E-05
137		2.09E-04				
138		2.07E-04				
139	7580B	3.43E-04	0.0003415	5.8	5.8879E-05	
140		3.39E-04				
141		3.43E-04				
142	7580C	3.53E-04	0.000351833	6.5	5.4128E-05	
143		3.52E-04				
144		3.51E-04				
145	8085A	1.81E-04	0.0001808	5.5	3.2873E-05	3.40153E-05
146		1.79E-04				
147		1.82E-04				

148	8085B	1.60E-04	0.0001592	4.6	3.4609E-05	
149		1.59E-04				
150		1.59E-04				
151	8085C	2.15E-04	0.0002143	6.2	3.4565E-05	
152		2.14E-04				
153		2.14E-04				
154	8590A	1.91E-04	0.0001899	6	0.00003165	3.1316E-05
155		1.89E-04				
156		1.89E-04				
157	8590B	2.09E-04	0.000208267	6	3.4711E-05	
158		2.07E-04				
159		2.10E-04				
160	8590C	1.28E-04	0.0001269	4.6	2.7587E-05	
161		1.26E-04				
162		1.26E-04				
163	9095A	1.82E-04	0.000181	6.1	2.9672E-05	2.99096E-05
164		1.81E-04				
165		1.81E-04				
166	9095B	1.59E-04	0.0001577	5	0.00003154	
167		1.57E-04				
168		1.57E-04				
169	9095C	1.72E-04	0.0001711	6	2.8517E-05	
170		1.71E-04				
171		1.71E-04				
172	95100A	8.82E-05	8.63067E-05	3.6	2.3974E-05	2.42276E-05
173		8.60E-05				
174		8.48E-05				
175	95100B	9.74E-05	0.00009583	4.2	2.2817E-05	
176		9.51E-05				
177		9.50E-05				
178	95100C	9.93E-05	0.00009839	3.8	2.5892E-05	
179		9.79E-05				
180		9.80E-05				

1992 Survey Area, Slope 2, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	010A	1.83E-04	0.000182433	4.4	4.1462E-05	3.92607E-05
2		1.82E-04				
3		1.83E-04				
4	010B	2.09E-04	0.0002079	5.4	0.0000385	
5		2.08E-04				
6		2.07E-04				
7	010C	1.90E-04	0.0001891	5	0.00003782	
8		1.89E-04				
9		1.89E-04				
10	1020A	1.84E-04	0.000183433	5	3.6687E-05	4.67629E-05
11		1.83E-04				
12		1.83E-04				
13	1020B	2.00E-04	0.000199533	4.4	4.5348E-05	
14		1.97E-04				
15		2.01E-04				
16	1020C	2.67E-04	0.000267967	4.6	5.8254E-05	
17		2.67E-04				
18		2.69E-04				
19	2030A	1.87E-04	0.0001861	7.5	2.4813E-05	3.04954E-05
20		1.86E-04				
21		1.86E-04				
22	2030B	1.77E-04	0.000176033	5.4	3.2599E-05	
23		1.75E-04				
24		1.76E-04				
25	2030C	2.16E-04	0.000214667	6.3	3.4074E-05	
26		2.14E-04				
27		2.14E-04				
28	3040A	1.45E-04	0.0001438	6.4	2.2469E-05	2.39617E-05
29		1.43E-04				
30		1.44E-04				
31	3040B	1.55E-04	0.000154	5.3	2.9057E-05	
32		1.53E-04				
33		1.54E-04				
34	3040C	1.01E-04	9.97633E-05	4.9	2.036E-05	
35		9.90E-05				
36		9.94E-05				
37	4050A	1.67E-04	0.000165333	5.2	3.1795E-05	4.16741E-05
38		1.66E-04				
39		1.63E-04				
40	4050B	3.91E-04	0.0003926	6.1	6.4361E-05	
41		3.91E-04				
42		3.96E-04				
43	4050C	1.48E-04	0.000144333	5	2.8867E-05	
44		1.42E-04				
45		1.44E-04				
46	5060A	2.50E-04	0.000251833	6.3	3.9974E-05	3.48564E-05
47		2.50E-04				

48		2.56E-04				
49	5060B	2.00E-04	0.0001992	5.7	3.4947E-05	
50		1.97E-04				
51		2.01E-04				
52	5060C	1.61E-04	0.0001601	5.4	2.9648E-05	
53		1.58E-04				
54		1.62E-04				
55	6070A	1.61E-04	0.000159733	5	3.1947E-05	4.13367E-05
56		1.58E-04				
57		1.61E-04				
58	6070B	2.50E-04	0.000250133	5.8	4.3126E-05	
59		2.50E-04				
60		2.50E-04				
61	6070C	2.59E-04	0.000259367	5.3	4.8937E-05	
62		2.60E-04				
63		2.59E-04				
64	7080A	1.39E-04	0.000137667	4.4	3.1288E-05	4.38056E-05
65		1.36E-04				
66		1.39E-04				
67	7080B	2.30E-04	0.0002288	4.3	5.3209E-05	
68		2.28E-04				
69		2.29E-04				
70	7080C	2.72E-04	0.000272133	5.8	4.692E-05	
71		2.72E-04				
72		2.72E-04				
73	8090A	1.35E-04	0.000133867	6.2	2.1591E-05	2.08729E-05
74		1.33E-04				
75		1.33E-04				
76	8090B	8.78E-05	0.0000872	4	0.0000218	
77		8.67E-05				
78		8.71E-05				
79	8090C	8.59E-05	0.0000846	4.4	1.9227E-05	
80		8.39E-05				
81		8.40E-05				
82	90100A	1.24E-04	0.0001223	5.7	2.1456E-05	1.91526E-05
83		1.21E-04				
84		1.22E-04				
85	90100B	1.11E-04	0.0001086	6	0.0000181	
86		1.07E-04				
87		1.08E-04				
88	90100C	1.11E-04	0.0001092	6.1	1.7902E-05	
89		1.09E-04				
90		1.09E-04				

1992 Survey Area, Slope 3, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.71E-04	0.000271167	4.9	5.534E-05	6.16902E-05
2		2.74E-04				
3		2.69E-04				
4	05B	2.90E-04	0.000290567	4.1	7.087E-05	
5		2.91E-04				
6		2.91E-04				
7	05C	2.52E-04	0.0002531	4.3	5.886E-05	
8		2.53E-04				
9		2.54E-04				
10	510A	2.50E-04	0.000254133	5	5.0827E-05	5.32345E-05
11		2.54E-04				
12		2.59E-04				
13	510B	3.02E-04	0.0003047	5.4	5.6426E-05	
14		3.03E-04				
15		3.09E-04				
16	510C	2.68E-04	0.0002675	5.1	5.2451E-05	
17		2.68E-04				
18		2.67E-04				
19	1015A	2.40E-04	0.000239367	4.3	5.5667E-05	5.45833E-05
20		2.39E-04				
21		2.39E-04				
22	1015B	3.31E-04	0.000330467	5.6	5.9012E-05	
23		3.30E-04				
24		3.30E-04				
25	1015C	2.75E-04	0.0002748	5.6	4.9071E-05	
26		2.75E-04				
27		2.75E-04				
28	1520A	1.40E-04	0.000139133	4.5	3.0919E-05	2.82052E-05
29		1.39E-04				
30		1.39E-04				
31	1520B	1.70E-04	0.0001693	6.6	2.5652E-05	
32		1.69E-04				
33		1.69E-04				
34	1520C	1.24E-04	0.0001234	4.4	2.8045E-05	
35		1.23E-04				
36		1.23E-04				

1992 Survey Area, Slope 3, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	3.67E-04	0.000364833	5	7.2967E-05	5.15186E-05
2		3.67E-04				
3		3.60E-04				
4	05B	1.45E-04	0.000142967	4.5	3.177E-05	
5		1.42E-04				
6		1.42E-04				
7	05C	2.83E-04	0.000283967	5.7	4.9819E-05	
8		2.83E-04				
9		2.86E-04				
10	510A	1.74E-04	0.000171133	5.2	3.291E-05	4.53216E-05
11		1.71E-04				
12		1.68E-04				
13	510B	2.47E-04	0.000245733	4.1	5.9935E-05	
14		2.47E-04				
15		2.43E-04				
16	510C	1.72E-04	0.000168167	3.9	4.312E-05	
17		1.67E-04				
18		1.66E-04				
19	1015A	1.65E-04	0.000164033	4.7	3.4901E-05	3.76766E-05
20		1.64E-04				
21		1.63E-04				
22	1015B	2.20E-04	0.000219167	5.5	3.9848E-05	
23		2.19E-04				
24		2.19E-04				
25	1015C	1.47E-04	0.000145467	3.8	3.8281E-05	
26		1.45E-04				
27		1.45E-04				
28	1520A	3.00E-04	0.000301433	6	5.0239E-05	6.26024E-05
29		3.02E-04				
30		3.03E-04				
31	1520B	4.41E-04	0.000441067	4.8	9.1889E-05	
32		4.40E-04				
33		4.42E-04				
34	1520C	2.38E-04	0.000237533	5.2	4.5679E-05	
35		2.38E-04				
36		2.37E-04				
37	2025A	1.80E-04	0.000174567	4.4	3.9674E-05	4.09088E-05
38		1.72E-04				
39		1.72E-04				
40	2025B	1.93E-04	0.000191167	5.2	3.6763E-05	
41		1.92E-04				
42		1.88E-04				
43	2025C	2.46E-04	0.000245333	5.3	4.6289E-05	
44		2.47E-04				
45		2.43E-04				
46	2530A	1.75E-04	0.0001738	4.5	3.8622E-05	4.17593E-05
47		1.73E-04				

48		1.73E-04				
49	2530B	1.73E-04	0.000173233	4.8	3.609E-05	
50		1.72E-04				
51		1.75E-04				
52	2530C	2.87E-04	0.000283167	5.6	5.0565E-05	
53		2.87E-04				
54		2.76E-04				
55	3035A	5.51E-04	0.0005526	4.9	0.00011278	6.0183E-05
56		5.51E-04				
57		5.56E-04				
58	3035B	1.73E-04	0.0001732	5.3	3.2679E-05	
59		1.72E-04				
60		1.75E-04				
61	3035C	1.63E-04	0.000161433	4.6	3.5094E-05	
62		1.62E-04				
63		1.59E-04				
64	3540A	2.32E-04	0.000230433	6.1	3.7776E-05	3.48346E-05
65		2.30E-04				
66		2.30E-04				
67	3540B	1.87E-04	0.0001859	6.4	2.9047E-05	
68		1.86E-04				
69		1.84E-04				
70	3540C	1.76E-04	0.0001771	4.7	3.7681E-05	
71		1.76E-04				
72		1.79E-04				
73	4045A	1.49E-04	0.000145733	6	2.4289E-05	2.65478E-05
74		1.46E-04				
75		1.43E-04				
76	4045B	1.28E-04	0.0001273	4.9	2.598E-05	
77		1.25E-04				
78		1.29E-04				
79	4045C	1.18E-04	0.0001175	4	2.9375E-05	
80		1.17E-04				
81		1.17E-04				
82	4550A	1.28E-04	0.000127067	5.7	2.2292E-05	2.22579E-05
83		1.27E-04				
84		1.27E-04				
85	4550B	1.27E-04	0.000127267	5.6	2.2726E-05	
86		1.26E-04				
87		1.29E-04				
88	4550C	9.30E-05	9.35467E-05	4.3	2.1755E-05	
89		9.20E-05				
90		9.56E-05				
91	5055A	1.57E-04	0.000156133	5.9	2.6463E-05	2.28441E-05
92		1.55E-04				
93		1.57E-04				
94	5055B	1.07E-04	0.000106367	5.6	1.8994E-05	
95		1.06E-04				
96		1.07E-04				
97	5055C	1.14E-04	0.000113067	4.9	2.3075E-05	

98		1.12E-04				
99		1.13E-04				
100	5560A	1.13E-04	0.0001129	5.4	2.0907E-05	2.19481E-05
101		1.13E-04				
102		1.12E-04				
103	5560B	1.54E-04	0.000153733	5.7	2.6971E-05	
104		1.52E-04				
105		1.55E-04				
106	5560C	9.83E-05	9.88133E-05	5.5	1.7966E-05	
107		9.71E-05				
108		1.01E-04				
109	6065A	6.87E-05	6.79067E-05	4.4	1.5433E-05	1.57756E-05
110		6.62E-05				
111		6.89E-05				
112	6065B	7.60E-05	7.40067E-05	4.8	1.5418E-05	
113		7.37E-05				
114		7.24E-05				
115	6065C	7.53E-05	0.00007414	4.5	1.6476E-05	
116		7.35E-05				
117		7.36E-05				
118	6570A	6.71E-05	6.63167E-05	4.5	1.4737E-05	1.46301E-05
119		6.56E-05				
120		6.62E-05				
121	6570B	9.49E-05	9.30367E-05	5.6	1.6614E-05	
122		9.16E-05				
123		9.26E-05				
124	6570C	5.92E-05	5.89367E-05	4.7	1.254E-05	
125		5.89E-05				
126		5.87E-05				
127	7075A	8.80E-05	8.77367E-05	5.7	1.5392E-05	1.38214E-05
128		8.75E-05				
129		8.77E-05				
130	7075B	6.06E-05	5.99767E-05	4.5	1.3328E-05	
131		5.97E-05				
132		5.97E-05				
133	7075C	5.77E-05	5.73467E-05	4.5	1.2744E-05	
134		5.72E-05				
135		5.72E-05				

2004 – 05 Survey Area, Slope 1, Soil Test Pit 2

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	3.86E-04	0.0003863	4	9.6575E-05	0.000111829
2		3.86E-04	0.0004225			
3		3.87E-04	0.000458533			
4	05B	4.94E-04	0.000494267	4.2	0.00011768	
5		4.94E-04	0.000535867			
6		4.94E-04	0.000577267			
7	05C	6.19E-04	0.000618267	5.1	0.00012123	
8		6.19E-04	0.000638767			
9		6.17E-04	0.0006593			
10	510A	6.80E-04	0.000680033	6.4	0.00010626	0.000122914
11		6.80E-04	0.000622967			
12		6.80E-04	0.000565933			
13	510B	5.09E-04	0.000508967	4.8	0.00010603	
14		5.09E-04	0.000589633			
15		5.09E-04	0.000670267			
16	510C	7.51E-04	0.000750967	4.8	0.00015645	
17		7.51E-04	0.000734633			
18		7.51E-04	0.000718533			
19	1015A	7.02E-04	0.000702333	5.2	0.00013506	0.000135381
20		7.03E-04	0.000678333			
21		7.02E-04	0.0006546			
22	1015B	6.30E-04	0.000630667	4.7	0.00013418	
23		6.31E-04	0.0006533			
24		6.30E-04	0.000675533			
25	1015C	6.98E-04	0.000698167	5.1	0.0001369	
26		6.98E-04	0.000677767			
27		6.98E-04	0.000657433			
28	1520A	6.37E-04	0.000637067	6.5	9.801E-05	9.12861E-05
29		6.37E-04	0.000594467			
30		6.37E-04	0.000551867			
31	1520B	5.09E-04	0.0005112	5.4	9.4667E-05	
32		5.09E-04	0.000495167			
33		5.15E-04	0.000480733			
34	1520C	4.61E-04	0.000462733	5.7	8.1181E-05	
35		4.66E-04	0.000309067			
36		4.61E-04	0.000153733			

2004 – 05 Survey Area, Slope 1, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	5.39E-04	0.0005385	4.2	0.00012821	0.000119392
2		5.39E-04	0.0005185			
3		5.38E-04	0.0004983			
4	05B	4.79E-04	0.000478333	4.1	0.00011667	0.000110103
5		4.78E-04	0.000481033			
6		4.78E-04	0.000483933			
7	05C	4.87E-04	0.000487167	4.3	0.00011329	0.000106713
8		4.87E-04	0.0004645			
9		4.88E-04	0.0004419			
10	510A	4.19E-04	0.000421467	4.2	0.00010035	0.000114134
11		4.19E-04	0.000494367			
12		4.27E-04	0.000567367			
13	510B	6.38E-04	0.000638967	6	0.00010649	
14		6.38E-04	0.000647833			
15		6.42E-04	0.000656733			
16	510C	6.64E-04	0.000664233	4.9	0.00013556	
17		6.65E-04	0.0006018			
18		6.64E-04	0.000539167			
19	1015A	4.77E-04	0.000474633	4.4	0.00010787	0.000136329
20		4.77E-04	0.0005508			
21		4.70E-04	0.0006271			
22	1015B	7.05E-04	0.0007057	4.5	0.00015682	
23		7.06E-04	0.0007449			
24		7.06E-04	0.000784467			
25	1015C	8.23E-04	0.000822467	5.7	0.00014429	
26		8.24E-04	0.000788			
27		8.20E-04	0.0007529			
28	1520A	7.20E-04	0.0007194	4.9	0.00014682	0.000147267
29		7.19E-04	0.000754933			
30		7.20E-04	0.000792033			
31	1520B	8.26E-04	0.0008273	5.7	0.00014514	
32		8.30E-04	0.0008609			
33		8.26E-04	0.0008929			
34	1520C	9.27E-04	0.000929033	6.2	0.00014984	
35		9.26E-04	0.000863333			
36		9.34E-04	0.0007978			
37	2025A	7.30E-04	0.000732533	5.2	0.00014087	0.000170646
38		7.30E-04	0.000993267			
39		7.38E-04	0.0012537			
40	2025B	1.51E-03	0.001513667	6.6	0.00022934	
41		1.51E-03	0.001321467			
42		1.52E-03	0.001129567			
43	2025C	9.35E-04	0.000935367	6.6	0.00014172	
44		9.35E-04	0.000772533			
45		9.35E-04	0.000609633			
46	2530A	4.47E-04	0.0004467	5.4	8.2722E-05	8.02204E-05
47		4.47E-04	0.0004211			

48		4.47E-04	0.000395567		
49	2530B	3.70E-04	0.000370167	5	7.4033E-05
50		3.70E-04	0.000395333		
51		3.70E-04	0.000419633		
52	2530C	4.46E-04	0.0004447	5.3	8.3906E-05
53		4.43E-04	0.000296167		
54		4.46E-04	0.000148533		

2004 – 05 Survey Area, Slope 1, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	6.95E-04	0.000694933	4.3	0.00016161	0.000145753
2		6.95E-04				
3		6.95E-04				
4	05B	5.93E-04	0.000592267	4.2	0.00014102	
5		5.92E-04				
6		5.91E-04				
7	05C	7.52E-04	0.000753933	5.6	0.00013463	
8		7.50E-04				
9		7.60E-04				
10	510A	1.02E-03	0.001015667	6.1	0.0001665	0.000182294
11		1.02E-03				
12		1.01E-03				
13	510B	1.38E-03	0.001379667	7.1	0.00019432	
14		1.38E-03				
15		1.38E-03				
16	510C	1.02E-03	0.001023333	5.5	0.00018606	
17		1.02E-03				
18		1.03E-03				
19	1015A	1.00E-03	0.001003333	6	0.00016722	0.000173964
20		1.00E-03				
21		1.00E-03				
22	1015B	9.58E-04	0.000958867	5.7	0.00016822	
23		9.60E-04				
24		9.58E-04				
25	1015C	1.14E-03	0.001137333	6.1	0.00018645	
26		1.14E-03				
27		1.14E-03				
28	1520A	1.33E-03	0.001334333	7.9	0.0001689	0.000167469
29		1.34E-03				
30		1.34E-03				
31	1520B	8.57E-04	0.0008576	5.5	0.00015593	
32		8.56E-04				
33		8.60E-04				
34	1520C	1.17E-03	0.001172	6.6	0.00017758	
35		1.17E-03				
36		1.18E-03				
37	2025A	1.49E-03	0.001481	6.7	0.00022104	0.000185698
38		1.49E-03				
39		1.47E-03				
40	2025B	8.53E-04	0.000853233	5	0.00017065	
41		8.53E-04				
42		8.53E-04				
43	2025C	1.09E-03	0.001091667	6.6	0.0001654	
44		1.09E-03				
45		1.09E-03				
46	2530A	6.80E-04	0.0006759	4.9	0.00013794	0.000156746
47		6.79E-04				

48		6.69E-04				
49	2530B	1.13E-03	0.001124667	6.2	0.0001814	
50		1.13E-03				
51		1.12E-03				
52	2530C	9.07E-04	0.0009054	6	0.0001509	
53		9.07E-04				
54		9.03E-04				
55	3035A	1.04E-03	0.001045667	7	0.00014938	0.000159645
56		1.04E-03				
57		1.05E-03				
58	3035B	9.53E-04	0.0009541	5.9	0.00016171	
59		9.53E-04				
60		9.57E-04				
61	3035C	1.14E-03	0.001141333	6.8	0.00016784	
62		1.14E-03				
63		1.14E-03				
64	3540A	7.61E-04	0.0007614	5.9	0.00012905	0.000138269
65		7.61E-04				
66		7.62E-04				
67	3540B	8.41E-04	0.000841033	5.4	0.00015575	
68		8.41E-04				
69		8.41E-04				
70	3540C	8.72E-04	0.000871067	6.7	0.00013001	
71		8.73E-04				
72		8.68E-04				
73	4045A	6.24E-04	0.000624433	6.4	9.7568E-05	0.000119944
74		6.25E-04				
75		6.25E-04				
76	4045B	1.16E-03	0.001159	6.9	0.00016797	
77		1.16E-03				
78		1.15E-03				
79	4045C	5.56E-04	0.000556333	5.9	9.4294E-05	
80		5.57E-04				
81		5.57E-04				
82	4550A	4.13E-04	0.000413167	5.5	7.5121E-05	7.02252E-05
83		4.14E-04				
84		4.13E-04				
85	4550B	3.79E-04	0.000378467	6.3	6.0074E-05	
86		3.79E-04				
87		3.78E-04				
88	4550C	4.45E-04	0.000445333	5.9	7.548E-05	
89		4.47E-04				
90		4.44E-04				
91	5055A	1.64E-04	0.000163133	5.7	2.862E-05	2.53203E-05
92		1.63E-04				
93		1.62E-04				
94	5055B	1.30E-04	0.000130733	6.8	1.9225E-05	
95		1.30E-04				
96		1.32E-04				
97	5055C	1.47E-04	0.0001462	5.2	2.8115E-05	

98		1.46E-04				
99		1.46E-04				
100	5560A	1.53E-04	0.000152433	6.1	2.4989E-05	3.06268E-05
101		1.52E-04				
102		1.53E-04				
103	5560B	1.69E-04	0.0001689	4.8	3.5188E-05	
104		1.69E-04				
105		1.69E-04				
106	5560C	1.72E-04	0.0001712	5.4	3.1704E-05	
107		1.72E-04				
108		1.70E-04				
109	6065A	1.55E-04	0.0001555	5.8	2.681E-05	1.88196E-05
110		1.54E-04				
111		1.58E-04				
112	6065B	6.20E-05	6.09733E-05	5.1	1.1956E-05	
113		6.04E-05				
114		6.05E-05				
115	6065C	7.52E-05	0.00007431	4.2	1.7693E-05	
116		7.38E-05				
117		7.40E-05				

2004 – 05 Survey Area, Slope 2, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	7.27E-04	0.000733433	5.3	0.00013838	0.000141726
2		7.32E-04				
3		7.42E-04				
4	05B	7.86E-04	0.0007833	5.5	0.00014242	
5		7.82E-04				
6		7.82E-04				
7	05C	7.64E-04	0.0007652	5.3	0.00014438	
8		7.64E-04				
9		7.68E-04				
10	510A	6.90E-04	0.000690267	4.7	0.00014687	0.000136577
11		6.90E-04				
12		6.90E-04				
13	510B	7.23E-04	0.000723133	5.7	0.00012687	
14		7.23E-04				
15		7.23E-04				
16	510C	6.80E-04	0.00068	5	0.000136	
17		6.80E-04				
18		6.80E-04				
19	1015A	6.23E-04	0.000623267	4.8	0.00012985	0.000133478
20		6.23E-04				
21		6.23E-04				
22	1015B	6.47E-04	0.000647567	4.6	0.00014078	
23		6.47E-04				
24		6.48E-04				
25	1015C	6.23E-04	0.0006231	4.8	0.00012981	
26		6.23E-04				
27		6.24E-04				
28	1520A	6.36E-04	0.000636567	5.1	0.00012482	0.000134117
29		6.37E-04				
30		6.37E-04				
31	1520B	6.66E-04	0.000665933	4.7	0.00014169	
32		6.66E-04				
33		6.66E-04				
34	1520C	7.60E-04	0.000760733	5.6	0.00013585	
35		7.61E-04				
36		7.61E-04				
37	2025A	9.97E-04	0.000996367	5.9	0.00016888	0.000149927
38		9.96E-04				
39		9.96E-04				
40	2025B	6.48E-04	0.000649333	4.6	0.00014116	
41		6.50E-04				
42		6.50E-04				
43	2025C	7.54E-04	0.000754633	5.4	0.00013975	
44		7.55E-04				
45		7.55E-04				
46	2530A	3.88E-04	0.0003868	5	0.00007736	8.38655E-05
47		3.86E-04				

48		3.86E-04			
49	2530B	4.12E-04	0.0004145	4.6	9.0109E-05
50		4.12E-04			
51		4.20E-04			
52	2530C	3.96E-04	0.0003954	4.7	8.4128E-05
53		3.95E-04			
54		3.95E-04			

2005 – 05 Survey Area, Slope 2, Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	1.37E-03	0.001378667	4.3	0.00032062	0.00029109
2		1.38E-03				
3		1.38E-03				
4	05B	1.51E-03	0.001507333	5	0.00030147	
5		1.51E-03				
6		1.51E-03				
7	05C	1.41E-03	0.001406667	5.6	0.00025119	
8		1.40E-03				
9		1.41E-03				
10	510A	1.40E-03	0.001397667	4.4	0.00031765	0.00030791
11		1.40E-03				
12		1.40E-03				
13	510B	1.43E-03	0.001427	5.1	0.0002798	
14		1.43E-03				
15		1.43E-03				
16	510C	1.44E-03	0.001435667	4.4	0.00032629	
17		1.44E-03				
18		1.44E-03				
19	1015A	1.50E-03	0.001494333	6.1	0.00024497	0.00023851
20		1.50E-03				
21		1.49E-03				
22	1015B	1.11E-03	0.001115667	4.5	0.00024793	
23		1.11E-03				
24		1.12E-03				
25	1015C	1.18E-03	0.00118	5.3	0.00022264	
26		1.18E-03				
27		1.18E-03				
28	1520A	1.19E-03	0.001194	6.4	0.00018656	0.00019844
29		1.19E-03				
30		1.19E-03				
31	1520B	1.17E-03	0.001175333	6.3	0.00018656	
32		1.17E-03				
33		1.18E-03				
34	1520C	1.22E-03	0.001222	5.5	0.00022218	
35		1.22E-03				
36		1.22E-03				
37	2025A	1.26E-03	0.001262667	6	0.00021044	0.00024997
38		1.26E-03				
39		1.26E-03				
40	2025B	1.50E-03	0.001495	4.7	0.00031809	
41		1.50E-03				
42		1.50E-03				
43	2025C	1.06E-03	0.001062667	4.8	0.00022139	
44		1.06E-03				
45		1.06E-03				
46	2530A	1.37E-03	0.001372667	6	0.00022878	0.00020794
47		1.37E-03				

48		1.37E-03				
49	2530B	1.13E-03	0.001126	6.1	0.00018459	
50		1.13E-03				
51		1.13E-03				
52	2530C	1.10E-03	0.001094333	5.2	0.00021045	
53		1.09E-03				
54		1.09E-03				
55	3035A	1.45E-03	0.00145	6.6	0.0002197	0.0002291
56		1.45E-03				
57		1.45E-03				
58	3035B	1.13E-03	0.001127333	4.9	0.00023007	
59		1.12E-03				
60		1.13E-03				
61	3035C	1.47E-03	0.001472667	6.2	0.00023753	
62		1.47E-03				
63		1.47E-03				
64	3540A	8.68E-04	0.000867333	5.3	0.00016365	0.00018138
65		8.67E-04				
66		8.67E-04				
67	3540B	1.04E-03	0.001034333	5.8	0.00017833	
68		1.03E-03				
69		1.03E-03				
70	3540C	9.71E-04	0.000970433	4.8	0.00020217	
71		9.70E-04				
72		9.71E-04				
73	4045A	1.10E-03	0.001100333	6.6	0.00016672	0.00019342
74		1.10E-03				
75		1.10E-03				
76	4045B	1.59E-03	0.001589	6.8	0.00023368	
77		1.59E-03				
78		1.59E-03				
79	4045C	1.30E-03	0.001295	7.2	0.00017986	
80		1.30E-03				
81		1.30E-03				
82	4550A	7.97E-04	0.000796733	5.1	0.00015622	0.00013632
83		7.97E-04				
84		7.97E-04				
85	4550B	8.33E-04	0.0008334	5.9	0.00014125	
86		8.34E-04				
87		8.33E-04				
88	4550C	6.80E-04	0.00068	6.1	0.00011148	
89		6.80E-04				
90		6.80E-04				
91	5055A	1.73E-04	0.000171733	4.9	3.5048E-05	3.4253E-05
92		1.73E-04				
93		1.69E-04				
94	5055B	1.71E-04	0.000170333	4.8	3.5486E-05	
95		1.69E-04				
96		1.71E-04				
97	5055C	1.62E-04	0.000161133	5	3.2227E-05	

98		1.61E-04				
99		1.61E-04				
100	5560A	9.32E-05	9.29267E-05	6.2	1.4988E-05	1.4444E-05
101		9.26E-05				
102		9.30E-05				
103	5560B	6.44E-05	0.00006397	4.7	1.3611E-05	
104		6.34E-05				
105		6.41E-05				
106	5560C	7.48E-05	0.00007514	5.1	1.4733E-05	
107		7.31E-05				
108		7.75E-05				
109	6065A	6.72E-05	0.00006805	3.9	1.7449E-05	1.7882E-05
110		6.63E-05				
111		7.07E-05				
112	6065B	7.30E-05	7.18333E-05	4.1	1.752E-05	
113		7.11E-05				
114		7.14E-05				
115	6065C	9.17E-05	9.15167E-05	4.9	1.8677E-05	
116		9.24E-05				
117		9.04E-05				
118	6570A	7.33E-05	0.0000722	4.5	1.6044E-05	1.6491E-05
119		7.10E-05				
120		7.23E-05				
121	6570B	7.40E-05	7.34633E-05	4.4	1.6696E-05	
122		7.31E-05				
123		7.33E-05				
124	6570C	8.58E-05	8.53367E-05	5.1	1.6733E-05	
125		8.49E-05				
126		8.53E-05				
127	7075A	7.00E-05	6.99067E-05	4.2	1.6644E-05	1.6724E-05
128		6.96E-05				
129		7.01E-05				
130	7075B	6.03E-05	0.00005948	3.5	1.6994E-05	
131		5.90E-05				
132		5.91E-05				
133	7075C	6.00E-05	0.00005952	3.6	1.6533E-05	
134		5.94E-05				
135		5.93E-05				
136	7580A	6.85E-05	6.93067E-05	4.2	1.6502E-05	1.9273E-05
137		6.78E-05				
138		7.17E-05				
139	7580B	1.01E-04	0.00010184	4.1	2.4839E-05	
140		9.96E-05				
141		1.05E-04				
142	7580C	8.16E-05	0.00008075	4.9	1.648E-05	
143		8.10E-05				
144		7.97E-05				
145	8085A	8.00E-05	0.00007895	4.7	1.6798E-05	1.7456E-05
146		7.78E-05				
147		7.90E-05				

148	8085B	8.69E-05	0.00008662	4.9	1.7678E-05	
149		8.65E-05				
150		8.65E-05				
151	8085C	9.49E-05	0.00009483	5.3	1.7892E-05	
152		9.36E-05				
153		9.60E-05				
154	8590A	8.64E-05	8.59833E-05	5.1	1.6859E-05	1.6997E-05
155		8.57E-05				
156		8.58E-05				
157	8590B	9.10E-05	9.21733E-05	5.2	1.7726E-05	
158		9.04E-05				
159		9.52E-05				
160	8590C	7.60E-05	0.00007547	4.6	1.6407E-05	
161		7.52E-05				
162		7.53E-05				
163	9095A	9.93E-05	0.00010023	5.6	1.7898E-05	1.8687E-05
164		9.86E-05				
165		1.03E-04				
166	9095B	9.84E-05	9.75533E-05	5.1	1.9128E-05	
167		9.75E-05				
168		9.68E-05				
169	9095C	7.71E-05	7.61333E-05	4	1.9033E-05	
170		7.56E-05				
171		7.57E-05				
172	95100A	1.04E-04	0.000102467	5.2	1.9705E-05	1.9546E-05
173		1.03E-04				
174		1.01E-04				
175	95100B	9.83E-05	0.00009746	5.1	1.911E-05	
176		9.70E-05				
177		9.71E-05				
178	95100C	1.14E-04	0.000113	5.7	1.9825E-05	
179		1.14E-04				
180		1.12E-04				
181	100105A	1.38E-04	0.000136467	6.2	2.2011E-05	2.1168E-05
182		1.36E-04				
183		1.36E-04				
184	100105B	1.20E-04	0.000120033	5.8	2.0695E-05	
185		1.19E-04				
186		1.21E-04				
187	100105C	9.65E-05	9.56767E-05	4.6	2.0799E-05	
188		9.55E-05				
189		9.50E-05				

2004 – 05 Survey Area, Slope 2, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	010A	1.37E-03	0.001374	4	0.0003435	0.00032697
2		1.37E-03				
3		1.38E-03				
4	010B	1.30E-03	0.001302	4.2	0.00031	
5		1.30E-03				
6		1.30E-03				
7	010C	1.18E-03	0.001178667	3.6	0.00032741	
8		1.18E-03				
9		1.18E-03				
10	1020A	1.49E-03	0.00148	3.9	0.00037949	0.00036902
11		1.49E-03				
12		1.47E-03				
13	1020B	1.35E-03	0.001352	4.5	0.00030044	
14		1.35E-03				
15		1.36E-03				
16	1020C	2.09E-03	0.002093	4.9	0.00042714	
17		2.09E-03				
18		2.09E-03				
19	2030A	1.85E-03	0.001846	5.1	0.00036196	0.00034838
20		1.85E-03				
21		1.85E-03				
22	2030B	1.97E-03	0.001973	6	0.00032883	
23		1.97E-03				
24		1.97E-03				
25	2030C	2.34E-03	0.002338667	6.6	0.00035434	
26		2.34E-03				
27		2.34E-03				
28	3040A	2.43E-03	0.002428	6.2	0.00039161	0.00040701
29		2.43E-03				
30		2.43E-03				
31	3040B	2.40E-03	0.002395	6	0.00039917	
32		2.40E-03				
33		2.40E-03				
34	3040C	2.19E-03	0.002194333	5.1	0.00043026	
35		2.20E-03				
36		2.20E-03				
37	4050A	3.07E-03	0.003067	6.6	0.0004647	0.0004708
38		3.07E-03				
39		3.07E-03				
40	4050B	2.69E-03	0.002693667	5.5	0.00048976	
41		2.69E-03				
42		2.70E-03				
43	4050C	2.38E-03	0.002381333	5.2	0.00045795	
44		2.38E-03				
45		2.38E-03				
46	5060A	1.88E-03	0.001875333	6.5	0.00028851	0.00033466
47		1.88E-03				

48		1.88E-03				
49	5060B	1.86E-03	0.001861333	5.8	0.00032092	
50		1.86E-03				
51		1.86E-03				
52	5060C	2.60E-03	0.002604	6.6	0.00039455	
53		2.60E-03				
54		2.61E-03				
55	6070A	5.33E-04	0.0005328	5.8	9.1862E-05	0.00011984
56		5.33E-04				
57		5.33E-04				
58	6070B	5.75E-04	0.0005749	6.2	9.2726E-05	
59		5.75E-04				
60		5.75E-04				
61	6070C	1.07E-03	0.001067	6.1	0.00017492	
62		1.07E-03				
63		1.07E-03				
64	7080A	3.75E-04	0.0003744	6.2	6.0387E-05	5.3309E-05
65		3.74E-04				
66		3.74E-04				
67	7080B	2.41E-04	0.000241733	5.1	4.7399E-05	
68		2.40E-04				
69		2.44E-04				
70	7080C	3.10E-04	0.000307633	5.9	5.2141E-05	
71		3.03E-04				
72		3.10E-04				

2004 – 05 Survey Area, Slope 3, Soil Test Pit 5

N	Aliquot	Bulk Suseptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	9.26E-04	0.000926733	4.6	0.00020146	0.000204519
2		9.27E-04				
3		9.26E-04				
4	05B	1.22E-03	0.001218667	5.5	0.00022158	
5		1.22E-03				
6		1.22E-03				
7	05C	1.11E-03	0.001105	5.8	0.00019052	
8		1.11E-03				
9		1.11E-03				
10	510A	1.32E-03	0.001317333	7.1	0.00018554	0.000185825
11		1.32E-03				
12		1.32E-03				
13	510B	1.24E-03	0.001243	6.3	0.0001973	
14		1.24E-03				
15		1.24E-03				
16	510C	1.03E-03	0.001030333	5.9	0.00017463	
17		1.03E-03				
18		1.03E-03				
19	1015A	1.09E-03	0.001092333	6.3	0.00017339	0.000172861
20		1.09E-03				
21		1.09E-03				
22	1015B	1.25E-03	0.001253667	6.9	0.00018169	
23		1.25E-03				
24		1.25E-03				
25	1015C	1.10E-03	0.001103667	6.75	0.00016351	
26		1.10E-03				
27		1.10E-03				
28	1520A	1.22E-03	0.001218	6.9	0.00017652	0.000179581
29		1.22E-03				
30		1.22E-03				
31	1520B	1.04E-03	0.001044	5.9	0.00017695	
32		1.04E-03				
33		1.04E-03				
34	1520C	1.02E-03	0.001019	5.5	0.00018527	
35		1.02E-03				
36		1.02E-03				
37	2025A	7.45E-04	0.000745167	5.6	0.00013307	0.000154313
38		7.45E-04				
39		7.45E-04				
40	2025B	1.03E-03	0.001032333	5.9	0.00017497	
41		1.03E-03				
42		1.03E-03				
43	2025C	1.05E-03	0.001053333	6.8	0.0001549	
44		1.05E-03				
45		1.05E-03				

2004 – 05 Survey Area, Slope 4, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	5.37E-04	0.0005375	5.6	9.5982E-05	0.000107378
2		5.39E-04				
3		5.37E-04				
4	05B	5.96E-04	0.0005961	5.1	0.00011688	0.000104176
5		5.96E-04				
6		5.96E-04				
7	05C	6.99E-04	0.000699333	6.4	0.00010927	0.000100507
8		6.99E-04				
9		7.00E-04				
10	510A	4.92E-04	0.000492333	5.7	8.6374E-05	9.46223E-05
11		4.93E-04				
12		4.92E-04				
13	510B	6.78E-04	0.0006776	6.4	0.00010588	8.59398E-05
14		6.78E-04				
15		6.78E-04				
16	510C	5.59E-04	0.000558867	6.1	9.1617E-05	7.33269E-05
17		5.59E-04				
18		5.59E-04				
19	1015A	3.20E-04	0.000319733	5.3	6.0327E-05	8.34293E-05
20		3.19E-04				
21		3.20E-04				
22	1015B	3.13E-04	0.000312967	4.6	6.8036E-05	9.38431E-05
23		3.13E-04				
24		3.13E-04				
25	1015C	7.56E-04	0.000755933	6.2	0.00012192	0.000121349
26		7.56E-04				
27		7.56E-04				
28	1520A	5.59E-04	0.000558567	6.1	9.1568E-05	0.000123652
29		5.58E-04				
30		5.59E-04				
31	1520B	7.98E-04	0.000797933	5.3	0.00015055	0.000136832
32		7.98E-04				
33		7.98E-04				
34	1520C	6.97E-04	0.0006957	5.4	0.00012883	0.000129316
35		6.95E-04				
36		6.95E-04				
37	2025A	8.78E-04	0.000878433	6.7	0.00013111	0.000125976
38		8.78E-04				
39		8.79E-04				
40	2025B	8.06E-04	0.000806433	6.3	0.00012801	0.000125521
41		8.06E-04				
42		8.07E-04				
43	2025C	7.37E-04	0.000736633	6.2	0.00011881	0.000125712
44		7.37E-04				
45		7.36E-04				
46	2530A	8.18E-04	0.0008174	6.3	0.00012975	0.000126156
47		8.18E-04				

48		8.17E-04				
49	2530B	7.71E-04	0.000771467	6	0.00012858	8.29069E-05
50		7.71E-04				
51		7.73E-04				
52	2530C	7.58E-04	0.0007569	6.3	0.00012014	4.00476E-05
53		7.56E-04				
54		7.56E-04				

2004 – 05 Survey Area, Slope 4, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	6.05E-04	6.05E-04	5.8	1.04E-04	0.00010734
2		6.05E-04				
3		6.05E-04				
4	05B	5.02E-04	5.01E-04	4.5	1.11E-04	
5		5.02E-04				
6		4.98E-04				
7	05C	7.02E-04	7.02E-04	6.6	1.06E-04	
8		7.02E-04				
9		7.02E-04				
10	510A	5.41E-04	5.42E-04	6.4	8.47E-05	0.000104806
11		5.42E-04				
12		5.43E-04				
13	510B	7.07E-04	7.07E-04	6.7	1.06E-04	
14		7.07E-04				
15		7.07E-04				
16	510C	5.82E-04	5.83E-04	4.7	1.24E-04	
17		5.87E-04				
18		5.81E-04				
19	1015A	5.94E-04	5.95E-04	5.4	1.10E-04	0.000126886
20		5.95E-04				
21		5.95E-04				
22	1015B	8.73E-04	8.73E-04	6.2	1.41E-04	
23		8.73E-04				
24		8.74E-04				
25	1015C	8.56E-04	8.56E-04	6.6	1.30E-04	
26		8.56E-04				
27		8.56E-04				
28	1520A	7.36E-04	7.35E-04	5.8	1.27E-04	0.000118029
29		7.36E-04				
30		7.34E-04				
31	1520B	7.67E-04	7.67E-04	6.6	1.16E-04	
32		7.67E-04				
33		7.67E-04				
34	1520C	7.11E-04	7.11E-04	6.4	1.11E-04	
35		7.12E-04				
36		7.11E-04				
37	2025A	7.47E-04	7.47E-04	7	1.07E-04	0.000108372
38		7.47E-04				
39		7.47E-04				
40	2025B	6.95E-04	6.95E-04	6.6	1.05E-04	
41		6.95E-04				
42		6.95E-04				
43	2025C	6.90E-04	6.90E-04	6.1	1.13E-04	
44		6.91E-04				
45		6.90E-04				
46	2530A	7.52E-04	7.53E-04	6.2	1.21E-04	0.000116741
47		7.53E-04				
48		7.53E-04				

49	2530B	7.23E-04	7.24E-04	6.8	1.06E-04	
50		7.24E-04				
51		7.25E-04				
52	2530C	7.96E-04	7.95E-04	6.5	1.22E-04	
53		7.95E-04				
54		7.95E-04				
55	3035A	5.34E-04	5.34E-04	7.2	7.42E-05	8.3904E-05
56		5.34E-04				
57		5.34E-04				
58	3035B	7.33E-04	7.32E-04	7.5	9.77E-05	
59		7.32E-04				
60		7.32E-04				
61	3035C	5.67E-04	5.67E-04	7.1	7.99E-05	
62		5.67E-04				
63		5.67E-04				
64	3540A	4.59E-04	4.59E-04	6.8	6.75E-05	7.47697E-05
65		4.59E-04				
66		4.59E-04				
67	3540B	4.71E-04	4.71E-04	6.1	7.72E-05	
68		4.71E-04				
69		4.70E-04				
70	3540C	5.26E-04	5.26E-04	6.6	7.96E-05	
71		5.25E-04				
72		5.26E-04				
73	4050A	5.76E-04	5.76E-04	6.3	9.14E-05	6.72433E-05
74		5.76E-04				
75		5.75E-04				
76	4050B	3.50E-04	3.50E-04	6.6	5.30E-05	
77		3.50E-04				
78		3.50E-04				
79	4050C	3.73E-04	3.73E-04	6.5	5.74E-05	
80		3.74E-04				
81		3.72E-04				
82	5060A	3.21E-04	3.21E-04	6.2	5.17E-05	5.3087E-05
83		3.21E-04				
84		3.21E-04				
85	5060B	2.59E-04	2.59E-04	6.6	3.93E-05	
86		2.60E-04				
87		2.59E-04				
88	5060C	4.18E-04	4.17E-04	6.1	6.83E-05	
89		4.18E-04				
90		4.14E-04				
91	6070A	2.08E-04	2.07E-04	5.6	3.70E-05	3.23768E-05
92		2.07E-04				
93		2.07E-04				
94	6070B	1.59E-04	1.57E-04	6.8	2.32E-05	
95		1.57E-04				
96		1.57E-04				
97	6070C	2.51E-04	2.52E-04	6.8	3.70E-05	
98		2.51E-04				
99		2.53E-04				

100	7080A	1.93E-04	1.93E-04	6.3	3.06E-05	2.75163E-05
101		1.93E-04				
102		1.93E-04				
103	7080B	2.42E-04	2.42E-04	7.7	3.14E-05	
104		2.42E-04				
105		2.42E-04				
106	7080C	1.18E-04	1.17E-04	5.7	2.05E-05	
107		1.16E-04				
108		1.16E-04				

2004 – 05 Survey Area, Slope 5, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.33E-03	0.00233	4.1	0.00056829	0.0005459
2		2.33E-03				
3		2.33E-03				
4	05B	2.96E-03	0.002960333	5.9	0.00050175	
5		2.96E-03				
6		2.96E-03				
7	05C	2.27E-03	0.002270667	4	0.00056767	
8		2.27E-03				
9		2.27E-03				
10	510A	4.00E-03	0.004003667	5.9	0.00067859	0.00063613
11		4.01E-03				
12		4.00E-03				
13	510B	3.12E-03	0.003120667	5.6	0.00055726	
14		3.12E-03				
15		3.12E-03				
16	510C	3.70E-03	0.003699	5.5	0.00067255	
17		3.70E-03				
18		3.70E-03				
19	1015A	2.79E-03	0.002789667	6.4	0.00043589	0.0005339
20		2.79E-03				
21		2.79E-03				
22	1015B	3.91E-03	0.003907667	6.7	0.00058323	
23		3.91E-03				
24		3.91E-03				
25	1015C	3.61E-03	0.003612	6.2	0.00058258	
26		3.61E-03				
27		3.61E-03				
28	1520A	2.42E-03	0.002420333	6.8	0.00035593	0.00047983
29		2.42E-03				
30		2.42E-03				
31	1520B	1.56E-03	0.001560333	6.3	0.00024767	
32		1.56E-03				
33		1.56E-03				
34	1520C	5.68E-03	0.005684	6.8	0.00083588	
35		5.69E-03				
36		5.68E-03				
37	2025A	6.55E-04	0.0006558	6	0.0001093	0.00010865
38		6.56E-04				
39		6.57E-04				
40	2025B	7.04E-04	0.0007019	6.6	0.00010635	
41		7.02E-04				
42		7.00E-04				
43	2025C	6.29E-04	0.000628767	5.7	0.00011031	
44		6.29E-04				
45		6.28E-04				
46	2530A	4.52E-04	0.0004521	5.2	8.6942E-05	0.00010703
47		4.52E-04				

48		4.52E-04			
49	2530B	3.75E-04	0.000375833	3.5	0.00010738
50		3.75E-04			
51		3.77E-04			
52	2530C	7.85E-04	0.000785967	6.2	0.00012677
53		7.87E-04			
54		7.86E-04			

2004 – 05 Survey Area, Slope 5, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.31E-03	0.002306333	3.9	0.00059	0.00058
2		2.31E-03				
3		2.31E-03				
4	05B	2.75E-03	0.002749333	4.6	0.0006	
5		2.75E-03				
6		2.75E-03				
7	05C	3.02E-03	0.003021667	5.4	0.00056	
8		3.02E-03				
9		3.02E-03				
10	510A	2.58E-03	0.002582	4.3	0.0006	0.00059
11		2.58E-03				
12		2.58E-03				
13	510B	2.92E-03	0.002912333	5.2	0.00056	
14		2.91E-03				
15		2.91E-03				
16	510C	3.93E-03	0.003928333	6.5	0.0006	
17		3.93E-03				
18		3.93E-03				
19	1015A	4.18E-03	0.004180667	5.8	0.00072	0.00068
20		4.18E-03				
21		4.18E-03				
22	1015B	2.89E-03	0.002885667	4.4	0.00066	
23		2.89E-03				
24		2.88E-03				
25	1015C	4.03E-03	0.004032333	6.2	0.00065	
26		4.03E-03				
27		4.03E-03				
28	1520A	4.08E-03	0.004078667	5.9	0.00069	0.00066
29		4.08E-03				
30		4.08E-03				
31	1520B	3.85E-03	0.003854667	6	0.00064	
32		3.85E-03				
33		3.86E-03				
34	1520C	4.65E-03	0.004652	7.1	0.00066	
35		4.65E-03				
36		4.66E-03				
37	2025A	4.07E-03	0.004065667	5.9	0.00069	0.00056
38		4.07E-03				
39		4.07E-03				
40	2025B	2.42E-03	0.002414333	5.5	0.00044	
41		2.42E-03				
42		2.41E-03				
43	2025C	3.24E-03	0.003242667	5.9	0.00055	
44		3.24E-03				
45		3.24E-03				
46	2530A	2.84E-03	0.002841	6.3	0.00045	0.00045
47		2.84E-03				
48		2.84E-03				

49	2530B	2.96E-03	0.002962333	6.6	0.00045	
50		2.96E-03				
51		2.96E-03				
52	2530C	2.97E-03	0.002971333	6.4	0.00046	
53		2.97E-03				
54		2.97E-03				
55	3035A	1.40E-03	0.001396	6.4	0.00022	0.00024
56		1.40E-03				
57		1.40E-03				
58	3035B	1.45E-03	0.001452333	5.8	0.00025	
59		1.45E-03				
60		1.45E-03				
61	3035C	1.63E-03	0.001628667	6.4	0.00025	
62		1.63E-03				
63		1.63E-03				
64	3540A	5.74E-04	0.000573267	6.2	9.2E-05	9.4E-05
65		5.73E-04				
66		5.73E-04				
67	3540B	4.85E-04	0.0004846	4.7	0.0001	
68		4.84E-04				
69		4.84E-04				
70	3540C	3.73E-04	0.000373267	4.3	8.7E-05	
71		3.73E-04				
72		3.73E-04				
73	4045A	1.57E-04	0.000157133	4.8	3.3E-05	3E-05
74		1.57E-04				
75		1.57E-04				
76	4045B	1.35E-04	0.0001344	4.7	2.9E-05	
77		1.34E-04				
78		1.34E-04				
79	4045C	1.68E-04	0.0001678	6.1	2.8E-05	
80		1.68E-04				
81		1.68E-04				
82	4550A	1.63E-04	0.0001629	6	2.7E-05	3.1E-05
83		1.62E-04				
84		1.63E-04				
85	4550B	2.10E-04	0.0002097	4.7	4.5E-05	
86		2.10E-04				
87		2.10E-04				
88	4550C	7.49E-05	7.48033E-05	3.6	2.1E-05	
89		7.48E-05				
90		7.47E-05				

2004 – 05 Survey Area, Slope 6, Soil Test Pit 3

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	2.86E-04	0.000286167	5.5	5.203E-05	3.62E-05
2		2.86E-04				
3		2.87E-04				
4	05B	1.75E-04	0.000174833	6.2	2.8199E-05	
5		1.75E-04				
6		1.75E-04				
7	05C	1.37E-04	0.0001362	4.8	2.8375E-05	
8		1.36E-04				
9		1.36E-04				
10	510A	2.39E-04	0.000238067	4.2	5.6683E-05	4.84E-05
11		2.38E-04				
12		2.38E-04				
13	510B	2.14E-04	0.0002129	4.2	5.069E-05	
14		2.13E-04				
15		2.12E-04				
16	510C	1.75E-04	0.000174633	4.6	3.7964E-05	
17		1.74E-04				
18		1.74E-04				
19	1015A	2.78E-04	0.0002784	5.8	0.000048	6.62E-05
20		2.79E-04				
21		2.78E-04				
22	1015B	4.64E-04	0.000465133	7	6.6448E-05	
23		4.64E-04				
24		4.67E-04				
26	1015C	5.39E-04	0.000538567	6.4	8.4151E-05	
27		5.38E-04				
28		5.39E-04				
29	1520A	3.22E-04	0.000321633	4.9	6.5639E-05	6.66E-05
30		3.22E-04				
31		3.22E-04				
32	1520B	2.26E-04	0.0002246	3.6	6.2389E-05	
33		2.24E-04				
34		2.24E-04				
35	1520C	3.66E-04	0.000366233	5.1	7.181E-05	
36		3.66E-04				
37		3.67E-04				
38	2025A	8.01E-05	7.96767E-05	4.1	1.9433E-05	2.43E-05
39		7.94E-05				
40		7.95E-05				
41	2025B	1.40E-04	0.000139233	4.6	3.0268E-05	
42		1.39E-04				
43		1.39E-04				
44	2025C	1.22E-04	0.000121233	5.25	2.3092E-05	
45		1.21E-04				
46		1.21E-04				
47	2530A	3.70E-05	0.00003631	3.5	1.0374E-05	1.07E-05
48		3.57E-05				

49		3.63E-05				
50	2530B	6.26E-05	0.00006175	5.1	1.2108E-05	
51		6.13E-05				
52		6.14E-05				
53	2530C	4.79E-05	0.0000477	5	0.00000954	
54		4.71E-05				
55		4.81E-05				
56	3035A	3.55E-05	0.00003485	5	0.00000697	2.37E-05
57		3.28E-05				
58		3.63E-05				
59	3035B	2.95E-05	2.91333E-05	4.1	7.1057E-06	
60		2.89E-05				
61		2.90E-05				
62	3035C	2.34E-04	0.000233733	4.1	5.7008E-05	
63		2.34E-04				
64		2.33E-04				
65	3540A	3.59E-05	0.00003554	5.5	6.4618E-06	6.56E-06
66		3.51E-05				
67		3.56E-05				
68	3540B	3.24E-05	3.23533E-05	4.9	6.6027E-06	
69		3.24E-05				
70		3.22E-05				
71	3540C	3.17E-05	3.17433E-05	4.8	6.6132E-06	
72		3.10E-05				
73		3.26E-05				
74	4045A	3.37E-05	3.32067E-05	4.4	7.547E-06	7.72E-06
75		3.28E-05				
76		3.32E-05				
77	4045B	4.63E-05	4.56067E-05	5.9	7.7299E-06	
78		4.53E-05				
79		4.53E-05				
80	4045C	3.30E-05	3.22767E-05	4.1	7.8724E-06	
81		3.20E-05				
82		3.18E-05				

2004 – 05 Survey Area, Slope 6, Soil Test Pit 4

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	05A	1.40E-04	0.000139567	3.6	3.877E-05	4E-05
2		1.39E-04				
3		1.40E-04				
4	05B	1.41E-04	0.0001414	5.1	2.773E-05	
5		1.41E-04				
6		1.42E-04				
7	05C	3.21E-04	0.0003203	5.9	5.429E-05	
8		3.20E-04				
9		3.20E-04				
10	510A	1.87E-04	0.000187133	7.6	2.462E-05	2.7E-05
11		1.87E-04				
12		1.87E-04				
13	510B	1.52E-04	0.000152	5.4	2.815E-05	
14		1.52E-04				
15		1.53E-04				
16	510C	1.84E-04	0.000183667	6.4	2.87E-05	
17		1.83E-04				
18		1.84E-04				
19	1015A	9.07E-05	9.05433E-05	4	2.264E-05	2.9E-05
20		9.05E-05				
21		9.04E-05				
22	1015B	1.75E-04	0.000175467	6.3	2.785E-05	
23		1.75E-04				
24		1.76E-04				
25	1015C	2.47E-04	0.000247267	6.6	3.746E-05	
26		2.47E-04				
27		2.47E-04				
28	1520A	6.96E-05	0.0000688	2.9	2.372E-05	2E-05
29		6.85E-05				
30		6.84E-05				
31	1520B	5.08E-05	5.05233E-05	2.5	2.021E-05	
32		5.04E-05				
33		5.04E-05				
34	1520C	7.61E-05	7.60667E-05	4.6	1.654E-05	
35		7.61E-05				
36		7.60E-05				

2004 – 05 Survey Area, Slope 6, Soil Test Pit 5

N	Aliquot	Bulk Susceptibility	Average/ aliquot	weight (g)	avg/g/aliquot	avg/g/sample
1	0-5	1.14E-04	0.0001137	4	2.843E-05	3.31E-05
2		1.14E-04				
3		1.14E-04				
4	05B	1.96E-04	0.000196033	4.7	4.171E-05	
5		1.96E-04				
6		1.96E-04				
7	05C	1.13E-04	0.0001138	3.9	2.918E-05	
8		1.14E-04				
9		1.15E-04				
10	5-10	1.60E-04	0.000159267	4.3	3.704E-05	4.434E-05
11		1.59E-04				
12		1.59E-04				
13	510B	1.13E-04	0.000112833	3.6	3.134E-05	
14		1.13E-04				
15		1.13E-04				
16	510C	2.98E-04	0.000297367	4.6	6.464E-05	
17		2.99E-04				
18		2.95E-04				
19	10-15	2.37E-04	0.000236967	7.1	3.338E-05	3.355E-05
20		2.37E-04				
21		2.37E-04				
22	1015B	2.04E-04	0.000203767	5	4.075E-05	
23		2.03E-04				
24		2.04E-04				
25	1015C	1.57E-04	0.0001564	5.9	2.651E-05	
26		1.56E-04				
27		1.56E-04				
28	15-20	1.81E-04	0.000180867	5.6	3.23E-05	2.638E-05
29		1.81E-04				
30		1.81E-04				
31	1520B	1.73E-04	0.000173267	6.9	2.511E-05	
32		1.73E-04				
33		1.74E-04				
34	1520C	1.22E-04	0.000121667	5.6	2.173E-05	
35		1.22E-04				
36		1.22E-04				
37	20-25	1.07E-04	0.000107	2.9	3.69E-05	2.56E-05
38		1.07E-04				
39		1.08E-04				
40	2025B	1.18E-04	0.0001181	5.2	2.271E-05	
41		1.18E-04				
42		1.18E-04				
43	2025C	6.75E-05	6.69967E-05	3.9	1.718E-05	
44		6.67E-05				
45		6.67E-05				
46	25-30	2.82E-04	0.000281733	2.3	0.0001225	6.343E-05
47		2.82E-04				

48		2.82E-04				
49	2530B	2.47E-04	0.0002437	5	4.874E-05	
50		2.42E-04				
51		2.42E-04				
52	2530C	7.64E-05	0.00007618	4	1.905E-05	
53		7.61E-05				
54		7.61E-05				
55	30-40	4.74E-05	4.68167E-05	3.6	1.3E-05	1.157E-05
56		4.65E-05				
57		4.65E-05				
58	3040B	5.25E-05	5.24467E-05	5	1.049E-05	
59		5.24E-05				
60		5.24E-05				
61	3040C	4.06E-05	4.04233E-05	3.6	1.123E-05	
62		4.03E-05				
63		4.03E-05				
64	40-50	1.18E-04	0.000117667	3.5	3.362E-05	2.045E-05
65		1.18E-04				
66		1.18E-04				
67	4050B	4.76E-05	0.00004689	3.6	1.303E-05	
68		4.62E-05				
69		4.68E-05				
70	4050C	5.31E-05	5.29033E-05	3.6	1.47E-05	
71		5.27E-05				
72		5.29E-05				
73	50-60	4.43E-05	4.43633E-05	4	1.109E-05	1.068E-05
74		4.37E-05				
75		4.51E-05				
76	5060B	3.76E-05	3.80367E-05	3.4	1.119E-05	
77		3.74E-05				
78		3.91E-05				
79	5060C	4.67E-05	4.68833E-05	4.8	9.767E-06	
80		4.63E-05				
81		4.77E-05				

APPENDIX 3: LUMINESCENCE DATA

This appendix presents the data used to arrive at the optical ages for sediment samples that are given in the text and in Appendix 1. All ages are based on optically stimulated luminescence in quartz grains. Two types of ages were calculated: multiple-grain and single-grain. Single-grain age estimates are based on at least 100 accepted grains, and final ages are calculated from the modal values for each sample. Multiple-grain ages are based on the mean De (dose equivalent) values for a minimum of 20 aliquots per sample. Single-grain data are presented first, and data for both types of age estimate are presented in the same order as in Appendix 1.

Single-grain age estimates:

Sample	UNL Lab #	Depth (m)	U (ppm)	Th (ppm)	$K_2$0 (wt %)	In Situ $H_2$0 (%)[a]	Dose Rate (Gy/ka)	D_e (Gy) ± 1 Std. Err.	Grains (n)[c]	Optical Age ± 1 σ
CL2	UNL-1860	0.3	2.4	8.6	1.4	2.0[b]	2.49 ± 0.13	2.2 ± 0.1	156/4800	880 ± 70
AL2	UNL-1856	0.3	2.6	7.9	1.7	2.0[b]	2.72 ± 0.16	6.0 ± 0.3	209/2000	2210 ± 180
AL3	UNL-1857	0.5	2.7	7.6	2.0	2.0[b]	2.74 ± 0.14	6.4 ± 0.3	100/1500	2340 ± 190
Queimada "upper"	UNL-1281	0.60	2.7	11.2	1.9	1.1	3.16 ± 0.16	2.5 ± 0.1	113/5500	790 ± 70
Q2	UNL-1853	0.5	2.6	9.9	2.0	2.0[b]	3.07 ± 0.16	0.4 ± 0.1	225/4500[d]	90 ± 10
Q3	UNL-1854	0.8	2.8	10.2	2.0	2.0[b]	3.12 ± 0.16	4.3 ± 0.1	123/4000	1370 ± 100

[a]Assumes 100% error in estimate or measurement
[b]Moisture contents were estimated at 2%
[c]Accepted grains/all grains run
[d] Includes 101 negitive De values

Multiple-grain age estimates:

Sample	UNL Lab #	Depth (m)	U (ppm)	Th (ppm)	K_20 (wt %)	In Situ H_20 (%)[a]	Dose Rate (Gy/ka)	D_e (Gy) ± 1 Std. Err.	Aliquots (n)[c]	Optical Age ± 1 σ
CL1 20 cm	UNL-1859	0.20	2.4	8.4	1.2	2.0b	2.33 ± 0.12	3.1 ± 0.3	24/33	1350 ± 170
CL2 30 cm	UNL-1860	0.30	2.4	8.6	1.4	2.0b	2.49 ± 0.13	4.5 ± 0.2	22/28	1810 ± 150
AL1 20 cm	UNL-1855	0.20	2.4	7.0	1.6	2.0b	2.53 ± 0.13	26.1 ± 3.6	21/24	10300 ± 1600
Queimada "upper"	UNL-1281	0.60	2.7	11.2	1.9	1.1	3.21 ± 0.16	5.0 ± 0.4	32/35	1570 ± 160
Q1 30 cm	UNL-1852	0.30	2.5	10.1	1.9	2.0[b]	3.00 ± 0.15	1.2 ± 0.3	22/23	390 ± 100
Q3 80 cm	UNL-1854	0.80	2.8	10.2	1.6	2.0b	3.12 ± 0.16	5.1 ± 0.3	22/24	1650 ± 140
OSA S1 STP5 "upper"	UNL-1283	0.55	2.7	13.2	2.2	8.2	3.31 ± 0.20	14.7 ± 0.9	30/38	4420 ± 480

[a]Assumes 100% error in measurement or estimate
[b]Moisture contents were estimated at 2%
[c]Weighted aliquots/All aliquots run