Characterization of fluvial facies distributions and cyclicity using terrestrial lidar: Paleocene Nacimiento Formation, Kutz Canyon, New Mexico

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CHARACTERIZATION OF FLUVIAL FACIES DISTRIBUTIONS AND CYCLICITY USING TERRESTRIAL LIDAR: PALEOCENE NACIMIENTO FORMATION, KUTZ CANYON, NEW MEXICO

BY

JEFFREY ALLEN CARRITT

B. S. Geology, University of Nebraska, Omaha, 2011

THESIS

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DEDICATION

This thesis is dedicated to my parents, Caroline and Kevin, for their unsurpassed support provided during my numerous years in college.
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ABSTRACT

The fluvial deposits of the early Paleocene Nacimiento Formation are comprised of variegated mudstones with interbedded paleosols and channel sandstone bodies. This study documents these strata in a ~1 km² outcrop area at Kutz Canyon, San Juan Basin, New Mexico, by employing fully georeferenced lidar intensity data collected from a terrestrial lidar scanner and an outcrop surface model constructed from the lidar data and calibrated digital field photographs. At this location, the lidar intensity data are responsive to lithology and distinct lidar facies are identified which correspond to facies types described in measured stratigraphic sections. One dimensional lidar intensity logs resemble subsurface gamma-ray logs in form and can be related with subsurface observations. Further, the structural dip of these strata was estimated by digitizing a key marker paleosol. We rotated the data along this dip using the scanner software, which provided more accurate correlations. Width-to-thickness ratios of a ribbon sandstone channel and a thick meter-scale sheet sandstone were also calculated.
Wavelet analyses conducted on the lidar intensity data yielded a periodic signal at 6.5 m over a vertical thickness of 25 m. The recurrence interval of this signal is estimated to be approximately 34 kya and is interpreted as depositional products of successive avulsion episodes, or depositional lobe switching on a distributive fluvial system.

Trenching through the weathering crust present on outcrop along two measured stratigraphic sections indicated that while gross lithology can be determined from the lidar intensity data, small-scale textural details cannot. As a result, a stacking-pattern analysis focused on identifying and then creating accommodation plots for fining-upward fluvial cycles was done exclusively on the measured sections. The cycle trends were only correlative when analyzed above the stratigraphic level that contained a thick sheet sandstone present in one of the sections.

The results of this work illustrate the versatility of using lidar datasets in stratigraphy. A future project could potentially apply these methods to a larger area across Kutz Canyon and may have to ability to document indistinct stratal geometries on a multi-kilometer scale that could further be used to better understand the large-scale architecture of fluvial systems.
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PREFACE

The focus of the research in this thesis involves the description of an extended area of ancient fluvial deposits using a combination of remotely gathered lidar (light detection and ranging) data, photogrammetry, and traditional field methods. Two different cyclicity tests were conducted on these strata to identify periodic trends in the succession. Chapter 1 begins by discussing the impetus behind using lidar in stratigraphy and introduces the geologic background of the field area, described facies, and a general account of lidar data acquisition methods. This methodology section also summarizes how the outcrop surface model was constructed. The chapter then delves into outcrop facies detection using lidar, lateral correlations between these facies, and a virtual calculation of the strike and dip of these deposits. Sandstone width-to-thickness ratios are also presented as determined from the outcrop surface model. Next, the effect of averaging large scale swaths of lidar data (up to 200 m) is examined. The chapter concludes by presenting the results of a wavelet analysis on an averaged lidar section. We expect this chapter to become a manuscript for the AAPG Bulletin or Geosphere.

Chapter 2 introduces an established 1D alluvial stacking pattern analysis that has been applied to similar deposits in other studies (e.g., Atchley et al., 2013). This analysis was conducted on two measured stratigraphic sections in the field area, and the results were then compared between the sections.

The third and last chapter is devoted to addressing the potential scientific merits of a more expansive lidar-based project in the vicinity of the study area. Finally, a summary of the conclusions from this research project are presented.
CHAPTER 1. AN EVALUATION OF A FLUVIAL SUCCESSION IN THE
NACIMIENTO FORMATION USING TERRESTRIAL LIDAR

Chapter Abstract

The fluvial strata of the Paleocene Nacimiento Formation at Kutz Canyon, in the
San Juan Basin of northwestern New Mexico, are widely exposed across kilometers of
outcrop. This project used terrestrial lidar intensity data, a constructed photorealistic
outcrop surface model derived from lidar, and measured stratigraphic sections to
investigate the lateral extent and cyclicity of these strata over a ~1 km² area. When
compared directly to a measured section, the lidar intensity values are clearly responsive
to lithology, and established lidar facies can be laterally evaluated across the extent of the
field area as expressed digitally by a point cloud surface. Correlations were more
accurately rendered through the removal of the structural dip by digitizing a marker bed
low in the succession. Sandstone width-to-thickness ratios of both a ribbon channel and
thick sheet sandstone were determined virtually by measuring the dimensions on the
outcrop surface model. Since a 1D lidar intensity log resembles a gamma-ray log, a total
of 23 lidar intensity logs were sampled and correlated across the point cloud, giving a
representation similar to the appearance of a group of closely-spaced subsurface well
logs. Lidar intensity logs integrated across increasing horizontal distances show intensity
responses that may be used to evaluate general lithologic trends of the succession.
Wavelet analyses conducted on several of the lidar intensity logs yielded a significantly
periodic interval occurring every 6.5 m over a ~25 m vertical span with an estimated
recurrence interval of 34 kya that is associated with either repetitive crevasse splays or
migrating lobes on a distributive fluvial system.
Introduction

The sedimentary record of fluvial deposits often exhibits a strong degree of complexity at multiple scales ranging from outcrop to basin scale. Fluvial successions contain aquifers and hydrocarbon reservoirs as well as economically significant placer and uranium deposits. Thick successions of fluvial deposits accumulating in sedimentary basins display geometric and spatial variations, known as alluvial architecture, in the vertical arrangement of channel-belt and floodplain deposits (e.g., Allen, 1964; Miall, 1985; Kraus, 2002). Understanding these facies geometries and correlations at all scales is critical in order to effectively develop resources contained in these deposits and advance the recognition of the dominant processes that control fluvial depositional patterns (e.g., Shanley & McCabe, 1994; Mackey & Bridge, 1995; Farrell, 2001; Nichols & Fischer, 2007; Weissmann et al., 2010, 2013; Huerta et al., 2011).

In recent years, numerous studies have documented the geological practicality of terrestrial lidar (light detection and ranging) scanning in the Earth Sciences (e.g., Buckley et al. 2008, 2010; Hodgetts, 2013). Each lidar scan consists of a highly accurate array of 3D surveyed points that represent the surface of an outcrop. These scans are particularly suited towards the collection of 3D quantitative stratigraphic data over 100s to 1000s of meters of outcrop (e.g., Eide et al., 2014; Rittersbacher et al., 2014). Lidar datasets are frequently combined with GPS stations and calibrated field photographs to generate photorealistic outcrop surface models (OSMs). Enge et al. (2007) discussed the usefulness of lidar datasets in stratigraphy by illustrating how these data typically span over most length scales exhibited by sedimentary structures; ranging from subsurface cores and logs to seismic data. Features mapped on varying scales from OSMs can also
be incorporated into reservoir models in order better understand scale-dependent influences on fluid flow (Buckley et al., 2010). Sand body dimension plots that display width and thickness ratios are another sedimentologic feature that can be calculated directly from lidar datasets and then quantitatively analyzed and/or imported into reservoir models (e.g., Labourdette and Jones, 2007; Fabuel-Perez et al., 2009; Rittersbacher et al., 2014). Several studies have also demonstrated how lidar intensity data can be used to classify lithology (e.g., Pesci et al., 2008; Franceschi et al., 2009; Klise et al., 2009; Burton et al., 2011; Nichols et al., 2011).

This study aims to describe fluvial facies distributions, cyclicity, and sandstone body dimensions over a ~1 km² area containing deposits of the Paleocene Nacimiento Formation in northwestern New Mexico. A terrestrial lidar dataset along with measured sections were used to accomplish this goal. Analyses were conducted on the lidar intensity point cloud and also on a photorealistic outcrop surface model.

This paper begins by describing the facies present in two measured sections in the study area. Documented facies are compared to the lithologic response recognized from the lidar intensity point cloud to establish distinct ‘lidar facies’ from the dataset. These defined lidar facies are then evaluated and laterally correlated across the entire point cloud and the fully constructed OSM. Next, a series of individual one-dimensional vertical logs of subsampled intensity data, hereafter called lidar intensity logs (LILs), were organized into groups from around the point cloud. The resulting correlations between the LILs illustrate and corroborate the lidar facies correlations. Additionally, channel dimensions of two different channel sandstone facies types were directly measured from the OSM.
The second component of this research involves the description of alluvial cyclicity in these deposits interpreted from the OSM and measured sections. Wavelet analyses were conducted on the lidar intensity data in order to test whether or not any periodic intervals exist in these strata using the open source wavelet package made available by Torrence and Compo (1998).

This project demonstrates the utility of lidar datasets in the stratigraphic evaluation of fluvial strata. A clear advantage to these datasets is that large field areas can be studied in a 3D environment where sedimentary contacts can be accurately correlated around ridgelines and other irregularities on outcrop that would be difficult or impossible to trace in the field. A larger scale application of these methods to the fluvial deposits in the Kutz Canyon may have the potential to extract details on stratal geometries not attainable through traditional field work.

Field Location and Geological Background

Positioned in the San Juan Basin of northwest New Mexico, the study area is located in the Angel Peak Scenic Area at Kutz Canyon (Fig. 2.1). Deposits of the Nacimiento Formation are exposed in this region as a complex of badlands that extend for ~ 22 km from the San Juan River south to a head scarp where the thickest vertical sections are exposed. This head scarp of Kutz Canyon forms the southern limit of the field area.

The San Juan Basin represents one of the many broken-foreland basins developed during the Laramide Orogeny (Smith, 1988). It is an asymmetric basin and possesses a
north to northwest trending axis. Sedimentary deposition occurred from the Late Cretaceous into the Eocene. The Paleogene sedimentary units are nonmarine in origin, and include the Ojo Alamo, Nacimiento, and San Jose Formations. The Paleocene Nacimiento Formation is composed of up to 500 meters of fluvial and lacustrine deposits with intercalated paleosols of varying maturity (Williamson, 1996). The fluvial deposits of the Nacimiento Formation developed on an alluvial floodplain which drained the San Juan Mountains to the north. These strata are thought to have been derived from volcaniclastic material sourced from the weathering of a thick succession of Late Cretaceous volcanics in the San Juan Mountain area that were subsequently uplifted and eroded during the incipient Laramide Orogeny. Based on magnetostratigraphic studies, the Nacimiento Formation was deposited within a 7 Myr time interval spanning C29n-C26r (65.5-58.0 Ma) during the early to middle Paleocene (Williamson, 1996). The studied alluvial succession at Kutz Canyon is positioned almost entirely within reversed polarity chron 27, and may extend into the lowermost portion of chron 28, though the exact position of this reversal is unknown at this location (Williamson, personal communication, 2012).
Figure 2.1. Generalized geologic map of the San Juan Basin showing the position of the field site in Kutz Canyon with inset aerial photographs (after Williamson, 2008).
Nacimiento Formation Lithologic Units

In the southern San Juan Basin the Nacimiento Formation has been divided into three formal members (Williamson and Lucas, 1992; Williamson, 1996; Fig. 2.2). In superpositional order these units include: the Arroyo Chijuillita, Ojo Encino, and Escavada Members. The Arroyo Chijuillita Member is dominated by fine-grained deposits, including dark mudstones and siltstones. Minor fine-to-coarse sandstone bodies are commonly lenticular in form. Thin lignite coal beds also occur within this unit. The Ojo Encino Member is also mud-rich, though this unit contains distinctive variegated (red-green) mudstones. These variegated mudstones typically overlie dark mudstones and are capped by trough cross-bedded sandstones that display ribbon-type geometries. The variegated mudstones in this unit are indicative of well-drained, oxidized conditions. In contrast to the lower two units the uppermost Escavada Member is dominated by coarse-grained multistoried sandstones with much lesser amounts of siltstone and mudstone. Thin, laterally extensive silcrete horizons are also common in the Escavada Member.

At Kutz Canyon the Arroyo Chijuillita and Ojo Encino members of the Nacimiento Formation cannot be differentiated, and have been assigned the informal designation “main body” by Williamson (1993). The red mudstones in this succession increase upwards towards the base of a thick extensive sheet sandstone that is correlative in subsurface logs and which separates the “main body” from the overlying Escavada Member. This sheet sandstone was originally designed as the “unnamed member” of the Nacimiento Formation. Based on additional correlations north of Kutz Canyon, Libed (2005) named this unit the Kutz Canyon Member of the Nacimiento Formation.
Figure 2.2. Nacimiento Formation composite section (after Williamson and Lucas, 1992).
Facies Descriptions and Interpretations

Two stratigraphic sections, separated horizontally by ~330 m, were measured in order to document the lithofacies on outcrop and determine how well the acquired lidar data capture these lithofacies (Figs 2.3, 2.4, and 2.5). Both sections were located on the north face of the headscarp of Kutz Canyon. The sections were measured at a resolution of 5 cm. In addition to textural details, other secondary stratigraphic details were recorded, including sedimentary structures, paleosol characteristics, and Munsell colors. As a means to understand the amount of textural information missing on the overall outcrop due to the presence of a weathering crust, and in turn evaluate the amount of stratigraphic detail missed in the acquired lidar data, both sections were measured with the original weathering crust present and with crust removed through trenching. Each facies will, therefore, be discussed as observed when both trenched and untrenched. In all, six different facies were recognized and described: 1) mudstones 2) siltstones 3) paleosols 4) ribbon sandstones 5) thick sheet sandstones and 6) thin sheet sandstones.

Mudstones

Mudstones without a significant silt component are uncommon in both measured sections. Where present, mudstones contain abundant centimeter-scale slickensides, and occasionally possess mottles that are dusky red (2.5 YR 3/2) in color. The typical mudstone matrix ranges in color from dark gray (5Y 4/1) to nearly black when freshly exposed. One organic-rich black mudstone bed in section I (at 24.5 m) contained abundant root traces. Mudstones are tabular in form and are laterally extensive across the field area. Although not documented in the measured sections, two lenticular mud-rich beds were observed on outcrop less than 100 m away from both sections.
Figure 2.3. Measured section I. Trenched section is shown on left, untrenched on right.

Location: 36°31'-14.1" N 107°55'-11.1" W
Figure 2.4. Measured section II located ~330 m to the east of section I. Trenched section is shown on left, untrenched on right.
Figure 2.5. Both measured sections showing trenched and untrenched details with relevant correlations. Five of the correlations are laterally connected ‘tiers’ comprised of ribbon channels and thin sheet sandstones/siltstones. The lowermost mature paleosol is treated as the stratigraphic datum; any deviations above this level are attributed to field measurement errors.
Figure 2.6. Field photographs depicting facies types and features. A) Mudstone bed, note dark-blue color indicative of reducing conditions. B) Siltstone with massive structure. C) Trench through moderately developed paleosol. Coco the dog for scale. D) Road cut exposure of a mature paleosol displaying probable root traces and mottling (location is ~750 m from study area). E) and F) Close ups of animal burrows in the paleosol from D). G) Mature paleosol, the entire trenched exposure is a slickenside surface. H) Ribbon channel sandstone body with superimposed channel form. I) Thick sheet sandstone body J) Thin sheet sandstone (located below paleosol).
On outcrop, the untrenched mudstone intervals are identifiable through the weathering crust that resembles the distinctive gleyed color of the trenched beds. The weathering crust commonly appeared coarse, with visible sand grains on the surface, therefore trenching was required to properly determine texture.

**Interpretations**

The tabular mudstone beds are interpreted as overbank deposits that formed on an alluvial floodplain with low topographic relief (e.g., Farrell, 1987; Willis and Behrensmeyer, 1994). Additionally, the dark colors of these beds suggest organic-rich conditions consistent with an inundated, backswamp depositional environment (Davies-Vollum and Kraus, 2001; Farrell, 2001). The presence of mottling in both the mudstones and in the coarser grained siltstones described later are indicative of some degree of pedogenic activity following deposition, since modern soils commonly display mottling in response to seasonal fluctuations in water-table height that causes a switch in oxidation/reduction states (Kraus and Wells, 1999). The mud containing passive channel fills are thought to represent fluvial channels that were rapidly abandoned during avulsion, and thereafter infilled with overbank muds (Kraus and Davies-Vollum, 2004).

**Siltstones**

Massive siltstones are by far the most common lithology in both measured sections. Pedogenically unmodified and modified siltstones account for ~20% and ~60% of the total sections, respectively. These beds consistently recorded Munsell hues of 5Y ranging from dark gray (5Y 4/1) to light olive gray (5Y 6/2). Two ~20 cm siltstone beds appeared grayish-brown (10YR 5/2). Overall, the siltstones are typically micaceous and usually contain observable amounts of fine-sand sized quartz grains. At some
stratigraphic levels these siltstones contain appreciable amounts of sand and can be more accurately classified as sandy-silts or coarser silty-sands. Distinct mottling is common in all the siltstones in the section, even in the sand-rich siltstone beds. These mottles are diffuse and dusky red (2.5YR 3/2) in color, which matches the color observed in the mudstone mottles. Slickensides are also found in the siltstone beds throughout both sections, but are much less common than in the mudstones. Carbonized root traces were observed in several siltstone beds and were highly abundant in the uniquely colored grayish-brown siltstones. Burrows were largely absent in the siltstones in both sections, though one bed possessed burrows that clearly showed a concave-upward meniscus-fill structure.

Determining textural and sedimentary details in the siltstones were difficult with the presence of the weathering crust on outcrop. In terms of color, the weathering crust was dull gray, and while mottling could be recognized through it, all other sedimentary details were indistinguishable. The untrenched intervals often contained fine-to-medium grained sand and usually appeared coarser than the siltstones beds behind it. Detailed grain size variations, such as fining-or-coarsening upwards trends were not discernable without trenching. Despite these complications, the general lithology of the untrenched siltstones could still be generally defined on outcrop.

*Interpretations*

The siltstones are interpreted as overbank sediments that were predominantly deposited by medial-to-distal portions of crevasse splays (e.g., Smith et al., 1989; Farrell, 2001). Siltstones laterally adjacent to a thick sandstone body in the field area are thought to be a component of a natural levee succession.
**Paleosols**

The most striking beds within the study area are the ubiquitous red bed horizons which display abundant features indicative of paleosols. These beds are consistently brick-red in color (dusky red-2.5 YR 3/2) through the entire succession. Typically, these units are comprised of siltstone, though similar pedogenic features were observed in silty-sands and even in fine sands. One very distinctive feature of these beds is the appearance of mottling within the horizons. The mottles are grayish-green in color and show Munsell values close to the olive gray color (5Y 5/2) of overbank siltstones. Commonly, the degree of mottling decreased upward until the red hues dominant the horizon. Another very common feature is the blocky, wedge-like structure that these horizons display when trenched. The boundaries between these structural features are separated by broad 10-20 cm wide slickensides. Other features observed within these beds include carbonized root traces and burrows. Ball-shaped chert concretions (or cannon-ball concretions) are highly abundant at certain paleosols horizons (Figs. 2.3-2.5).

On outcrop, these red paleosol horizons are identifiable on both the uncovered and covered sections. The upper contacts of these horizons appear diffuse on the untrenched sections; due to this the untrenched contacts were usually offset by ~5 cm when compared to the trenched contacts. As with the siltstones, trenching was required in order to observe detailed textures and structures.

*Interpretations*

The visible sedimentary structures in these red beds are interpreted to be the result of pedogenic processes. In particular, the blocky wedge-like structure and ubiquitous slickensides observed in these horizons are indicative of features found in modern
vertisols (Mack et al., 1993, 2001; Retallack, 2001). The formation of modern vertisols is driven by pedoturbation caused by the shrinking and swelling of expandable smectitic clays in response to seasonal wet-dry cycles. In terms of color, there are no observed modern vertisols that display the red hues present in these horizons. Therefore, the presence of the red hues in these beds is attributed to the precipitation of fine-grained iron-bearing minerals during diagenesis.

A typical paleosol profile in this succession is characterized by a lightly mottled grayish-green siltstone (with or without slickensides) that grades upward into a red horizon with slickensides and other paleosol features. The horizon containing abundant slickensides is most representative of vertisols and is commonly referred to as a Bss horizon (Mack, 2001). Within this profile, the lower siltstone is interpreted as a C horizon upon which an overlying Bss horizon is developed. Thin (< 1 m) siltstone beds with an olive gray matrix above these Bss horizons may be interpreted as A horizons, however these overlaying beds do not commonly possess specific characteristics, like root traces, that are most indicative of A-horizons.

Paleosols that display anomalously thick Bss horizons are generally thought to have been exposed to longer periods of pedogenesis, and are thus considered better developed, or more mature than other thinner, immature paleosols (Kraus and Wells, 1999). There are two well-developed (mature) paleosols in the study area. For the purposes of this study, in which facies described on outcrop are compared to their respective lidar intensity response, the mature and immature paleosols are considered as separate paleosol facies.
Ribbon Sandstones

Meter-scale ribbon sands possess scour-shaped erosional bases and flat upper boundaries. The ribbons are comprised of medium quartz-rich sands that consistently fine upward into silty-sands and siltstones. While trough cross-bedding is visible on outcrop these beds are difficult to fully resolve and can more accurately be referred to as relict cross-bedding. Lateral accretion sets are discernable on several of these sandstone bodies in the succession. The ribbons are moderately cemented and are white (5Y 8/1) in color.

The field expression of the ribbon sandstones is similar between the trenched and untrenched sections. If present, the weathering crust on these sandstones is thin and easily removable through trenching. Surficial trenching was required to determine textural changes.

Interpretations

Many studies that focus on both ancient and modern alluvial deposits describe similar ribbon sandstone bodies as crevasse channels that feed river discharge and sediment into adjacent floodplains (Smith et al., 1989; Kraus and Wells, 1999). The ribbon sands in Kutz Canyon also appear to be crevasse channels, especially since several thin sheet sands extend laterally off the flanks of the ribbons, forming thin sandstone ‘wings’. Alternatively, these ribbon sands may be the product of distributive channels on distal portions of an alluvial plain of an ancient distributive fluvial system (Weissmann et al., 2013).
**Thick sheet sandstones**

This interval of the Nacimiento Formation at Kutz Canyon contains at least three sheet sandstones which range from 5 to 15 m in thickness. Through most of the study area these sandstones occur both underneath and above a ~50 m package of finer-grained alluvial sediments. Texturally, the sandstones are composed of coarse sand to gravel sized particles and are dominated by sub-rounded quartz and feldspar grains and minor amounts of rock fragments. These sandstones bodies are only moderately cemented and are generally friable on outcrop. Externally, these sandstone bodies typically appear massive and form sheets that extend over 100s of meters across the field area. Distinct trough and planar cross-beds are locally visible, which allowed for the collection of several paleocurrent measurements. The readings (n = 6) are divided equally into NE and SE paleoflow directions In places where these sandstones are better cemented and more detail on the internal geometry of these sheets can be observed the sand bodies appear to be comprised of multistoried channel bodies.

The lowest extensive sheet sandstone body observed in the area is ~15 m thick and terminates within ~20 meters of one the measured sections. The exposure of this termination is poor due to gullying through differential weathering at the contact, however the laterally equivalent facies are well exposed in an adjacent measured section. Thick sandstone sheets extend vertically for 10s of meters from the top of the measured stratigraphic intervals. These upper sandstones display broad channel scours, and farther up-section, within the Kutz Canyon Member, appear to be comprised of distinctly amalgamated channel forms.
Although most thick sandstone exposures are covered with sheet wash and/or a weathering crust composed of weakly cemented coarse sand, the overall coarse texture of this facies makes it discernable both on covered and uncovered sections. The only feature missing on the untrenched sections are distinctly visible sedimentary structures.

**Interpretations**

These thick, horizontally extensive sheet sands are interpreted as the deposits of large, laterally mobile channels; based mainly on the presence of lateral accretion sets and multistoried channel forms.

**Thin Sheet Sandstones**

Both measured sections include thin sub-meter scale sandstones. Texturally, these sandstone bodies are comprised of quartz-rich medium sands. Cross-bedding appears to be absent. Subtle grain size changes are occasionally present when observed in the trenched outcrop, with both upward fining-and-coarsening trends present. The lower and upper transitions of these sands are sharp, and non-erosive. These sand bodies form thin sheets and are correlative across the ~330 m separating the measured sections.

This particular facies generally lacked a weathering crust on outcrop. Most of the thin sheet sands appeared identical between the trenched and untrenched sections. A few of these beds did show a thin, sub-centimeter layer of sand that was easily removed in order to determine textural changes.
Interpretations

The thin sheet sandstones in this succession are interpreted as laterally extensive crevasse splay and proximal overbank deposits. Several of these thin sands are laterally adjacent to the terminus of the thick sheet channel sand mentioned above and are likely representative of repeated crevassing events from this channel.

Lidar Data Acquisition and Processing, and Outcrop Surface Model Development

This project employed terrestrial lidar scans collected using an Optech-ILRIS-3D laser scanner operated by the University of New Mexico’s Lidar Lab. The instrument acquires highly accurate digital surveys consisting of x, y, and z coordinates by calculating a two-way travel time of an emitted laser between the outcrop and the point of emission. A total of six lidar scans were collected to cover the outcrop area; three scans were positioned with downward perspectives at stations along the headscarp of the field site, and the other three at points below the headscarp in the canyon (Figs 2.7 and 2.8). The intensity of the returned beam is a function of the reflected infrared energy, which is controlled by target reflectivity, distance, and angle of incidence (e.g., Burton et al., 2011).

Once collected, the lidar scans were internally registered using InnovMetric’s Polyworks software package. Following registration, tie-points between the scans were manually selected and then aligned according to a preset algorithm. Up to this point in the workflow, the scans were assigned a local coordinate system as defined by the scanner. Four high-accuracy static GPS stations collected precisely at lidar scanner positions were
imported into Polyworks to register the scans into the NAD 83/UTM Zone 13 coordinate reference system. The resulting product is a georeferenced point-cloud representation of the field area (Fig. 2.7). A poisson surface reconstruction was implemented to the point cloud, using the algorithm PoissonRecon, to create the 3D mesh (Kazhdan and Hoppe, 2013).

After the mesh was successfully created, rectified field images were imported and draped over the entire 3D surface (Fig 2.7). Hundreds of digital field images were taken using a Nikon D700 digital SLR camera with a 28 mm lens. Two separate stages of photograph processing were conducted on the images once collected. First, the images shot initially in raw format, were converted to scene-linear working files. Next, both the distortion parameters and scene pose were calibrated for each image. This step was conducted on all of the photographs simultaneously by using stereo algorithms developed in the photogrammetric program PhotoScan. The fully calibrated images were textured on the polygonal mesh to produce the outcrop surface model. Some editing of the textures was done using the open-source 3D graphics software Blender to improve quality. The fully textured mesh comprises the outcrop surface model, upon which geological interpretations and measurements were made.
Figure 2.7. Top: Plan view of the complete lidar point cloud as visualized in IMSurvey. The gray scale display shows lidar intensity. Scan positions are indicated by the yellow camera symbols. The three scans along the south canyon rim were captured over a ~180° span; the three scans in the canyon and on the north face gathered data over a 360° span. Bottom: Plan view of the fully developed outcrop surface model from the same perspective as the point cloud above. The orange bar in both figures is 100 m across
Figure 2.8. Oblique view of the lidar point cloud in IMSurvey. View is towards the southeast. The more reflective thick sheet sandstones that display higher intensity values are visible just below the canyon rim. Beneath these sandstones are darker, less reflective siltstones and paleosols. The vertical orange bar in the foreground is 25 meters in length; the horizontal field of view is ~1.35 km. Measured section II, which is graphically compared to the point cloud in Fig. 2.9, is indicated by a yellow line.
Facies Detection From Lidar Point Cloud Intensity Data

In order to illustrate the relationship between lithology and lidar intensity response, a one-dimensional lidar intensity log (LIL) was collected over a 1 m horizontal width from the point cloud at the approximate position of a measured section (Fig. 2.9). Because intensity data contains significant noise, the LIL data were smoothed using a 0.5-m moving-window average. While each LIL used in this study is plotted as true vertical depth, there is a vertical deviation between the top and bottom of each LIL created by the sloping topographic surface of the field area. A cross section of the sampled point cloud shown as the inset in Fig. 2.9 shows this vertical deviation. If compared to the subsurface, the LILs can be thought of as representing sub-vertical boreholes.

Upon inspection, several lidar intensity trends in the LIL correspond with facies described from the measured section in a manner similar to an inverted gamma ray geophysical log. The highest lidar intensity responses directly correlate to sandstone facies (Fig. 2.9). Thick (>10 m) sheet sandstones present below and above the finer-grained interval in the section correspond directly to high intensity values. Predictably, a ribbon sandstone in the measured section located ~17 m above the bottom thick sheet sandstone also shows high intensity values. In contrast, lower lidar intensity readings are associated with finer grained siltstones. Thin meter-scale sheet sandstones and sandy siltstone beds intercalated within the siltstone intervals were differentiable based on their relatively high intensity values. While these variable lidar intensity responses are associated primarily with grain size differences, distinctly low intensity values are linked
with the brick-red color displayed by the paleosols in this succession; the thick Bss horizons present in the mature paleosols are characterized by the lowest intensity returns.

Figure 2.9. (Following Page) Correlation between measured stratigraphic section II and the 1D lidar intensity log with key beds marked. The lidar intensity response is tied to the untrenched section on the right, in comparison to the trenched section on the left. The lower mature paleosol is considered the stratigraphic datum. Sandstones and coarse grained siltstones show consistently high intensity readings, while finer siltstones and thin paleosols display lower values. The thick mature paleosol shows the most pronounced low intensity deflection. Although not apparent in the untrenched section, the low intensity response at 1928 m does indicate a relatively coarse fine sandstone/siltstone bed that caps a paleosol in the succession. A similar ‘lithology log’ figure appears in Burton et al., (2011). The upper inset figure shows the change in thickness of a ribbon sandstone between the lidar (red) and measured section (yellow); only the top of this ribbon sandstone is visible in the lidar section. The lower inset figure illustrates that the sampled point cloud surface slopes upwards; as a result there is a slight distance fade that exists in the intensity data.
Figure 2.10. Visual comparison of the lidar point cloud (top) and the outcrop surface model (bottom) as viewed from the same perspective. The red line on the point cloud is where the LIL was sampled, the yellow line is the approximate location of the measured section. Both arrows on the point cloud are indicating the presence of thin sheet sandstones that flank the sides of the ribbon sandstone channel. The thick sheet sandstones on the point cloud in the above figure are outlined faintly in yellow. View is to the south.
When evaluating lidar intensity data from point clouds and from 1D lidar sections on sub-vertical outcrops, such as the LILs in this study, it is important to understand that in addition to the reflectance properties of the target material lidar intensity returns are affected by the diameter of the laser footprint (laser contact area) with distance to the target and the scanner-to-target incidence angle (e.g., Pesci et al., 2008; Burton et al., 2011; Hodgetts, 2013). The Optech ILRIS scanner parser software does apply a distance correlation algorithm to raw intensity data so generated point clouds can be viewed in the lidar processing software IMSurvey (e.g., Pesci et al., 2008; Burton et al., 2011). Despite the application of this internal software correction the increasing scanner-to-target distance creates an intensity distance fade that is visible in the point cloud in this study, especially over vertical strips where adjacent scans overlap. These overlapping regions are also noisy due to the different incidence angles between scans. Some workers have further refined lidar intensity data by applying statistically based distance normalizations that reduce variability and provide consistent median values (Burton et al., 2011; Hodgetts, 2013). These distance normalizations were not used in this project since, as discussed below, intensity values could readily be associated with specific lithologic types and correlated across the point cloud without their application.
Lidar Facies

Based on the observations made between the measured section and the LIL, a number of lidar intensity facies were established from the point cloud that could readily be associated with specific lithologic facies (Table 2.1). The exact intensity values used to define these facies are dependent on the outcrop-to-scanner distance, thus relative intensity values, rather than distinct value thresholds, were used. First, all of the fine-grain deposits and thin, immature paleosols are combined into a single lidar facies type marked by dark, lower value lidar intensity returns. The three lithologic sandstone facies (thick and thin sheet sands, and ribbon sand bodies) all show high intensity readings in the LIL and therefore each can be considered distinct lidar facies. Coarser siltstone beds that display high intensity readings are grouped into the thin sheet sandstone lidar facies category. Finally, the mature paleosols are treated as a lidar facies since these beds consistently show the lowest lidar values.
Table 2.1. Comparison between the properties of the described lithologic and lidar facies

<table>
<thead>
<tr>
<th>Facies</th>
<th>Characteristics</th>
<th>Geometry</th>
<th>Interpretation</th>
<th>Lidar Facies</th>
<th>Characteristics on Point Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>Finely bedded, breaks into fine aggregates</td>
<td>Tabular</td>
<td>Overbank deposits, back swamp</td>
<td>Fine-grained deposits</td>
<td>Moderate to low response values due to a combination of color and textural differences</td>
</tr>
<tr>
<td>Siltstone</td>
<td>Massive to blocky structure, commonly micaceous, mottled, slickensides, grayish-green to red</td>
<td>Tabular</td>
<td>Overbank, medial to distal crevasse splay</td>
<td>Mature Paleosol</td>
<td></td>
</tr>
<tr>
<td>Low to Moderately Mature Paleosol</td>
<td>Mottled muds &amp; silts, blocky structure, slickensides, burrows, root traces, cannon-ball chert concretion, dusky-red</td>
<td>Tabular</td>
<td>Pedogenically modified muds &amp; silts formed on an aggrading alluvial surface</td>
<td>Mature Paleosol</td>
<td>Lowest lidar response values from red colored matrix of thick Bss horizons</td>
</tr>
<tr>
<td>Mature Paleosol</td>
<td>Pervasively mottled muds &amp; silts, blocky structure, thick ~ 1 m Bss horizons, slickensides, burrows, root traces, cannon-ball chert concretions, dusky-red</td>
<td>Tabular, locally truncated by thick sheet &amp; ribbon sands</td>
<td>Pedogenically modified muds &amp; silts formed over a greater time span than other paleosols</td>
<td>Mature Paleosol</td>
<td></td>
</tr>
<tr>
<td>Ribbon Sandstone</td>
<td>Medium to fine grained sands, relict trough cross-bedding</td>
<td>Tabular</td>
<td>Crevasse channels, Distributive channels on a DFS</td>
<td>Ribbon Sandstone</td>
<td>High lidar response due to coarse texture</td>
</tr>
<tr>
<td>Thick Sheet Sandstone</td>
<td>Coarse-grained, generally massive sands, tabular &amp; trough cross-bedding, locally amalgamated channels</td>
<td>Tabular, laterally correlative to ribbon sands</td>
<td>Large laterally mobile channels</td>
<td>Thick Sheet Sandstone</td>
<td>High lidar response due to coarse texture</td>
</tr>
<tr>
<td>Thin Sheet Sandstone</td>
<td>Medium to fine grained massive sands</td>
<td>Lenticular</td>
<td>Crevasse splay deposits, distally fine to sandy silts</td>
<td>Thin Sheet Sandstone</td>
<td>High lidar response due to coarse texture</td>
</tr>
</tbody>
</table>
Study Area Virtual Strike and Dip Calculation

One demonstrable advantage of using lidar datasets to study sedimentary successions is the ability to implement algorithms that can change the orientation of the entire dataset. Such algorithms can provide information on subtle geometric variations present in given successions. The fluvial strata of the Nacimiento Formation are nearly flat-lying, with a dip of <5° towards the northeast, perpendicular to the structural axis of the San Juan Basin (Williamson, 1996). In order to quantify the local strike and dip of the strata in Kutz Canyon thirty-six points were digitized along the top of the lowermost mature paleosol in the section. This bed was selected since it is assumed this paleosol represents an ancient land surface and was reasonably flat over hundreds to thousands of meters. Once the points were selected a best-fit plane was applied to the points in IMSurvey. Next, a normal vector was assigned to this plane and a macro was run on the entire dataset that effectively ‘undipped’ the strata in the point cloud. Based on the calculated normal angles to the best-fit plane the strata in the field area possess a dip angle of 0.295° and strike direction of N0.238W (Fig. 2.10). Multiple sources of error could be responsible for the low R² value (0.4695) of the plane. The initial registration of the lidar scans likely contributed some degree of spatial error into the dataset. Also, the roughness of the key paleosol horizon on the point cloud may have affected the resolution of the selected points. However, the agreement between the plane geometry and previously cited field measurements of the strike and dip of the Nacimiento Formation lends credibility to the calculation. The removal of the structural dip from the dataset before conducting the lidar facies analysis potentially lead to more accurate correlations.
between the LILs, despite the very low calculated dip angle, as described in the next section.

**Figure 2.11.** Modeled paleosol surface displayed in MatLab’s curve fitting application. The x and y axes are UTM coordinates plotted with elevation. This modeled surface dips slightly (0.295°) to the northwest. The bottom figure shows a 2D view of the surface looking along strike.
Lidar Facies Correlations

The lateral extent of the lidar facies could readily be correlated across 100s of meters over nearly the entire point cloud. One region on the point cloud displayed relatively high data noise due to multiple scan overlaps. Relevant correlations in this region where represented on the OSM.

The thick sheet sandstone lidar facies are correlative at both the upper and lower outcrop positions across the study area and can be discerned from the moderate intensity returns characteristic of the intervening finer-grained siltstone-paleosol lidar facies (Fig. 2.10). Of the defined lidar facies, the high intensity values of the thin sheet sands contrasted sharply with the darker siltstones, which enabled the thin sheets to be easily identified and correlated despite the sub-meter thickness of these beds. Additionally, the thin sheet lidar facies is consistently correlative to the ends of several ribbon sandstone bodies forming ‘tiers’ that are commonly observed in similar deposits (Kraus and Gwinn, 1997; Figs 2.10 and 2.12). At least four of these sandstone body tiers were identified on the point cloud. Figure 2.12 shows the expression of several of these tiers where data noise due to multiple scan overlaps on the point cloud obscure their visibility. The mature paleosol lidar facies was also easily correlated across the length of the point cloud. The lower mature paleosol extended throughout the field area without any erosional breaks, while the upper mature paleosol is clearly truncated by thick sheet sandstone bodies on both the north and south regions of the point cloud.
Figure 2.12. Screenshots of the OSM with (top) and without (below) digitized ribbon sandstone channels (orange) and flanking thin sheet sandstone/siltstone wings (yellow). These channels are only partially visible on the point cloud seemingly due to data noise from multiple scan overlaps. The labeled elevations do represent sandstone wings mapped on the point cloud and digitized on the OSM. Interestingly, the thin sandstone wing at 1920 MASL (Meters Above Sea Level) also intersects with another ribbon channel ~320 meters to the east of this position.
Sandstone Body Width to Thickness Ratios

Several geologic lidar investigations have emphasized the ability to directly calculate sandstone body dimension from virtual outcrop models (Labourdette and Jones, 2007; Fabuel-Perez et al., 2009; Rittersbacher et al., 2014). In these studies the measured sandstone dimensions are quantitatively analyzed through traditional width versus thickness plots (Gibling, 2006). Understanding the distributions of sandstone body dimensions is important because these data can be used to improve subsurface alluvial stratigraphy models focused on predicting the connectivity of sandstone bodies in reservoirs and aquifers.

Although not very abundant in the study area, sandstone bodies present at Kutz Canyon can easily be measured from the outcrop surface model due to the fact that the outcrop face tends to run perpendicular to the general N-S paleocurrent direction (Fig. 2.13). Channel dimensions were calculated from one thick sheet and one ribbon sandstone. After measuring the dimensions of the thick sheet sandstone a paleocurrent measurement (163°) allowed for a true width calculation (Fig. 2.13). The calculated width to thickness ratio for this sheet sand proved was 465 m/16.5 m = 28.2. While a paleocurrent measurement was not obtained from the ribbon sandstone body, an estimated width to thickness ratio was calculated with the assumption that the exposure of the sandstone body is oriented approximately normal to paleoflow direction (Fig. 2.13). The same ribbon sandstone is thought to be exposed on both the north and south faces of the field area across a distance of 430 m based on similar elevations determined from the point cloud and since both exposures incise the lowermost mature paleosol. An estimated paleocurrent direction of 181° was found by digitizing the channel endpoints of
both exposures and then calculating the azimuth of the line joining these endpoints (Fig. 2.13). The channel W/T ratio for this ribbon sandstone was determined to be 141 m/8.0 m = 17.6. This approach does assume a minimal degree of channel sinuosity between the ribbon exposures, though the estimated paleocurrent direction is consistent with other measured paleocurrents.

Figure 2.13. (Following Page) Channel sandstone dimensions calculated from the OSM. Orange band is 25 meters except for figure C. A) Cross section view of ribbon sandstone channel with calculated paleocurrent determined by the midpoint between the two exposures. View to the north. B) Southern exposure of the ribbon channel thought to be coincident with the channel in A. C) Plan view showing the interpreted channel path of the ribbon channel (assuming minimal sinuosity). D) Thick sheet sandstone channel with paleocurrent calculated in the field; view to the south. This sandstone body terminates just to the west of the ridge in the figure, where its extent is shown by dashed boundaries.
Lidar Intensity Log Correlations

The feasibility of making accurate correlations between the proposed lidar facies was also examined by sampling 23 LILs across the entire point cloud. Each LIL was sampled every 100 meters laterally in four spatially separate groups (see inset in Fig. 2.14). The correlations between the LILs are comparable to what these fluvial strata may resemble in a series of closely-spaced gamma-ray logs collected from the subsurface. Correlations between the north facing LILs were more confidently selected due to a lesser degree of surface weathering and slope wash on these exposures, which is expressed by less noise in the intensity signal. Some correlations were also verified through comparison with the outcrop surface model and field observations.

Cross sections were constructed to illustrate the correlations between the LILs (Fig. 2.14). Each lidar facies could be identified in the LILs. The thick sheet sandstone bodies were especially prominent in the LILs and several could be traced across the diagram. An increase in the sandstone density towards the east of the northern line of LILs could also be recognized. This greater sandstone interval appears amalgamated on outcrop and is only laterally exposed for ~300 m on the north side of the field area until it enters the subsurface towards the east. The two mature paleosols visible in the LILs also showed a distinctive response between adjacent logs where truncated by sandstones in which the low intensity paleosol values contrast sharply with the relatively high sandstone response. Within the fine-grained siltstone and paleosol intervals several thin sheet sands could be traced between LILs.
Figure 2.14. (Following Page) LIL correlation diagram. The inset figure shows the position of each LIL. Representative correlations include: thick sheet sandstone are indicated in yellow, ribbon sandstones in orange, thin sheet sandstone in green, siltstone & paleosol interval in tan, and mature paleosols in red. Covered intervals are shown in gray. Importantly, this diagram illustrates how the distribution of lidar facies can be successfully mapped over a large area (~1 km²). The vertical scale of each LIL is in meters above sea level, the horizontal in intensity.
**Integrated Lidar Intensity Sections**

In order to examine how the lidar intensity signal varies laterally across an entire outcrop face one LIL was sampled over increasing widths of 1, 5, 25, 50, 100 and 200 meters. This was accomplished by selecting the lidar intensity data over the successive horizontal distances and running a moving average window set at 0.5 m.

Each successive LIL that is sampled over a greater width can be considered an integrated representation of lidar intensity and thus displays an averaged lithologic vertical section (Fig. 2.15). Averaging the intensity data over a greater area also appears to dampen the effect of noise in the data, such as vegetation or surficial rock cover.

This consideration of an average lithology on outcrop is similar to a method described by Craig (1955) in which lithofacies measured in five sections at selected locations in the Morrison Formation were averaged together to provide an idea of the relative thicknesses and proportions of facies.
Figure 2.15. Eight integrated LILs sampled over increasing horizontal widths. The intensity signal gradually becomes more refined when a greater horizontal swath of data is sampled.

The 1 m integrated LIL was also compared to the seven greater width LILs in a series of cross-plots (Fig. 2.16). This was conducted to quantitatively examine the differences in lidar intensity, and therefore lithology, across the sampled portion of the point cloud. Data were selected within a specific interval in each LIL above the thick sheet sandstone visible in Fig. 2.15. The embedded scatter plot in Fig. 2.16 illustrates the decreasing trend in correlation coefficient with increasing horizontal sample width. While there is undoubtedly some intensity value changes due to scan overlaps, the observed trend is attributed to slight differences in lithology included in the greater sample widths.
Figure 2.16. Cross plots of the 1 m sampled LIL with the integrated LILs. The decrease in the correlation coefficient between the successively greater LILs is attributed to slight changes in lithology and point cloud scan overlaps.
Wavelet Analysis

One quantitative method used to describe cyclic processes involves displaying a given time series in both time and frequency space by applying a wavelet transform to a dataset (Torrence and Compo, 1998). A wavelet operates as a function that separates a particular signal into scaled components. The application of the wavelet transform highlights the spatial variation of a cyclic succession by tracking distinct changes in frequency. In contrast to the Fourier transform, which uses a fixed window analysis size, the wavelet transform uses small window sizes at high frequencies and wide window sizes at lower frequencies. This characteristic of the wavelet transform allows separate components of a signal to be analyzed individually. In the Earth sciences, wavelet analyses have typically been applied to climate datasets, such as sea surface temperate and El Nino Southern Oscillation time series (Torrence and Compo, 1998). Several workers have also used wavelet analyses in stratigraphic studies as a means to identify and correlate cyclic trends observed in geophysical well logs (Prokoph and Agterberg 1999, 2000; Labrecque et al., 2011). Such analyses are done on depth series rather than time series datasets. A clear benefit of analyzing sedimentary successions using wavelets is that different wavelengths of cyclicity can be resolved at discrete depth intervals.

In this study, wavelet analyses were conducted on the 200 m width integrated lidar intensity log, since the wider averaged window provides a more refined intensity response, and thus a better average lithologic signal. The red channel derived from sampled RGB data in the outcrop surface model was also analyzed in order to test for possible cyclicity in the paleosol horizons. The data were entered into a pre-developed wavelet program made available online by Torrence and Compo (1998). This program
allows for user-defined settings before running the wavelet analysis. The resulting plots illustrate the spatial change in periodicity as a color-coded display of variation in the wavelet power spectrum.

The 200 m integrated LIL showed a distinct periodic field on the generated wavelet plot positioned at ~7 m, spanning horizontally 35 m. However, this LIL did include a ~15 m thick sheet sandstone at the base of the section, so a second run was conducted on the section with this sandstone omitted. This was primarily done in order to focus on describing the cyclicity present in the thin sheet sands encased in the finer paleosol-bearing interval. The wavelet plot of this subsampled interval exhibited a significant periodicity centered at 6.5 m over a ~25 m vertical interval (Fig. 2.17). The periodicity band positioned around 3 m is believed to be unimportant, and was ignored. Upon inspection the high lidar intensity peaks in the integrated LILs which exhibit the observed wavelet periodicity are all thin sheet sands or coarse siltstones. These facies are nearly always correlative with ribbon sandstones, and appear to form thin wings that extend laterally from both ends of the ribbon sands (Figs. 2.10 and 2.12).

Two wavelet runs done on vertical 1 m sections of red channel data collected from the OSM did not detect any significant periodic fields in the wavelet power spectrum. This result indicates either the lack of cyclicity present in the paleosols, or that the resolution of the OSM was not adequate for such analyses.
Figure 2.17. A) Sampled data taken from the 200 m integrated LIL. B) Wavelet power spectrum. The strongest field of periodicity occurs at 6.5 m between 1905-1928 MASL. The cross-hatched region is the cone of influence where edge effects become significant. Data peaks in this interval are relatively coarse grained thin sheet sandstones/siltstones. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. The black contour represents the 90% confidence interval using a red-noise (autoregressive lag1) background spectrum. C) The global wavelet power spectrum.

Figure 2.18. (Following Page) Wavelet analysis results of a 1 m LIL sampled from the same ridge as the 200 m integrated LIL (top) and from a 1 m LIL positioned ~150 m away (bottom). The same parameters were used in these analyses as were in the wavelet analysis displayed in Fig. 2.17. Both analyses reveal a similar periodicity band centered ~6.5 m.
Additionally, two separate wavelet analysis runs were conducted on 1 m sampled LILs from the same ridge as where the 200 m wide LIL was collected, and also from the south side of the point cloud ~150 m adjacent from the ridge (Fig. 2.18). The wavelet power spectrum of the 1 m ridge section shows a similar periodic field that occurs over approximately the same vertical interval as the 200 m LIL. The wavelet power spectrum of the south LIL does display a relatively high power in the same band (~6.5 m) as the previous wavelet plots, though this field is most pronounced at a higher stratigraphic level and does not fall within the 90% confidence interval. This less pronounced periodicity is attributed to a combination of data noise and distance fade, both of which are mainly absent from the 1 m ridge LIL. These two wavelet analyses corroborate the results of the initial 200 m integrated LIL analysis that indicate a ~6.5 m periodicity band is present in the intensity data and that it extends horizontally on outcrop for at least 150 m.

The full interval of the studied section lies within the reversed zone of the geomagnetic polarity chron 27 (Williamson, 1996). Based on the most recently published geomagnetic polarity time scale this chron has a duration of 0.977 Ma (Gradstein et al., 2012). However, the exact positions of the reversal boundaries of C27r are not precisely known in Kutz Canyon. It is estimated that the stratigraphic interval consists of ~0.75 Ma of the duration of C27r (Williamson, personal communication, 2014). The entire thickness of the succession at the field site in Kutz Canyon is around 140 m. From these values, an approximate accumulation rate for these strata is 0.19 mm yr⁻¹. Using this accumulation rate value, an estimate of the amount of time represented by the recorded 6.5 m periodicity field determined from the wavelet analysis can be calculated. Each 6.5
A 6.5 m cycle was found to possess an average recurrence interval of 34 kyr. This value increases to 37 kyr if the ~7 m wavelet periodicity found in the LIL containing the thick sheet sandstone is considered.

The 34 kyr average recurrence interval estimated for the 6.5 m periodicity is interpreted as the amount of time that separated avulsion events in the Nacimiento fluvial systems. This assertion is supported by the stratigraphic interpretation that the ribbon sandstones and thin sheet sands represent crevasse channels and splays, respectively. A similar time period of 41 kyr was documented between avulsion deposits in the lower interval of the Paleocene Fort Union Formation in the Bighorn Basin of Wyoming (Kraus & Wells, 1999). An alternative explanation for the 34 kyr recurrence interval is that the ribbon channels and thin sheet sands are deposited during lobe switching events on a distributive fluvial system. Reoccupation intervals between channel-fill sandstones on a documented DFS from the Miocene of the Ebro Basin in Spain yielded values between 120 kya-270 kya, depending on the inferred position on the fan surface (Nichols, 2013). These larger reoccupation intervals were due to a much greater estimated accumulation rate (90 mm yr⁻¹) for this basin.

More extensive stratigraphic field work would have to be conducted in the Nacimiento Formation succession in order to test the hypothesis that the observed 34 kya reoccurrence interval is related to lobe switching on an ancient DFS.
Discussion

This work demonstrated several lidar applications that, when combined with traditional field methods and measured sections, can be used to advance the understanding of fluvial successions. While previous work demonstrated by Burton et al. (2011) indicated that lidar intensity values were sensitive to lithology in specific deposits, this work expanded upon these findings by introducing distinct lidar facies and by illustrating how these facies can be correlated across 100s of meters of outcrop. The presented LIL correlations provide a unique analog of how these deposits may appear in subsurface gamma ray logs. Further, quantitative tests conducted on lidar datasets, as demonstrated in the wavelet analyses in this project, have the ability to reveal cyclicity that may not be discernable with measured sections alone. Discretion must be exercised on specific outcrops if this analysis is conducted in order to confirm that the lidar signal is properly representing lithology. Although only two sandstone body dimensions were recorded in this study, evaluating channel dimensions using lidar datasets at outcrops with abundant sandstone exposures has proven that significant detail on vertical trends in fluvial architecture can be discerned, as recently conveyed by Rittersbacher et al. (2014).

Another important application of lidar datasets in stratigraphy is the ability to calculate the geometry of stratal units. In this study, after removing the minute dip (0.295°) from the point cloud, all of the subsequently digitized beds paralleled the removed dip direction. This indicated that these beds were essentially flat and that no distinctive bed geometries were being recorded. It is possible that the 1 km-scale of the field area is too small to begin to discern intermediate, or meso-scale, fluvial geometries such as channel-belts and crevasse splay complexes. This assertion is supported by the
observation that the thin sandstone-siltstone ‘wings’ that flank ribbon channels in the field area extend across the length of the point cloud.

The inability of the lidar intensity data to show fine textural details on the cm-scale highlights one disadvantage of this workflow. This issue is particularly evident at field sites with badland topography, like the strata in Kutz Canyon, where a surface weathering crust exists.

**Conclusions**

This investigation of the fluvial strata of the Nacimiento Formation using a 3D lidar dataset and outcrop surface model combined with measured sections yielded the following results:

1. Intensity data values collected from the lidar surveys are responsive to specific lithologic types. The relative intensity responses can be categorized into lidar facies; however these lidar facies may be site specific. The defined lidar facies are correlative over an area of approximately 1 km².

2. Width to thickness ratios of different sandstone channel bodies, including ribbon and thick sheet sandstones, can be directly calculated from an outcrop surface model generated from lidar scans and aligned field photographs. In situations where paleocurrents are not known channel orientations across outcrop exposures can be determined in order to estimate true channel widths.

3. Vertical 1D lidar intensity logs (with an inverted x-axis) approximate the form of subsurface gamma ray logs. When correlated across the point cloud, a suite of intensity logs resembles a group of closely-spaced gamma ray logs.
4. A lidar intensity log sampled over a 200 meter horizontal distance integrates the intensity signal associated with specific lidar facies, and hence provides an averaged view of lithology.

5. Wavelet analyses conducted on a sample of intensity data from the point cloud indicated a vertical swath of periodicity centered at 6.5 m at this study site. The beds responsible for this periodicity are thin sheet sandstones and coarse-grained siltstones that are adjacent to ribbon sandstone channels. A return interval of 34 kya was determined for these beds based on an estimated deposition rate. These cyclic beds are thought to represent episodes of avulsion, or possibly lobe switching on a distributive fluvial system. This method could be used at other outcrop locations in the area to determine if this return interval is a reasonable estimate.

Chapter References


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CHAPTER 2. A CASE STUDY OF ALLUVIAL STACKING PATTERN
ANALYSIS ON MEASURED STRATIGRAPHIC SECTIONS FROM THE
NACIMIENTO FORMATION, KUTZ CANYON, NEW MEXICO

Introduction

Numerous studies on mud-rich alluvial successions containing intercalated paleosols have documented a hierarchy of cyclic aggradational deposits generated in response to both allogenic and autogenic processes (e.g., Kraus 1987; Kraus and Aslan 1999, Atchley et al., 2004, 2013; Cleveland et al., 2007). These studies report a typical hierarchical scheme consisting of a three-tiered depositional cyclicity including meter-scale and ten-meter scale cycles that stack into hundred-meter scale fluvial sequences.

Several recent studies have also focused on describing the stacking-patterns of observed cycles within alluvial successions (Prochnow et al. 2006; Atchley et al., 2004, 2013; Cleveland et al., 2007). These studies report meter-scale fining-upward cyclic deposits as fluvial aggradational cycles (FACs) that stack into fining-upward 10 meter-scale fluvial aggradational cycle sets (FACSEtS) and 100 meter-scale fluvial sequences. Atchley et al. (2004) and Cleveland et al. (2007) employed a stacking-pattern analysis to evaluate stratal thickness trends and to assign potential nonmarine sequence boundaries and systems tracts. This stacking-pattern analysis was originally developed by Fischer (1964) and subsequently adopted by other carbonate stratigraphers as a means to examine thickness trends in peritidal carbonate successions. This method was adopted by Atchley et al. (2004) and Cleveland et al. (2007) for use in alluvial deposits and involves plotting each FAC thickness as the cumulative deviation from the mean FAC thickness. The mean
grain size for each FAC is also plotted in this manner. In addition, trends in paleosol maturity within the studied alluvial successions were used as measures of sedimentation rate. Each fining-upward FAC has an abrupt basal boundary that is overlain by sandstone or mudstone which grades upward into either an overlying paleosol or the base of the succeeding FAC. Assemblages of FACs are grouped into fining-upward FAC sets that are composed of groups of thinning-upward or thickening-upward cycles. The largest scale cyclic units are fluvial sequences which usually span 100s of meters and are comprised of stacked FAC sets that also reportedly fine upwards.

In this project meter-scale fining-upward cycles recorded in both measured sections from the field area discussed in Chapter 1 were evaluated using an alluvial stacking pattern analysis advocated by Atchley et al. (2013). All of the previously cited papers that focus on the FAC analysis describe these cyclic units from 1D stratigraphic sections in their respective field areas. Atchley et al. (2013) discusses the potential to correlate these cyclic units on outcrop and does emphasize that FAC analysis is best suited to field areas with significant 2D to 3D exposures. The impetus in this study to do FAC analysis was to determine the similarity of accommodation trends revealed from FACs measured from two closely spaced stratigraphic sections; both sections are separated by approximately 330 m. FACs were only recorded in the trenched sections since textural trends are masked by the weathering crust on outcrop.
Cumulative Deviation Plot Analysis

As mentioned previously, the two measured sections are mainly comprised of a paleosol-rich succession capped by thick sheet sandstones. After measuring both sections each FAC and FACset boundary was identified and recorded (Figs. 2.1 and 2.2). Next, the calculated FAC thicknesses were then imported into an Excel program developed by Husinec et al. (2008) specially designed to output cumulative deviation plots of mean cycle thickness rather than constructing them manually.

The generated plot trends that include all of the measured cycles from both sections show clear up-section differences in form (Fig. 2.3). The FAC (n = 58) thicknesses in section I display a gradual thinning trend over 22 cycles, followed by a thickening trend that eventually levels and then thins over the last 10 cycles. The plot of section II (n = 41) thins over 5 cycles, abruptly thickens and then gradually thins to the section top. Nine FACsets were identified in section I, and 8 in section II. While both sections are similar lithologically, only two of the designed FACsets from the accommodation plots are directly correlative (Fig 2.3). A thick (15 m) sheet sandstone body present in section II is visible in the plot as the large deflection towards thicker than average cycles. The other FACsets are comparable between the sections, though these differ in number and thickness due to bed thickness changes. Although not at the same stratigraphic level, the last two FACsets in both sections thin upward.
Figure 2.1. Measured stratigraphic section I with marked FACs and FACsets
Figure 2.2. Measured stratigraphic section II with marked FACs and FACsets

Legend
- Mature Paleosol
- Clay
- Siltstone
- Sandy Silt
- Silty Sand
- Sandstone
- Tabular cross beds
- Trough cross beds
- Mottles
- Burrows
- Slickensides
- Root Traces
- Cannon-Ball
- Concretions
- Mud rip-up clasts
- Strike & Dip
- Paleocurrent
Since the anomalously thick sandstone body in section II clearly influenced the resultant accommodation plot, the analysis was also conducted on both sections starting with the FACs above the stratigraphic level of the sandstone body (Fig 2.4). The trends in these plots are significantly more congruous. Both plots show a gradual thickening trend that peaks at the same FAC and then slowly thins for the remainder of the plot. This second analysis demonstrates the sensitivity of the accommodation plots to exceptionally thick beds in a stratigraphic section.

The different up-section cycle trends expressed by running the analysis on the original thickness of the two measured sections, which are only separated by ~330 meters, do emphasize the problem of using cumulative deviation plots in alluvial successions that can be notoriously heterogeneous. This problem is best expressed in section II, where the presence of the anomalously thick sheet sandstone skews the mean cycle average and causes the remainder of the cycles to show a thinning upward cycle trend that contrasts with the thickening upward trend present in section I. While the second analysis showed that the thickness trends were certainly more correlative without the sheet sandstone, any two full sections that span ~100 m vertically that are separated by a few 100s of meters in the field area would also likely contain thickness deviations in accommodation plots due to horizontal lithologic variability. The differences in the form of the two cumulative deviation plots generated from the full measured sections would complicate any interpretation of accommodation changes or designation of nonmarine sequence systems tracts.

Alternatively, the accommodation trend indicated in the cumulative deviation plot of section II (n = 41) may be compromised by a low number of recorded cycles since it
has been demonstrated that statistical conclusions from these plots are suspect if the number of included cycles is below a threshold of 50 (Sadler et al., 1993). This complication is especially relevant to the second FAC analysis done above the thick sheet sandstone because both of these accommodation plots contained less than 40 cycles each. Any future studies that seek to use cumulative deviation plots in alluvial successions should be cognizant of this minimum cycle number, as well as the potential that lateral lithologic variations in stratal thickness can significantly affect the overall plot trends.
Figure 2.3. Fischer plots generated from both measured sections. The plot trends are significantly different though the sections are separated by ~330 m. This observation complicates any potential accommodation interpretations. The three correlation lines indicate FAC sets with identical cycles.
Figure 2.4. Fischer plots generated from both measured sections above the stratigraphic level of the thick sheet sandstone present in section I. The cycle thickness trends are significantly more correlative without the influence of the thick sandstone body. Both cycle trends show a gradual thickening trend followed by a gradual thinning trend. The low cycle numbers in both sections (<40) may make these results statistically questionable.
Conclusions

While fluvial aggradational cycles were recognized in the measured stratigraphic sections in the field area, the resulting accommodation plots displayed different trends as a result of local lithologic variation, mainly from a thick sheet sandstone body. These trends suggest different accommodation interpretations between sections separated by ~330 m. However, a second accommodation plot run above this sandstone produced consistent thickness trends between the two sections. Despite the improved results of the second plot run the alluvial stacking pattern analysis based on FAC cycle thickness trends could not be effectively applied between the two full measured sections in this study. As mentioned in Atchley et al., (2013) conclusions based on this methodology are strengthened when the observed results can be laterally traced over kilometers across multiple stratigraphic sections. Atchley et al., (2013) also indicate that stacking pattern results are likely best represented in eustatically controlled tributary fluvial systems where sea-level changes directly influence fluvial accommodation changes.

Chapter References


CHAPTER 3. FUTURE WORK POTENTIAL AND GENERAL CONCLUSIONS
ON USING LIDAR TO EVALUATE FLUVIAL STRATA IN KUTZ CANYON

Future Research Directions

Based on the results of this study, several recommendations can be made on using lidar-derived data and virtual geologic models to investigate the fluvial deposits of the Nacimiento Formation. Fully surveyed lidar datasets seem to be best suited towards a larger scale project that would cover several kilometers of outcrop in Kutz Canyon that would focus on tracing lateral changes in fluvial geometries. With a developed outcrop surface model, 3D bounding surfaces present in sandstone bodies could also be digitized at this scale. A future lidar-based study could potentially examine over 7.5 km of outcrop along Kutz Canyon (Fig. 3.1). Fluvial geometries calculated at this scale could be compared to modern systems, such as the Taquari megafan in Brazil, to test whether or not the deposits of the Nacimiento Formation are consistent with those observed on modern distributive fluvial systems (Fig. 3.1). However, a lidar based study on a multi-kilometer scale would face complications, such as the high number of scans and computer processing resources required to construct a large scale virtual object. This problem is especially evident with terrestrial laser scanning, which requires ground based data collection. A large project using terrestrial scanning would likely need a scanner that could rapidly acquire data along with ground targets to speed internal scan alignments. A possible, though costly, solution to facilitate lidar data collection over large areas would be to acquire the data with a helicopter, as was done recently by Rittersbacher et al. (2014).
Figure 3.1. Above: An oblique Google Earth screenshot depicting the areal extent of the field area in this study (oval). A future digital project could potentially study fluvial exposures over a 7.5 x 4 km area across Kutz Canyon. View is to the south. Scale bar is 7.5 km. An expanded lidar project may discover intermediate fluvial geometries that may resolve if the deposits of the Nacimiento Formation contain distinct avulsion belts that are observed on modern distributive fluvial systems, such as the Taquari megafan shown below. Bottom: Satellite image of a portion of the Taquari megafan showing avulsion belts and abandoned splay complexes (from Assine, 2005).
Chapter references


CONCLUSIONS

This work serves as another demonstration of the applicability of using digitally rendered outcrops to better understand and quantify fluvial systems. The observation that lidar intensity data are responsive to lithology is probably to some degree site-specific, and should be validated at other locations, though the relative intensity data returns from the fluvial deposits in Kutz Canyon are distinctly tied to facies types and are laterally correlative across the ~1 km² field site. These lidar facies correlations were improved through the removal of the structural dip in the deposits using 3D lidar processing software. Sandstone dimensions calculated from the outcrop surface model exhibit another practical use of these data; one channel paleocurrent was estimated graphically between canyon exposures. The correlated pseudo-gamma ray lidar intensity logs also provide a unique view of what a closely grouped series of subsurface wells would resemble. Additionally, lidar intensity logs integrated over greater horizontal distances (>1 m) show refined intensity values that provide an averaged depiction of lithology. Wavelet analyses conducted on one of these integrated logs discovered a zone of periodicity centered at 6.5 that extended vertically for ~25 m across at least four thin sheet sandstones all connected laterally to ribbon channel sandstones. Based on an estimated depositional rate, a return interval of 34 kya was determined for these thin sheets, which are interpreted as either repetitive crevasse splays or lobe switching events on a distributive fluvial system.

An alluvial stacking pattern analysis conducted on two measured sections in the study area produced conflicting results due to horizontal lithologic variation across ~330 m of outcrop. However, the same analysis performed on the sections above the thick
sandstone body yielded congruent accommodation trends. Although this second run was more successful only around 35 cycles were documented, which is below the cycle number \( n = 50 \) that has been recommended for statistical robustness when using such plots. Studies that draw conclusions from this analysis should establish that the observed cycle trends are laterally continuous over significant distances.
APPENDICES

Appendix A. Virtual outcrop reconstruction summary

Appendix B. Code for macro written to iteratively step through lidar dataset using a plane

Appendix C. Code written to average lidar intensity data over a given depth window
Appendix A. Virtual outcrop reconstruction summary

Lidar Scan and Static GPS Station Acquisition

All six lidar scans in the field area were collected using an Optech ILRIS-3D terrestrial laser scanner. In the field, the scanner body is attached to a rotating pan/tilt extension that allows for custom field-of-views. The scanner and the pan-tilt are both mounted on a portable tripod. The scanner is operated on site through a network connected laptop that is used to select the desired scan settings and the region of interest (ROI) over the target area where the data will be collected. At four of the lidar stations, three located on the south rim of Kutz Canyon and one on a high ridge on the north side of the field area, survey-grade static global positioning measurements were collected with a Topcon GR-3 receiver system. This system gathers data from all three available global satellite positioning systems to provide centimeter scale spatial accuracy.

Scan Processing

Once collected, the lidar scans must be internally registered and edited. Registration is done using the scanner software Polyworks IMAlign and IMSurvey, developed by InnovMetric. First, the scans are parsed using the Optech ILRIS-3D Parser software. Next, each scan subgroup was imported into IMAlign and internally aligned using an iterative best-fit technique. This method requires that at least one 3D image is locked during the iterative process. After the scans are internally aligned they are still not spatially linked, so a series of image control points were digitized on the individual scans in IMSurvey. The image control points are then imported into IMAlign and each scan group is aligned according to corresponding control points using an N-point pair.
alignment function. Each unaligned scan group is then added to the aligned subgroups piece-by-piece until all of the scans are successfully aligned. The computed alignments are stored as a series of alignment matrices that can be applied in IMSurvey using a data-file transform macro to visualize and study the fully aligned point cloud. Following this step the global reference points from the GPS stations are loaded into IMAlign and the determined huge translation (238160, 4045578, 2014) is set which transfers the scanner coordinate system into the large-number UTM coordinate system. The max edge length for all of the calculated normal in the scans was set to 0.5 m prior to importation into IMSurvey. Prior to mesh construction the point cloud is edited in IMSurvey. The foreground between the outcrops in the point cloud was deleted, as was any data points collected outside of the field area.

**Photo Collection and Processing**

A total of 1100 digital field images were collected at the field site using a Nikon D700 12.1 MP digital SLR camera fitted with a AF-S Nikkor 1:18 G lens. All images were shot in raw format, thus avoiding any unwanted processing by the camera. In the field, right before acquiring the photographs, the camera’s exposure and white balance was manually set by metering an 18% gray card. The camera parameters were set for all of the photographs with an aperture of f/13, shutter speed of 1/320, and an ISO setting of 200. The lens focus was set to infinity during acquisition. After setting the camera exposure and white balance, a reference image of a ColorChecker 24 patch target was collected for later photo processing to normalize the scene’s brightness. Images were collected along the canyon rim of Kutz Canyon looking down at the outcrop and also along the floor of the canyon.
The photo processing of the collected images consisted of developing the raw images, then aligning the images using Agisoft’s PhotoScan software. The raw images were processed by empirically determining the luminance values from the ColorCheck card and running a linear regression through the data. This value (1.841) was then added to the command script that generated the sRGB JPEG image files. Next, the images are imported in PhotoScan and aligned. PhotoScan aligns the images by determining the position and orientation of the images and then building a point cloud model of the results. After several poor alignment results the foreground and background of each image was masked using PhotoScan. This method eliminates areas that can complicate image reconstruction. Once the masks were applied three separate exposure areas were independently aligned in chunks. Next, the entire scene was successfully aligned by merging these three chunks after using the highest point-based alignment accuracy setting. At this point the constructed meshes (described in the next section) can be imported and textured using the calibrated images.

**Mesh Construction**

This step in the workflow involves building a 3D triangular mesh from the lidar point cloud. The mesh is constructed in IMEdit by running an algorithm called PoissonRecon that has been added to PolyWorks through a macro. The octree depth, which controls the resolution of the mesh by determining the number of cells in the voxel grid, was set to 12. Once generated, the mesh must undergo post-processing. First, the large triangles created in unsampled areas containing no point cloud data are removed by selecting specific triangles by edge length and then deleting them. Next, the remnant triangle shards that remain after the previous step are eliminated by deleting selected triangle shells. The
triangle vertices were merged within a tolerance of 0.02 m. Following this step the number of faces in the mesh are reduced by running IMCompress. This application generates fully subsampled meshes at 25-50-75-90 percentiles. Most meshes contain sufficient accuracy even with 50-75% polygon reduction. The mesh used in this project was subsampled at 75%. After subsampling the mesh any intersecting triangle faces are removed; any small holes creating by removing the intersecting faces are then filled. The final stage involves smoothing sharp edges on the mesh by running an optimization process. The next stage in the overall workflow, uv unwrapping, can demand significant computing resources. In order to speed this process the final mesh product was split into 25 separate .ply files.

**Texture Mapping**

This stage in the workflow involves texturing the acquired field photographs onto the generated mesh surface, ultimately producing the photo-realistic outcrop model. The photogrammetric software package PhotoScan is used to texture mesh. Texture editing is accomplished using the program Blender, which is a sophisticated 3D graphics and animation software. All operations using Blender were conducted using Linux in order to expedite processing time.

**UV Unwrapping**

UV unwrapping is the process of creating a 2D representation of a 3D surface. The created meshes must be UV unwrapped in order to be textured. A summary of the UV unwrapping process follows. Blender’s Smart UV Project tool is used for unwrapping.
Three specific tools control how a mesh is unwrapped. The angle limit controls how the faces are grouped. Higher limit values produce a higher number of groups with less distortion and vice versa. The Island Margin controls the packing density of the UV islands (or groups). The third parameter is the Area Weight. The Area Weight functions by weighting the contribution of each face’s area to the overall mean normal direction of all the faces in the island. All 25 of the unwrapped subsampled meshes were executed using an Angle Limit of 50, an Island Margin of 0.01, and an Area Weight of 1.00.

**Baking Photos and Texture Painting**

After each mesh has been UV unwrapped it is exported as an OBJ file from Blender and imported into PhotoScan. All of the aligned photos in the vicinity of the individual meshes are selected and are baked onto a texture map. The Keep uv texture mapping mode was used to build the textures. The Blending mode was set to Average, which averages the pixel color from all of the selected images. Also, the Atlas width and height was set to 8K. Once all 25 meshes were textured they were then exported as OBJ files and selected textures were reimported into Blender for touch-up texturing.

Additional texture painting in Blender was only done around 10 of the meshes texturing in PhotoScan. The remaining textures were deemed accurate enough for inclusion in the final outcrop surface model product. The process of texturing painting in Blender is fairly complex; it begins with setting up the necessary Blender project parameters and then importing the specific mesh object with its respective cameras. These undistorted camera poses are preselected from PhotoScan as the best perspectives of the given texture. To begin painting the specific camera perspective is selected and the Texture Paint mode is
enabled. Two texture painting options exist: either the entire camera perspective can be applied to the mesh, or more refined edits can be performing using a paint brush feature. A combination of both options was used to paint textures in this project. When finished, the textured meshes were individually imported into IMSurvey to complete the generation of the outcrop surface model.
Appendix B. Code for macro written to iteratively step through lidar dataset using a plane

# Copyright (C) 2013 Jed Frechette
#
# This program is free software: you can redistribute it and/or modify
# it under the terms of the GNU General Public License as published by
# the Free Software Foundation, either version 3 of the License, or
# (at your option) any later version.
#
# This program is distributed in the hope that it will be useful,
# but WITHOUT ANY WARRANTY; without even the implied warranty of
# MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
# GNU General Public License for more details.
#
# You should have received a copy of the GNU General Public License
# along with this program. If not, see <http://www.gnu.org/licenses/>.
#
#----------------------------------------------------------------------------------
# Jed Frechette <jed@lidarguys.com>
# Created: 15 January 2013, Modified Code Written By Jeff Carritt with assistance from Jed Frechette, July #2013
# version "4.0"
#
# Use a plane to iteratively step through slices of a data set.
# # Three user specified variables must be set. These variables are hard
# # coded into this script so that after they are entered once the script can be
# # run multiple times without reentering them. These variables are:
# # plane_num The index of the reference plane.
# # width The width of each slice.
# # overlap_percent The overlap, as a percent, between adjacent slices.
# # Each time the macro is run the reference plane will be moved along
# # its normal before the slice is created. The distance the plane moves is
# # determined by the slice width and overlap_percent

##################################################################
# Edit these variables
##################################################################
DECLARE plane_num 1
DECLARE width 1
DECLARE step 100
DECLARE base_name "section"
DECLARE n_sections 11

##################################################################
# Do not make changes below this line
##################################################################
DECLARE normal_x 0
DECLARE normal_y 0
DECLARE normal_z 0
DECLARE max_distance EXPR ($width/2)
DECLARE error_stat
DECLARE out_dir
DECLARE section_num 1

INPUT DIRECTORY_PATH (out_dir, "Output Directory")
MACRO GET_ERROR_STATUS(error_stat)
IF $error_stat == "Error"
    MACRO END
ENDIF
#WINDOW REFRESH ("Off")

TREEVIEW SELECT NONE
TREEVIEW DATA SELECT ALL
VIEW VISIBILITY OBJECT_ELEMENTS RESTORE ()
TREEVIEW OBJECT_ELEMENTS SELECT NONE ()
TREEVIEW SELECT NONE
SELECT MODE MARK
FILE EXPORT_OBJECT SELECTED_DATA_POINTS_TO_TEXT_FILE NB_DIGITS ( 3 )
SELECT OPTIONS MAX_DISTANCE ($max_distance)
SELECT OPTIONS ERROR_DIRECTION ( "Shortest" )
SELECT OPTIONS MULTIPLE_REFERENCES_PRIMITIVES ( "Close to One" )
SELECT OPTIONS KEEP_ERRORS SIGN ( "All" )
SELECT OPTIONS KEEP_ERRORS TOLERANCES ( "All" )
SELECT OPTIONS USE_MAX_ANGLE ( "Off" )

WHILE $section_num <= $n_sections
    TREEVIEW PRIMITIVE PLANE SELECT ( $plane_num, "On" )
    TREEVIEW PRIMITIVE PLANE PROPERTIES NORMAL GET (normal_x, \normal_y, \normal_z)
    ALIGN MANUAL TRANSLATION (EXPR($step*$normal_x), \EXPR($step*$normal_y), \EXPR($step*$normal_z))
    SELECT DATA_POINTS FROM_PRIMITIVES ()
    TREEVIEW DATA SELECT ALL
    FILE EXPORT_OBJECT SELECTED_DATA_POINTS_TO_TEXT_FILE ( "$\{out_dir\}\$\{base_name\}\$\{section_num\}.txt", \"Points + Intensities\")
    TREEVIEW OBJECT_ELEMENTS SELECT NONE
    TREEVIEW SELECT NONE
    ++ section_num
ENDWHILE
TREEVIEW PRIMITIVE PLANE SELECT ( $plane_num, "On" )
ALIGN MANUAL TRANSLATION (EXPR(-$n_sections*$step*$normal_x), \EXPR(-$n_sections*$step*$normal_y), \EXPR(-$n_sections*$step*$normal_z))

WINDOW REFRESH ("On")
WINDOW REFRESH NOW
Appendix C. Code written to average lidar intensity data over a given depth window

program lidardepthavg

c  CREATED TO TAKE POINT CLOUD DATA AND FIND THE AVERAGE OVER A DEPTH
  WINDOW.

character*40 infile,outfile
real z(10000000), intens(10000000)

c  Read in the parameter file
print*,'What is the input file name?'
read(5,*) infile
print*,'What is the output file name?'
read(5,*) outfile
print*, 'Zmin, Zmax?'
read(5,*) zmin, zmax
print*, 'What is the step window size?'
read(5,*) zstep
print*, 'how many lines of data (how many points in point cloud?)'
read(5,*) nlines

c  Begin to search data and compile the window averages

print*, 'opening data file'
open(8,file=infile,status='old',form='formatted')
print*, 'opening output file'
open(9,file=outfile,status='unknown')
print*, 'opened input and output files'

c  Read input file

  do i=1,nlines
    read(8,*) xdummy, ydummy, z(i), intens(i)
  enddo

print*, 'I read the file'

elev=zmin
steps = (zmax-zmin)/zstep
nsteps = nint(steps)

print*, 'elev, zstep'
print*, elev
print*, steps
print*, nsteps

do i=1,nsteps
  total=0
  ni=0
  print*,'here i am', i
  do j=1,nlines
    if(z(j).gt.elev) then
      if(z(j).le.elev+zstep) then
        total = total+intens(j)
        ni = ni+1
      endif
    endif
  enddo
  avg=total/ni
  print*,'average = ',avg
  elev1=elev+(zstep/2)
  write(9,*), elev1, avg, ni
  elev=elev+zstep
enddo

close(9)
print*, '**************************************************'
print*, 'Averages file written,'
print*, '**************************************************'
print*, '(:

stop
end