Quaternary incision history of the Black Canyon of the Gunnison, Colorado

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QUATERNARY INCISION HISTORY

OF THE

BLACK CANYON OF THE GUNNISON, COLORADO

by

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B.S., Geological Sciences, University of Oregon, 2005
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ABSTRACT

The Gunnison River, a major tributary of the Colorado River houses the Black Canyon, one of the narrowest (350 m) and deepest (700 m) bedrock canyons in North America and is an excellent location to study Cenozoic river evolution. The modern longitudinal river profile exhibits a prominent knickpoint within the Black Canyon. In the last 640ka, average bedrock incision rates surrounding the knickpoint are unbalanced and vary from 130-150 m/Ma (downstream) to 470-600+ m/Ma (within) to 90-95 m/Ma (upstream), necessitating knickpoint migration. The 640ka profile, reconstructed from terraces containing Lava Creek B ash, indicates ~25km upstream migration. The best age constraint and incision rate of Black Canyon comes from projecting the ~640 ka Shinn-Boswick tributary to its intersection with the Gunnison, suggesting 350-400 m of incision 700m total depth in the last 640ka.
Assuming steady average rates this indicates that Black Canyon has been carved in the last 1.4 Ma. Ten strath terraces ascend from the North Fork -Gunnison River to 670 m above the modern river. A cosmogenic burial date of ~ 1 Ma on the seventh terrace anchors the 640ka paleoprofile (at Qt 5/6) giving an average incision rate of 220 m/Ma. Approximately graded with the North Fork terrace, the Redlands Mesa pediment is tentatively assigned the ~1Ma age. Strath terraces and pediments are inferred to record glacial-interglacial stages.

Long-term incision rates on the Gunnison River over the time span of 10 Ma are ~160 m/Ma below and ~55 m/Ma above the knickpoint. A paleo-Gunnison was in approximately its present course ~30 Ma as indicated by ash flow units, but the bedrock strath was ~500 m lower than at 10 Ma; hence bedrock incision rates were small (or negative due to surface uplift) and gradients were low from 30 Ma to 10 Ma. Although driving forces remain poorly constrained, a hybrid model includes recent rapid incision, knickpoint migration, drainage reorganization, and unequilibrated river profiles are responding to base level fall accompanying increased climate erosivity, local neotectonics, and epeirogenic surface uplift with accompanying basaltic magmatism.
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Introduction, Motivation, and Goals

Major questions about the Rocky Mountains involves the time(s) of their 1) uplift above sea level and 2) of the generation of the high relief. As firm constraints: the region was at sea level until 70 Ma (late Cretaceous) and now stands at an average elevation of > 3000 m, with peaks extending to 4500 m. Several models have been published. 1) all Laramide uplift (refs), 2) Oligocene uplift (refs), 3) multistage uplift and ongoing uplift (Pazzaglia and Kelley, 1998), 4) all young uplift (Trimble, 1980; Epis and Chapin, 1975; Eaton, 1987). Most agree that relief generation is young and influenced by increased erosivity of climate (Molnar and England, 1990), as well as young faulting (Hansen, 1965), and/or ongoing neotectonic activity in the Rocky Mountains in response to surface uplift due to underlying buoyant mantle (Karlstrom et al., 2005).

The Gunnison-Colorado drainage system traverses the entire southwestern portion of a wide western U.S. orogenic plateau, from the Rockies, crossing the Colorado Plateau and Basin and Range before entering the Gulf of California (Figure 1). The upper Colorado River system is commonly thought to have existed since the Oligocene (Hunt, 1969; Hansen, 1987) based on observations that Oligocene ash flow units thicken into paleovalleys that approximately coincide with today's Gunnison (Hunt 1969). However, the entire river system was not integrated into its present configuration until after 6 Ma, when the Gulf of California opened and the closed basins of the lower basin became integrated with upper basin drainages into a single river that flowed through Grand Canyon (Luccitta et al., 2002). One of the
goals of this paper is to evaluate whether this post-6Ma drainage integration and or other young influences on the drainage pattern is reflected in the upper parts of the basin in terms of young features and perhaps rapid Pliocene to Quaternary incision (Hansen, 1987; Kirkham et al., 2002; Karlstrom et al., 2005) and drainage reorganization (Cater, 1966; Hanks et al., 2001; Stevens, 2002). In order to evaluate the evolution of the upper Colorado/Gunnison River system, it is important to examine both short- and long-term histories of different reaches of the upper Colorado/Gunnison River system.

**RIVERS CARVE THE LANDSCAPE**

Rivers are a sensitive record of both climatic (Pederson et al., 2002; Bonnet and Crave, 2003) and tectonic (de Broekert and Sandiford, 2005; Karlstrom et al., 2007) events and the evolution of topography (Whipple and Tucker, 1999; ). The Gunnison River is a major tributary within the upper Colorado River system. Originating in the Sawatch and Elk Mountain ranges of west-central Colorado, the Gunnison River flows westward from the Sawatch Range, between the San Juans and West Elks, then parallel to the south side of Grand Mesa, to Grand Junction, where it meets the Colorado River (Figure 2). Together, these two rivers drain the entire western slope of the southern Rocky Mountains. The Gunnison itself is a primary drainage for the region of the highest topography (Figure 3) and highest relief (Pazzaglia and Kelley, 1998) in the southern Rockies, an area that contains 34/56 of Colorado’s > 4593
Figure 1. Map of physiographic provinces of the western United States: the Rocky Mountains, Colorado Plateau, Basin and Range, and Rio Grande Rift. The Colorado river system is the single, major drainage network of the region west of the continental divide (green dash). US States and Mexico for reference.
Figure 2. Simplified geologic and location map of west-central Colorado and eastern Utah. Major units shown are: Precambrian basement (purple), bundled Jurassic strata (dark green), bundled Cretaceous strata (pale green) Cretaceous Mancos Shale (tan), Tertiary volcanics (dark pink), 10Ma volcanics (red), and Quaternary deposits (yellow). Major rivers, including the Colorado, Gunnison and Green River (blue); major tributaries to the Gunnison include the North Fork Gunnison, Uncompahgre River, Lake Fork Gunnison River, Cebolla Creek, Curecanti Creek, and Crystal Creek. Mountain ranges include the West Elk Mountains, Sawatch Range, and San Juan Ranges.
Figure 3. Digital elevation model of Colorado, showing high elevation regions (white). Peaks higher than 14,000 feet elevation are indicated (stars). Major rivers show the radial drainage pattern that drains this region of high topography. The continental divide (black dash) follows the crest of the Rocky Mountains, highlighting the split drainage of this region.
meter (14,000ft) elevation peaks (Sawatch 15 + Elks 5 + San Juans 14). The overall goal of this paper is to summarize what is known about the incision history of the Gunnison River as a way to better understand the evolution of the Colorado River system and its relationship to Colorado's highest topography.

Width to depth ratios of bedrock canyons can be an indication of youthful topography (Finnegan et al., 2005; maybe Berlin paper?) and using a Canyon comparison (Figure 4; Hansen, 1965), Black Canyon is one of the narrowest (350 m) and deepest (829m: Warner Point; 561m: Gunnison Point; 555m: Chasm View) bedrock canyons in the Grand Canyon drainage system. At Chasm View the canyon is 335m across at the rim while its depth is 555m; at the Narrows, the canyon is a mere 12 m across at river level (Hansen 1965). Although not as deep as Hells Canyon (2411m) nor the Grand Canyon of the Colorado (average 1524m), the Black Canyon is ~1/3 the depth in ~1/9 the width of Hells Canyon (Figure 4). This width/depth ratio (~0.4-0.6) is comparable to bedrock canyons in tectonically active regions such as the Himalayas (Burbank et al., 1966), New Zealand (Koons, 1989), and Taiwan (Hartshorn et al., 2002).

QUATERNARY INCISION HISTORY

The modern drainage system in the Colorado Rockies began to take its shape after the Oligocene-age construction of the West Elk and San Juan Mountains. Long term incision history is well recorded in this region. Structure contour maps on the Oligocene ash flow tuffs that came from the San Juans and West Elks indicate an E-W trending river valley in the approximate position of the present Gunnison River
Figure 4. Taken from Hansen’s canyon comparisons (1965). The Black Canyon of the Gunnison compared – in cross sectional profile – to other major US Canyons, including the deepest (Hells Canyon of the Snake), and the widest (the Grand Canyon of the Colorado), and the Grand Canyon of Yosemite.
(Hansen, 1971; Lipman, 2007). These rivers likely flowed west, as the Oligocene volcanic edifices would have been considerably higher (Lipman, 2007) but they may have fed internally drained basins on the Colorado Plateau. From 30-20 Ma, there is little record, but drainages must have developed radially around these volcanic highlands, similar to the modern drainage network of the West Elk and San Juan mountains. By 10 Ma, basalts were emplaced in river valleys; these topographic lows have since been inverted, creating basalt-capped high regions such as Grand Mesa. Basalts of ~ 10 Ma are present in several locations and are underlain by river gravels that we interpret to represent a west-flowing paleo Gunnison-Colorado River. In Glenwood Canyon, there is an incomplete record from 10-3 Ma (Kirkham, 2002), but there is no record for this time interval in the Gunnison River.

Late Quaternary incision history in this region is recorded in terraces that can be dated by their association with the Lava Creek B ash, a 0.639ka-age ash from the Yellowstone Caldera (CITE). Dethier (2001) summarized these results and concluded that this region was the highest incision rate area of the southwestern United States. Our approach is to summarize new as well as all existing incision data in terms of the longitudinal river profiles of the Gunnison and Colorado rivers. The result is a presentation of paleo-river elevations based on strath terraces and related gravels stranded by river incision. Terraces interbedded with Lava Creek B ash (e.g. Dethier, 2001) are summarized and new locations presented. Additional cosmogenic burial dating has been conducted as part of this study and is also presented here to date Gunnison River terraces. We conclude that this region has both the highest and the lowest incision rates in the Southwest.
The Gunnison River longitudinal profile and paleoprofiles also offer numerous opportunities to discuss incision processes. The modern profile, from headwaters to confluence with the Colorado River, displays a striking convexity associated with the Painted Wall- Chasm View reach in the Black Canyon (Figure 5). The process of river knickpoint formation is recognized as a response to disturbances such as sudden lowering of the relative base level within the stream system (Gardner, 1983; Burbank and Anderson 2001). This pattern forms during both regional plateau uplift (Whipple, 2004) and basin lowering, and further data sets are needed to resolve the relative importance of uplift of the headwaters, dropping of base level, and drainage reorganization within a previously uplifted landscape. The influence of rock substrate on long profile form and concavity has been studied (Gilbert, 1877; Stock and Montgomery, 1999; Phillips et al, 2003; Duvall et al., 2004) and are considered in this study. The Black Canyon forms an important field laboratory for such studies because of the marked rock strength contrasts (from Precambrian basement to Cretaceous Mancos Shale) over 10-km-scale distances. The data and models discussed below of the paleo-Gunnison long-river profile suggest the temporal and geometrical persistence of this knickpoint as an upstream migrating feature, with the rates of migration and shape of the knickpoint likely influenced by bedrock.

Our approach involves empirical reconstructions of geologic history using many available geologic data sets. We also present new geochronology and begin discussion of process-oriented geomorphic studies. Methods of this study include: 1) compilation and evaluation of existing river incision data pertaining to the Gunnison River and upper Colorado River basin and tributaries; 2) mapping and
characterization of terrace deposits along the Gunnison River and tributaries; 3) sampling and characterization of ash localities for tephrochronologic assignment (or confirmation) of ages; and 4) cosmogenic $^{26}$Al and $^{10}$Be burial dating of terrace deposits associated with the Gunnison river. This paper builds on the careful work and observations of Hansen (1965, 1967, 1971, 1981, and 1987).
Figure 5a. The modern long-profile of the Gunnison River from the confluence with the Colorado River to headwaters in the Rocky Mountains (blue) shown with generalized geology (Precambrian bedrock in gray, Mesozoic strata in green) and a composite of the highest points of the north and south rims of the Black Canyon in heavy black line. Faults are narrow black lines with sense of motion indicated in red. Modern dams (Crystal, Morrow Point, and Blue Mesa) are show in purple.
Figure 5b. Black and red rectangles indicate Lava Creek B ash locations and elevations within the Black Canyon. Locations within tributaries are at projected elevations. Black dashed line reconstructs the Gunnison River profile using the Lava Creek B locations to tie river level at that location. Cosmogenic sample from Qt7 at the North Fork – Gunnison confluence area is the star.
Figure 5c. Older reconstructions based off the shape of the modern river profile are shown for 1 Ma using the Lava Creek B rate (pink), the Red Rocks Canyon (Shinn-Bostwick river) confluence level (green), and the Grizzley Gulch locations (blue).
Long-term incision rates from 10Ma Grand Mesa and Flat Tops basalts (high-elevation black filled areas) are shown with red arrows. Long orange dash indicates approximate elevation of the low-relief surface in which these basalts were emplaced. Oligocene-age tuffs are indicated in small orange dash. The restored base of the Blue Mesa Tuff as mapped by Hansen (1971) is upper dashed elevation; the very basal elevations of West Elk Breccia that crops out today is the lower orange dashed line. Both indicate a relatively low-relief surface. Primary Cretaceous-aged deposits removed by erosion: Mancos, Mesa Verde, Green River and Wasatch.
Previous models

The extraordinary presence of the Black Canyon of the Gunnison, incised deeply into Precambrian rocks atop the Gunnison uplift (Figure 2), has led to numerous hypothesis regarding its origin, formation, and evolution. The Gunnison Uplift is a NW-trending Laramide uplift bound by oppositely verging monoclines that are themselves interpreted to represent the reverse-fault reactivation of Precambrian normal faults and/or Ancestral Rockies structures (Hansen, 1965; Marshak et al., 2000). The Black Canyon of the Gunnison follows the crest of this uplift even though the adjacent Montrose basin (host to the Uncompahgre River) is both at a lower elevation and floored by soft Cretaceous rocks. Previous hypotheses are discussed in this text, and summarized below. The dominant hypothesis for the Black Canyon (Hansen, 1987) ascribes coincidental superposition of the Gunnison River onto a basement-cored uplift. In this model, the river established a course at higher stratigraphic levels in an E-W oriented topographic low formed by Oligocene ash flow tuffs ~30Ma and became superposed (Hunt, 1965) on the bedrock uplift during later incision. In one end-member version of this model, the uplift and its bounding NW-SE faults, the Red Rocks and Cimarron faults, have had no significant movement since the Laramide formation of the uplift (Lettis, et al., 1996; Dethier, 2001)

Other models involve a component (major to minor) of neotectonic influences on drainage evolution. The course of the river may have been superposed in Oligocene volcanic rocks (as in Hansen’s model), but tributary geometries and incision rates (including differential incision across the knickpoint) may have been influenced by
neotectonic amplification from the Gunnison uplift and ongoing regional tectonic modification, including reactivation in the Neogene by slip on the bounding faults. Hansen (1987) suggested possible rotation of the Gunnison block as a cause for abandonment of the Grizzley Creek and Shinn-Bostwick drainages. Laramide uplift, beveling until ~10Ma, followed by renewed Miocene-Pliocene uplift of the Uncomahgre Plateau along reactivated Laramide faults is believed to have been responsible for the initiation of consequent streams that evolved into bedrock gorges (such as the nearby Unaweep Canyon); cessation of uplift, stream capture, and adjustments in local tectonically controlled base level are responsible for the abandonment of these canyons to the modern stream bed (Stevens et al., 2002).

Late Cenozoic-aged evaporite collapse features are documented in many areas in the region, and are especially notable in areas along the Colorado River and have influenced stream drainage networks in areas affected by these units by their easily dissolution and topographic collapse (e.g. Eagle Valley Evaporite in the Roaring Fork Valley; Kirkham et al., 2002). However, the Pennsylvanian Eagle Valley Evaporite, responsible for the flow and dissolution associated with these collapse events, is not present and not a factor Gunnison River region as Mesozoic strata directly overlie Precambrian basement.

On a more regional scale, drainage evolution may have been influenced by epeirogenic surface uplift due to broad doming of the central Rocky Mountains (Epis and Chapin, 1975; McQuarrie, 2000; McMillan, 2002; Leonard, 2002, Morgan; 2003; Karlstrom et al. 2005; McMillan, 2006). The central Rocky Mountains of Colorado is a high-elevation, ruggedly topographic region that sources numerous rivers. Of
particular interest, the radially drained, NE-trending Aspen Anomaly region is underlain by a marked low-velocity seismic anomaly in the upper mantle (Dueker et al., 2001), and lies at the intersection of the Colorado mineral belt, the San Juan volcanic field and Rio Grande Rift (Figure 6); suggesting persistent mantle magmatism and buoyancy (Karlstrom et al., 2005) affecting regional drainage and landscape evolution (Moor and Blenkinsop, 2002).

In a third major hypothesis, a global (Molnar and England, 1990) to regional (Dethier et al., 2001; McMillan, 2005) change to flashier climate in the last few million years may have been a mechanism for increased relief production in the Rockies since ~3Ma (Pazzaglia and Kelley, 1998; Molnar and England, 1990; Dethier, 2001; Zaprowski, 2001; Morgan, 2003). Rapid transitions from a glacial to interglacial climate is thought to destabilize hillslopes, resulting in a large increase in sediment flux within the fluvial system facilitating aggradation above previously carved bedrock straths (Bull, 1979; Pazzalgia et al., 1998; Hancock and Anderson, 2002). Mountain glaciers were common in the Rockies above elevations of ~ 2700 meters (9000 feet). The last two major glacial episodes were 10,000 years (Pinedale) and 120,000 years (Bull Lake/Wisconsin) ago. Earlier glaciations of this region are less well documented, but the widespread preservation of the Lava Creek B ash may have been facilitated by the coincident transition from glacial to aggradational interglacial condition at the end of marine oxygen isotope stage 16 at ~0.64Ma (Dethier, 2001; Sklar and Dietrich 2001; Zhao et al., 2001).

These models are not necessarily mutually exclusive; composite models involving two or three of these models could explain the rapid formation of the Black
Figure 6. The low-velocity seismic Aspen Anomaly defined by Bouger gravity lows (green) resides in southwestern Colorado, near the intersection of the San Juan Volcanic Field, Colorado Mineral Belt and Rio Grande Rift. Neogene basins (yellow), Neogene volcanics (red), and the radial pattern of major modern river drainages (blue). Rocky Mountains are outlined in black.
Canyon. One such fusion involves the incising Gunnison River being constrained by superposition to begin cutting Precambrian rocks atop the Gunnison uplift and later affected by local and regional neotectonic adjustments, all in the context of regional climate change. Recognizing and quantifying the role of neotectonics in the evolution of the topography, relief, and drainage patterns is thus an important goal in interpreting observed features. In all of the models, shorter temporal scale climatic changes have induced cyclic aggradation and incision events superposed on the longer-term bedrock incision history (Dethier, 2001; Pederson et al., 2002; Sharp et al., 2003).

In all models, incision history of the upper Colorado Basin (Grand Junction-Gunnison region) is affected by drainage reorganization and integration of downstream reaches. Integration of the entire Colorado River system to the opening Gulf of California did not take place until 6 Ma (Kirkham et al., 2001; Hanks et al., 2000) such that the downstream path any pre-6 Ma course of the Colorado River system for the western slope of the Rockies remains unconstrained. In addition, incision history of the Black Canyon may have been strongly influenced by downstream events involving the abandonment of Unaweep Canyon, bedrock canyon with dimensions and underfit and abandoned tributaries comparable to Black Canyon, through which the Gunnison river and perhaps the Colorado river flowed prior to abandonment and re-routing of the river system around the Uncompahgre uplift in the last few million years (Figure 1). The Unaweep abandonment story is beyond the scope of this paper and is under continued investigation in order to establish its timing, as summarized in Appendix A.
**Conceptual framework for drainage system evolution**

Our conceptual framework for drainage evolution in the Black Canyon region utilizes present drainages as analogs for past drainages. This is an especially powerful approach in the Grand Junction region as the present drainage system flows across rock types that vary from Precambrian basement to Cretaceous Mancos shale. This system has been active across these varied lithologies for the past 30Ma, and modern rivers can be used to infer the effect of different rock types on river profiles and knickpoint migration (e.g. Kirby and Whipple, 2001; Zaprowski et al., 2001; Mason and Anderson, 2005; Berlin and Anderson, in press). Stream piracy (Pederson et al., 2002) is considered here to be the main mechanism for rapid abandonment of river reaches reorganization of drainage patterns, although there can be a variety of driving forces for piracy events, as discussed above.

A comparison of the Gunnison River to other tributary profiles in the Colorado River basin network is shown in nested profile diagram (Figure 7). This diagram shows that the Gunnison through Black Canyon and Colorado through Glenwood Canyon have similar profiles and gradients above their confluence, facilitating comparisons of their history (discussed below). Major features of this set of profiles include: that the Gunnison and Colorado Rivers are comparable in steepness and both are steeper that the Green river system draining the Wyoming Rockies; and tributaries to the Gunnison are steep consequent steams with sub parallel gradients.
Figure 7. Nested profiles of the Colorado River. The Colorado River (blue) extends from the Gulf of California to the Rocky Mountains, covering nearly 250,000km and rising from sea level to >2500m. Major tributaries within the upper Colorado River system include the Little Colorado, San Juan and Animas Rivers, the Green River and the Gunnison River. Note the similar presence of knickpoints within the Gunnison River (the Black Canyon Painted Wall knickpoint) and the Colorado River (at Glenwood Canyon).
Oligocene volcanism

The earliest record of the Gunnison River system is in the Oligocene. According to Hansen (1965) the paleo-Gunnison River was confined to its course by surface inflation and volcanic aggradation from construction of the West Elk Mountains (to the NE) and the San Juan volcanic field mountains (to the S). The establishment of the river between the growing volcanic edifices forced the Gunnison River into the east-west oriented and probably westward-draining pattern we see today. Although Laramide structures and uplifts had already shaped the region, it was the building of these massive volcanic edifices during the Oligocene and potential additional surface uplift of the southern Rockies (Roy et al., 2004; Cather 2006; McMillan et al., 2006) that initiated the drainage pattern for the Gunnison River and likely other ancestral Colorado River drainages. The West Elk mountains formed 35-29 Ma (Lipman, 2007); the San Juan volcanic field formed in the same timeframe, ~35-29Ma (Lipman, 2007).

Longest-term "bedrock" incision rates can be estimated by comparing the pre-Oligocene topography to the modern river profile straths. The basal volcanic deposits (West Elk Breccia) flowed onto a subdued topography that was mostly underlain by Mesozoic strata (Figure 5). As is also seen in the San Juan volcanic field, the lowest West Elk ash and debris flows locally rest on Precambrian basement. Elevations of the basal Oligocene-age ash flows nearest the present river are reconstructed (modified from Hanson, 1971) and shown in Figure 5 as a small segment of an Oligocene paleo Gunnison River profile. West Elk Breccia deposits from the north underlie the basal San Juan ash flow sheet of the Blue Mesa Tuff.
Both of these restored bases dip gently east and have low gradient sections that are sub parallel to the modern low gradients between Blue Mesa Dam and Gunnison. We interpret this to reinforce models for persistence of areas of low relief, early Tertiary high elevation erosion surfaces preserved in the high Rockies (Epis and Chapin, 1975). The gentle east dips (Figure 5; Hanson, 1971) may be an artifact of the incomplete preservation of the lowest portions of the contacts, as we assume the river flowed west from the highest topography.

Accumulation of numerous ash flow sheets from the San Juans and the nearly 600m-thick West Elk Breccia from the West Elks resulted in filling of the Oligocene paleovalley to depths of perhaps a km or more based on mapped thicknesses of ash flow sheets. The geomorphology during and following building of these two Oligocene volcanic edifices likely involved high relief, unstable slopes, high discharge, and highly erosive rivers, similar to rivers draining modern volcanic edifices like Mount St Helens, Mt. Rainier and others in the Cascade Mountain Range of the Pacific Northwest (Montgomery and Brandon, 2002). Coarse river gravels interbedded with the West Elk Breccia (Hansen, 1971) may attest to a high competence, high discharge Oligocene Gunnison river system that may have tried to keep pace with volcanic accumulations.

From 25-10 Ma, there is little record of drainage evolution in the Gunnison River drainage, but sedimentary evidence from the Colorado Plateau suggest an overall aggradational system in adjacent regions, sourced from the southern Rockies, that delivered coarse fluvial sediments south towards early basins of the Rio Grande rift, southwest towards the Chuska Mountain (Cather, 2006), and east to form the lower
parts of the Ogalalla sediment blanket. Although most of the sedimentary evidence for the 25-10 Ma Gunnison and Colorado river deposits have been eroded, we assume that there was a major river system draining the high elevation regions of the southern Rockies throughout this time. The presence of gravels beneath 25 Ma basalt flows in the Flat Tops (Larsen et al., 1975; Kunk et al., 2001) indicates that areas that were 25-10 Ma river lowlands are now at elevations of ~10,000 feet west of Glenwood Canyon. McMillan (2005) discusses the evidence for a "turn around" point between regional depositional to incisional regimes to have taken place around 8-4 Ma.

Evidence for the ca. 10 Ma paleo Gunnison River system is preserved only scantily as gravels that underlie dated basalt flows. The two best known are the Flat Tops (Stork, 2006) and the Grand Mesa basalts (Kunk et al., 2001; Shagahain et al., 2002). These basalts represented some of the lowest points on the landscape at the time of their eruption and are preserved as high standing inverted topography in today's landscape. Their locations and elevations relative to the present Gunnison River are shown in Figures 2 and 5. The Flattops --- get description from Storks GSA talk—underlain by cobble and boulders of Proterozoic basement similar to provenance source in the Monarch Pass region. The sub-basalt gravels rest on Mesozoic strata, some 549 m above the modern more northerly fork of the Gunnison (Tominichi Creek), they contain clasts of Precambrian lithologies from the adjacent Sawatch range. The Grand Mesa basalts are similar in age 10.7Ma (Larson 1975—need more recent reference by Kunk, 2002) basalt flows that accumulated to thicknesses of 500 meters over a short time span on Grand Mesa. They are
underlain by river gravels that are exposed at the east end of Grand Mesa (Mount Darlene) and both basal and interflow gravels have been drilled to thicknesses xx meters in western Grand Mesa (Cole). The sub basalt gravels at Grand Mesa contain mostly West Elk- derived volcanic pebbles that range in size to 10 cm. As shown in Figure 5, the long-term incision rate at the eastern end of Grand Mesa location (measured from the basal elevation of the gravels to the current elevation of the Gunnison River) is 140-160 m/Ma as measured from the base of the basalt flows to the modern river (Kirkham, 2002; Aslan, 2006). In contrast, long term incision rate of the Flat Tops is about 55 m/Ma.

Several ca. 7 Ma basalts were also emplaced in the Gunnison/Colorado River vicinity that have been used to calculate incision rates for the Colorado River itself, and may be pertinent to regional incision history. Many of these basalts are located within regions known to have undergone modification due to salt tectonics; thus, precise knowledge of their original elevations is uncertain (Kirkham, 2002; Kunk, 2002). Need a better summary-- These data suggest slow incision rates from the time span 10-7 Ma of xx m/Ma.

2-3 Ma basalts are also present in the Colorado River drainage system. Gobbler Knob and Triangle Peak (Figure 2) and incision rates calculated from the base of these basalt flows to the Roaring Fork indicate a sharp increase in incision rate beginning 1-3 Ma (Kirkham et al., 2001). In the Gunnison area, Grizzley Creek tributary may have been this old, as discussed below, but no basalts of this age are known. Similarly, very high gravels on the rim of Black Canyon near the present confluence of Grizzley Creek are perched some 560 m above the present Gunnison
River. These gravel deposits contain volcanic and basement clasts, indicating the beginning of incision into basement rocks probably at 1-2 Ma, as discussed below.

Tributaries to the modern Gunnison River (Figure 2) drain the highlands to the north and south of the Gunnison River and form a tributary framework of consequent rivers (Hunt, 1956) with steep gradients and narrow canyons that flow north from the San Juans and south from the West Elk Mountains. Modern north-flowing tributaries include the Uncompahgre, Cimmaron, Cebolla, and Lake Fork Rivers. A paleo-tributary with similar geometry is the Shinn-Bostwick drainage. Now captured by the Uncompahgre; this paleodrainage, with its massive river gravel deposits, provides the best constraint on timing of incision of Black Canyon, as discussed below. South-flowing rivers from the high topography of the West Elks include the Curecanti, Crystal, Red Creeks and Dry Gulch. A paleoriver system of this type is the Grizzley Gulch system, now captured by Iron Creek, also discussed below.

The North Fork Gunnison intersects the Gunnison River at the northern end of the Black Canyon of the Gunnison and Gunnison Gorge. The modern confluence displays a distinctive T-shaped geometry. In one model discussed below, this geometry may have been maintained through time as the confluence has migrated down the dip slope on the monoclinal Gunnison Uplift, north from Red Canyon, to Smith Canyon, to it's present location (Figure 2).
Constraints on Incision History of the Gunnison River System

THE BOSTWICK RIVER (PALEO-UNCOMPAHGRE) TRIBUTARY

The best constraint on the late Quaternary incision history of the Gunnison and the age of Black Canyon comes from terrace gravels with a major – and now abandoned - tributary that once flowed through Shinn and Bostwick Parks and into the Gunnison via Red Canyon. Quaternary-age river deposits provide a challenge for accurate dating. In cases where volcanic flows (Wisniewski and Pazzaglia, 2002; Karlstrom et al., 2007) or travertine deposits (Pederson et al., 2006; Sharp et al., 2003) directly overlie a bedrock strath and/or incorporate river gravels, the age of the strath can be approximated from the age of the overlying unit. This section adds important new tephrochronology and cosomgenic dating to the database for Gunnison area Quaternary incision.

Gravels are preserved in several localities (Figure 8a) beneath the Shinn-Bostwick Park areas. These gravels are up to ~20m thick and are part of a Quaternary stratigraphic section depicted in Figure 7b—strath in Mancos, 14 meters of gravel, with thicknesses greatest in center of paleochannel and thinning to the edges. Clasts range in size from <1cm to 40cm and consist of the following clast types: quartzite, volcanics (andesites, dacite, and minor basalt), schists, pegmatites and rare sandstones and shales. Top of gravel is overlain by yellow fine grained material interbedded with locally derived colluvial gravel (sandstone clasts). About 2.5 m above the top of the river gravel is a white ash layer identified as Lava Creek B
Figure 8. (a) Paleo-Shinn-Bostwick River drainages on map of Black Canyon and vicinity; (b) Stratigraphic section of the Bostwick Quarry, samples taken for cosmogenic burial datingn (MS-06-20) and tephrrochronology (K06-CO-2) are indicated.
by Hanson (in Izett, 1982). This ash has now been found in several locations above the gravel. The abrupt change in the section between far traveled river deposits and locally sources reworked Mancos and Dakota marks an abrupt change in deposition in this paleovalley due to abandonment of this river, presumably by stream capture.

The size of the mapped channel and the clast size and composition suggest this paleo tributary was similar in scale to the modern Uncompahgre river. The location of gravels suggest a course that underlies the hay fields in Shinn and Bostwick parks, sub parallel to the Uncompahgre. As noted by Hanson, the present course of the Bostwick Park points towards a bedrock notch at Red Canyon that now forms an underfit tributary to Black Canyon. Red Rocks Canyon now hosts an ephemeral stream and has a mouth well above the modern Gunnison River (Figure 8a). Hence we agree with previous workers in interpreting Red Canyon to be the course of the Bostwick River (paleo Uncompahgre River tributary) before this river was abandoned because of stream piracy in its headwaters.

Figure 9 shows projections of the paleo Bostwick River relative to Black Canyon. The gradient of the strath under Shinn and Bostwick Parks is well constrained by heights of several outcrops in gravel quarries and road cuts. These project towards the modern lip of Red Canyon, where a steeper gradient modern stream continues towards a major knickpoint on the walls of Black Canyon. Our preferred projection of the Bostwick channel is based on the measured straths and projection based on analogy to the Cimarron (and Uncompahgre) River gradient(s). This is strongly
Figure 9. Cross sectional view of Red Canyon and paleo-Bostwick River incision. Draining from the south, the Shinn-Bostwick drainage joins the Black Canyon through Red Rocks Canyon. Lava Creek B ash locations are indicated (red/black rectangle). Reconstructed river profiles are projected from the “active” tributary bed to the modern canyon.
analogous modern drainage that has a steep bedrock gorge that, like Red Canyon, crossed the basement rocks in a steep side canyon before intersecting the Gunnison. Using the preferred projection, we estimate that the confluence of paleo-Bostwick and Gunnison was at an elevation of 325 m. Uncertainty in this projection can be estimated by using two other end member projections (as shown) providing values ranging from 250 m to 396 m. These heights indicate that Bostwick was abandoned when Black Canyon was ~ half its present depth.

A date on the gravels will provide an estimate of incision rates since the time of abandonment. The age of the gravels has been problematic. Hansen and Dickinson identified Lava Creek B, but also identified a 2 cm thick ash bed lower in the section that was attentively identified as the 1.2 Ma Mesa Fall ash, an older Yellowstone ash (Figure 10). Thus Hansen suggested that the Bostwick River abandonment was 1.2 Ma. However, using photos from Dickinson, we re-visited this locality and were unable to find the reported ash. This road cut was cleaned and scoured and the strath with the Mancos Shale is an irregular surface close to the position of the reported ash. One possible explanation is that the reported Mesa Falls Ash was instead a thin lens of reworked ash of Miocene age that was slumped and washed into the fine grained fill of the Shinn-Bostwick drainage. Trace element data from Dickinson were sent to USGS for re-identification. The USGS tephrochrology lab re-examined the documented Dickenson sample and further work is needed in order to confirm the identification and age of the ash.

There are also other field-based arguments that the ash was not Mesa Falls Ash. Lava Creek B ash is found to directly overlie paleo river gravels in the center of the
Figure 10. Presently active Bostwick Park Quarry with dump truck for scale; Lava Creek B ash overlies this deep gravel deposit. The site of refuted Mesa Falls ash (from Dickinson, 1966) in roadcut.
channel (Figure 8). The thickness and character of the fine-grained locally derived deposits is only several meters. There is no hint in any of the sections of a 0.6 Ma hiatus in this section. Instead, it looks like a progressive infilling of an abandoned channel with soft Mancos slopes that place in relatively short time intervals after abandonment.

**Bostwick Quarry samples:**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Dating Method</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-06-20</td>
<td>Bostwick Quarry</td>
<td>Cosmogenic burial</td>
<td>Discarded</td>
</tr>
<tr>
<td>K02-CO-02</td>
<td>Bostwick Quarry</td>
<td>USGS Tephro. lab</td>
<td>Lava Creek B</td>
</tr>
</tbody>
</table>

**Tephrochronology:**
A new ash location is presently exposed in the working face of a gravel quarry as shown in Figure 10. The active quarry is 60m+ deep and its gravels are overlain by a 1-2m-thick ash layer. This ash was sent to USGS tephrochronology lab, analyzed by Elmira Wan. In her assessment, the Bostwick quarry ash is 96% glass shards, and provided excellent chemical (major and minor elements) and morphological (shard, bubble wall shape and hydration) matches with confirmed Lava Creek B samples in the USGS database (identified based on Ar-Ar dating of sanadine). The remaining 4% of the sample consist of plagioclase feldspars, quartz, magnetite, microline, hornblende, oxyhornblent, biotite, orthopyroxene, and zircon.

**Cosmogenic Burial dating:**
For additional confirmation, we sampled gravels at the base of the Bostwick Quarry to test whether the gravels are close in age to Mesa Falls (1.2) or Lava
Creek B ash (0.64) using the cosmogenic burial method. This provides an excellent location to cross-test different geochronologic methods.

The cosmogenic burial radionuclide ($^{10}$Be and $^{26}$Al) decay dating method (Granger and Musikar, 2001) was used to determine depositional ages of gravels sampled from the Bostwick quarry and terrace Qt7 at the North Fork Gunnison-Gunnison River confluence. These analyses are being conducted at Purdue Rare Isotope Measurement (PRIME) laboratory under the supervision of Darryl Granger. The relative decay of $^{10}$Be and $^{26}$Al nuclides produced in quartz form distinctive ratios from which burial and exposure ages can be calculated. Due to the fact that these buried sediments could have received secondary cosmic ray bombardment and since the time of their deposition, these dates represent minimum depositional ages. Optimal shielding for samples of depositional age range approximated for the Gunnison River terraces (2-4Ma) requires >6m of continuous shielding by overlying sediments since the time of deposition and burial in locations where this depth of gravel is marginal or unobtainable, a vertical sample profile is collected to estimate degree of shielding (Wolkowinsky and Granger 2004).

Results from the cosmogenic burial dating conducted on the Lava Creek B ash have assigned an age of 700 ka ± 100 ka to these gravels. This age assignment is slightly older than the 639 ka (Lanphere, 2002) Lava Creek B ash that overlies the deposit (Figure 10). This 700 ka age constrains the time of major depositional activity within the Bostwick River.

In summary, the incision rate for the Bostwick River paleo-tributary is based on the interpretation that this paleo-Uncompahgre River had its confluence with
Gunnison through what is now Red Rocks Canyon. This paleo-drainage was active until the waters flowing through Shinn-Bostwick were captured in its headwaters by a stream that has evolved into the modern Uncompahgre River. The abandonment of this drainage occurred somewhat after the time of the Lava Creek B ash deposition (<640ka). Stream capture by the headward-cutting Uncompahgre River is likely responsible for the diversion of former Gunnison-bound waters.

Lava Creek B was deposited in the early stages of fine-grained filling of the paleochannel by soft sediment derived from nearby Mancos Shale. As the ash directly overlies and is within close (<2m) proximity of the far-traveled gravels and intermixed with colluvial fill near the base of the fine grained unit, we take the 640 ka age as the best estimate of the age of the gravels, an age that is within error of the cosmogenic burial age. Grouping several of the known LCB locations and elevations along the axis of the Shinn-Bostwick-Red Canyon drainage, the paleo-elevation of the drainage at 0.64Ma can be reconstructed. Projection of the Lava Creek B age drainage from Red Canyon to a hypothesized “best-fit” intersection with the Gunnison River provides a height above the modern Gunnison River from which an incision rate can be calculated. For the Shinn-Bostwick-Red Canyon drainage, an incision distance of 350.5m and incision rate of 507m/Ma has been calculated. The overall depth of the Black Canyon at the confluence of Red Rocks Canyon is 685m. Using the incision rate from the Red Rocks Canyon projection, the entire depth of the Black Canyon has been cut in 1.35Ma.
THE NORTH FORK OF THE GUNNISON RIVER

The North Fork of the Gunnison River is the major tributary to the Gunnison River that drains the West Elk Mountain Range and southern flanks of Grand Mesa (Figure 2). This junction hosts a suite of abandoned river gravel terrace deposits perched on the sides of the Gunnison River gorge (Figure 11) that are preserved as strath terraces near the confluence, continuing to higher elevations at greater degrees of degradation until they are present only as scattered gravel deposits. They extend from the modern river surface (at ~5100’ elevation) to over 6000’ elevation and provide an important record of aggradation and incision episodes during incision of the Black Canyon.

Progressive denudation of the landscape and incision of Black Canyon is supported by the presence of remnant inset terraces preserved on the sides of the Gunnison.

Mapping in the North Fork area concentrated on detailing the extent and character of these river gravels, terraces and terrace remnants. Fig 13 shows a map of the confluence area and its terrace deposits; a cross section shows the relative heights of the different mapped deposits—Table 2 shows the heights, thicknesses, and clast content of the various terrace deposits,

Mapping in this region focused on terrace identification, extent and thickness, and clast classification (Figure 12). Field mapping, aerial photos, and pervious maps were utilized to form a detailed map of the area. Thickness is taken from the strath elevation to the top of the gravel mound, although the terraces are preserved imperfectly and are in fact more of a veneer than an deep infill. Gravels were separated into three main lithologic types: volcanic, granitic, and metamorphic
Figure 11. Cross sectional view of the terraces at the North Fork – Gunnison River confluence. (Cross section line in Figure 13).
rocks. In order to obtain an accurate assessment of lithologies, a pebble count was conducted using the following method: 100 clasts within a 1m² area were picked at random and identified. These were then tallied to create a percentage.

All the terraces at the North Fork are dominated by volcanic clasts (.57-.75). These volcanics range from angular vesicular basalt boulders to rounded rhyolites and dacites. Granite was the next most abundant (.18-.28), followed by metamorphics (.2-.28) Terraces begin at the active river alluvium surface (Qt0). This active surface is reworked sands, gravels, and debris that is actively being moved downstream. Qt1, just above the active surface, is at low enough elevation that it could be overtopped in large flooding events. Qt2 is poorly preserved in patches. Qt3 has three lobes of ascending height, although the gravels form a continuous terrace; maximum thickness of this terrace could be as much as 44m, however, it has undergone erosion and its gravels have been removed.. Qt3 is well-preserved and widespread, and is characterized by abundant basalt boulders on the lowest (3a) lobe. Qt4 and 5 are only present in small patches, perched on the narrow canyon rims. Qt6 is small, and inset into Qt7, the terrace of largest extent and greatest height/depth. Qt6 and 7 have nearly identical strath elevations (222 and 223m above the Gunnison River), although Qt6 is only present along the rim of the Gunnison Gorge, whereas Qt7 is preserved extensively to the west (downstream) of the North Fork-Gunnison confluence area. Qt7 has a maximum potential thickness of 39m, and this was the site of the cosmogenic dating profile collected (see discussion below). Above Qt7, terraces are present only as remnant patches of
Figure 12. Map of North Fork Gunnison – Gunnison River confluence and terraces. Cross section line follows rim of Gunnison Gorge, passing through numerous terraces. Comogenic burial sampling sites are indicated with stars.
gravel. Qt8, 9 10 and 11 are characterized by increasingly less distinct geomorphic boundaries.

The North Fork terraces were likely deposited during a time of high sediment output; one scenario that suits this hypothesis is that terrace building was maximized during the late stages and after a glacial period (Dethier, 2001). Initially high discharge and sediment levels would initially cause widespread strath cutting and erosion, followed by a period of sediment deposition (Bull, 1979). Revitalized downcutting and incision would occur with a return to higher discharge/energy levels (Bull, 1979).

Sampling for cosmogenic burial dating of terrace deposits at the North Fork Gunnison-Gunnison River confluence region was conducted in August 2006. We chose the thickest and most widespread of the deposits and dug a 5.00 m pit with a back hoe (Figure 13). A 7-part vertical profile collected from Qt7 consisted of quartz-rich material picked from gravel deposit. Methods and protocols followed for cosmogenic burial sampling are expanded on in Appendix B of Thesis; samples are described in Table 3.

Preliminary results of this dating are that the gravels are of ~1Ma. This gives an incision rate of 221m/Ma and suggests that either Qt5 or Qt6 is the likely (younger) Lava Creek B age terrace.

Relationships to pediments on the flanks of grand Mesa is shown in Figure 14. Pediments from Grand Mesa are projected to grade to terrace Qt5 at the North Fork confluence. These fragmented paleo-erosional surfaces illustrate the exhumation of the Gunnison River valley from 10Ma (the age of the Grand Mesa basalts). Ages of
Figure 13. Cosmogenic profile as taken from Qt7 at the North Fork – Gunnison River confluence. Sample heights and numbers are indicated.
these pediments, if available, would help constrain the incision history of the Gunnison-North Fork Gunnison region. We samples an ash on the flanks of Redlands Mesa thinking it may be the Lava Creek B ash. The sample was taken from a slumped face of the south-facing cliff on the edge of Redlands Mesa. The ash was sent to the USGS for identification by Elmira Wan. The ash sample was 58% angular, heavily (FeO and clay) coated platy glass shards; 38% plagioclase, quartz, biotite, hornblende, magnetite, rutile, microcline, garnet and pink zircon residue; and 4% consisting of highly altered grains. The ash is of Miocene age, likely from the southern Nevada volcanic field; and perhaps part of the youngest, Un-named unit that directly underlies Grand Mesa.

We tentatively correlate the Redlands Mesa surface with QT7 and infer the age of both to be 1.0 Ma. Oak Mesa is higher and may correlate with Qt 15 (at the rim of Black Canyon); other correlations based on projecting pediment surface towards the confluence are shown in Figure 14.

The terrace record also records aspects of the evolution of the distinctive T-confluence of the Gunnison and N Fork of the Gunnison. Our hypothesis is that this confluence between the Gunnison River and its major tributary, the North Fork Gunnison, has migrated northward, down the dip slope, while simultaneously incising into the surrounding landscape. The northward migration of the T-junction is supported by the presence of two major tributary canyons (Red Canyon, Smith Canyon) that we speculate were paleo North Forks. Joining the Gunnison River at more southerly positions than the modern North Fork, these tributaries canyons would also draw from the same drainage basin as the North Fork (Figure 2).
Cretaceous sedimentary units in which the Gunnison River has entrenched itself dip to the North, and overly the hard, crystalline basement rock which is exposed in the Black Canyon; incision by the tributary would be influenced by the north-dipping Cretaceous bedrock and would be the logical direction of movement of a stream interacting between two different lithologies. The character of these sedimentary units facilitates the relatively rapid migration of this junction.

**GRIZZLEY GULCH AND NORTH RIM GRAVELS**

Grizzley Creek, an abandoned tributary to the Gunnison River from the southern Elk Mountains joins the Gunnison from the north roughly half-way along the length of the Black Canyon (Figure 15). This underfit drainage hangs ~600m (1800ft) above the modern Gunnison River. Grizzley Gulch was the major tributary draining the West Elk Mountains into the Gunnison River. This broad valley is now abandoned and displays only intermittent flow.

A series of terraces were mapped by Hanson that define a paleotributary that had a confluence with the Gunnison river when the river was incising Mesozoic strata above the Precambrian lip of Black Canyon. These gravels contain exclusively West Elk volcanic cobbles and pebbles, with grain size of the largest clast decreasing away from the source (Schneeflock et al., 2005). Remnant river gravels within the Grizzley Creek drainage are preserved in nine patches (Figure 15).

Gravels at the paleo confluence of Grizzley Creek with the lip of Black Canyon are 105m m (320ft) lower than the Grizzley Creek terraces, but we infer them to
Figure 14. Schematic cross section from the North Fork – Gunnison terraces north to Grand Mesa. Projected erosional surfaces are drawn in off of Oak Mesa, Redlands Mesa, Rogers Mesa and Shamrock Mesa.
represent a later, lower deposit from when Grizzley Creek was still active. Grizzley Creek drainage grades to the top of the exposed crystalline bedrock of the Gunnison Uplift. Locations on the North Rim (near the North Rim ranger station at Chasm View) show rounded gravels and cobbles deposited directly upon the bedrock strath of the Grizzley Creek drainage. These gravels contain both West Elk gravels (like Grizzley) and basement clasts indicating that they were deposited just as the Gunnison was beginning to incise into Precambrian basement. Hence, any dates on these gravels would provide an excellent long-term incision rate for the bedrock canyon at Black canyon.

The Grizzley Gulch gravels in a quarry within Grizzley Gulch were sampled as shown in Figure 16. The National Park Service quarried one of the Grizzley Creek gravel deposits; in 2002, a quartz sand sample was collected for possible cosmogenic burial dating at this quarry. Recent (2006) attempts to gather more samples revealed that the quarry is no longer active and environmental reclamation efforts have infilled the quarry, rendering it no longer a viable sampling location. The collected samples from 2002 are being processed in the PRIME lab under Darryl Granger.

Using the rim gravels as guide, since the cessation of active flow through Grizzley Creek, the Gunnison River trunk stream has incised ~340m. At long term rates of 160 m/Ma (from Grand Mesa), this suggests these gravels may be more than 2.4 Ma. In the heart of the Black Canyon, this rate is the leading edge of the high incision rates associated with the presence of the Painted Wall knickpoint. The calculated age of the river gravels at this location gives an age to the drainage; the
Figure 15. Grizzley Gulch: Terrace elevations as taken from Hansen (1971) and Schneeflock (2002). Proposed evolution of Grizzley Gulch as major player in the Gunnison River drainage system.
presence of crystalline lithologies within the gravel deposits here indicate that incision into the bedrock was occurring.

Grizzley Creek must have had insufficient flow or been diverted to another tributary prior to the beginning of bedrock incision in the Black Canyon: sustaining only ephemeral flow, would have been unable to keep pace with the rapidly incising main canyon. The canyon would thus be left hanging as the Gunnison River cut further and further into it’s gorge. Abandonment of Grizzley Creek was hypothesized by Hanson to have been influenced by northward tilting of the Gunnison block due to neotectonics movement on the Cimmaron fault. This model remains possible (see later discussion), but, as with other stream piracy events in the region, it is difficult to prove the effects of neotectonics on drainage reorganization (Stevens) and scenarios involving a denudation-driven capture of Grizzley Creek by Iron Creek are possible with or without neotectonic faulting (Schneeflock et al, 2005).

Additional attempts to date incision history included a reconnaissance sampling effort for cosmogenic surface exposure ages collected by Jon Gosse and Karl Karlstrom (2002) at Chasm View (on the North Rim vertically below Grizzley Creek). These have preliminary dates assigned to them and are undergoing further analysis (Figure 17). These ages are minimum ages, as these sheer surfaces may have spalled off since canyon formation and the specific area sampled has actually had a shorter period of exposure than the age of the canyon as a whole. These river-polished bedrock samples are located at near-river level (2 samples) and at the very upper lip of the canyon rim (1 sample). Preliminary ages for the two near-river surfaces are 0.039ka (at 1.5m above river level) and 52.2ka (at 9m above river
Figure 16. Grizzley Gulch quarry (2002). Map shows selected gravel patches as mapped by Hansen (1971) in yellow; basement rock of the Black Canyon in purple. The Grizzley Gulch quarry is in the far NE patch on the topographic map.
level). Presuming 10m of alluvium within the river channel, incision rates at these locations are 295m/Ma and 365m/Ma. These rates are comparable to rates throughout the knickzone, suggesting that rapid incision is being maintained.
Figure 17. Photo from base of Black Canyon. Cross Section of Chasm View, showing locations and heights of cosmogenic surface exposure samples (2002).
Summary of Differential Incision of the Gunnison River System

Figure 5a-d shows the best-constrained Gunnison-river region incision rates superimposed on a long profile that extends from the confluence with the Colorado River at Grand Junction to the headwaters of the Gunnison River. A summary of incision rates used in paleo-profile reconstruction are listed in Table 1.

River incision is shown through four snapshots in Figure 5a-d. From youngest to oldest: modern, 0.64 Ma -, 1 Ma-, 10 Ma, and Oligocene river profiles are depicted.

5a, the modern profile: The main features of this modern profile of the Gunnison River (heavy blue line) are a low gradient headwaters above Black Canyon, a steep knickzone within Black Canyon, and a return to moderate gradients upon exit from the Black Canyon and Gunnison Gorge. Generalized geology is superimposed on the modern profile: Precambrian basement of the Gunnison Uplift (grey) dominates the majority of the rivers length; the resistant 1.42Ga Vernal Mesa granite (pink); Mesozoic strata (green) drapes this uplift and forms the bottom of the wide downstream valleys. Major known faults and their offsets are indicated. Modern dams and cities along the river are indicated.

5b, short-term incision rates: At 639ka (ref) the Yellowstone Lava Creek B ash was erupted. Wide distribution and excellent conditions for ash preservation in the Gunnison River region has resulted in the recognition and accurate identification of the Lava Creek B ash in numerous locations pertinent to this study, as listed in Table 3 and discussed below. When found in close proximity to or in conjunction with river
gravels, the age of the ash can be used to date past river positions and elevations. The ash has been found in association with strath terraces in numerous places along the Gunnison River are shown as black and red rectangles. The “LCB”-age profile (black dashed line of Figure 5) is drawn to link these data points. In the downstream reaches of the Gunnison River, the LCB ash is found on erosional pediments from Grand Mesa. Near Grand Junction (B), and projected to the modern river at Kelso Gulch (C; Darling et al., 2007) and Petrie Mesa (D), incision rates are consistently low (130-150m/Ma). These low rates indicate the relative stability of this section of the river since 640ka.

Table 1. Lava Creek B locations

<table>
<thead>
<tr>
<th>Lava Creek B locality</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Shinn-Bostwick</td>
<td>Izett, 1982</td>
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<tr>
<td>Shinn-Bostwick</td>
<td>Izett, 1982</td>
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<tr>
<td>Shinn-Bostwick</td>
<td>Izett, 1982</td>
</tr>
<tr>
<td>Shinn-Bostwick</td>
<td>Izett, 1982</td>
</tr>
<tr>
<td>Shinn-Bostwick Quarry</td>
<td>Izett, 1982; Karlstrom, 2006</td>
</tr>
<tr>
<td>Shinn-Bostwick non-MFalls</td>
<td>Dickenson, 1966</td>
</tr>
<tr>
<td>Lake Fork</td>
<td>Izett, 1982</td>
</tr>
<tr>
<td>Chukar Ridge</td>
<td>Aslan, 2002</td>
</tr>
<tr>
<td>Kelso Gulch</td>
<td>Darling et al., 2007</td>
</tr>
<tr>
<td>Petrie Mesa</td>
<td>Aslan and Cole, 2002</td>
</tr>
</tbody>
</table>

Further west and at higher elevations on the Gunnison River, the major –and abandoned – Shinn-Bostwick tributary allows for the next LCB-calculated incision rate. The Shinn-Bostwick drainage deposited massive amounts of gravels along its path; in places, the Lava Creek B ash interfingers with and overlies these deposits. Along the abandoned path of the Shinn-Bostwick river (Red Rocks Canyon), Chukar Ridge provides the highest rate calculated: 640m/Ma (F). This patch of gravels sits on the edge of the Red Rocks Canyon, stranded as the canyon incised. The
preferred projected rate from the Shinn-Bostwick Park drainage (Figure 9) is 500m/Ma (G, Figure 5). These rates are some of the highest rates in the Rockies (Dethier, 2001), and are at the down-stream end of the knickpoint reach.

5c, intermediate incision rates: The next constructed river profiles at 2.4 and 1.4 and 1.0 Ma are based on incomplete dating, but extrapolation of known ages and long term rates. Red Canyon, Grizzley Creek, and 1Ma North Fork data are extrapolated into speculative paleoprofiles using only single points, (point E Figure 5, Table 1), but with paleoprofiles drawn parallel to the better constrained 0.64 Ma paleoprofile.

There is no direct record from 10-1 Ma in the Gunnison River. During this interval, the integration of the lower and upper Colorado River systems took place starting 6 Ma. This integration caused drop in base level (from Colorado Plateau height eventually to sea level) and accelerated incision in the lower reaches, but it is uncertain whether and when these effects are recorded in Black Canyon and into the headwaters of the Gunnison River (Howard et al., 1994). Also, presumed climate changes on the regional and global scale may have contributed to accelerated erosion from 3Ma (Molnar and England, 1990; Dethier, 2001).

5d, long-term incision rates: Reinvigorated volcanism at ~10Ma in the form of large basalt flows allows for the next assessment of the Colorado landscape. The profile reconstructed from 10Ma basalts (large orange dash) indicates a low-relief landscape with an established westward-draining river system. Gunnison river gravels found below and incorporated with the basal basalt flows of Grand Mesa contain volcanic and basement (?) clasts. Gravels found on the Flat Tops (north of
Gunnison) are similar in lithology and underlie the ~10Ma basalt. These two basalts, while similar in age and preservation of river gravels have very different calculated incision rates. The Grand Mesa basalt flow is 1550m above the modern Colorado River, while the Flat Tops are 549m above the very headwater regions of the Gunnison River. Excavation by the well established Gunnison and Colorado Rivers in the lower parts of the river has removed nearly three times the height (and volume?) of rock from the lower reaches of the Gunnison River, and allows for a regional long term incision rate of 160m/Ma (A) to be calculated. Upstream in the high elevations of the Rocky Mountains, erosion is obtained only through the action of small streams in steep, narrow canyons. The headwaters of the Gunnison River have been incising at 55m/Ma (Table 1) for the past 10 Ma in this region. As seen in Figure 5, this upstream region is above the modern knickpoint, is adjusted to a base level that is the upper low-gradient section of the Gunnison River, and has yet to feel the effects of events that have modified the lower reaches of the river.

Estimates of the Oligocene paleo profile (fine orange dashed lines) are reconstructed by projecting the basal elevations of the Oligocene volcanic rocks where they rest on Mesozoic or Precambrian rocks near the modern Gunnison. There are two profiles for this age: the upper profile, modified from Hansen’s (1971) cross section D-D’ show structure contours at the base of the Oligocene Blue Mesa Tuff. The lower profile is created from the elevations of Oligocene West Elk Breccia at their closest and lowest proximity to the current Gunnison River. Taking the lower profile as representative of the lowest points within the Tertiary landscape at ~30 Ma, these lowlands were filled in with many hundred m (check) of volcanic materials,
and likely drained to the west. The massive volcanic edifices that erupted these volumes of breccia and tuff perhaps reached elevations of 7000 m (Lipman 2007). Following cessation of volcanism, a poorly understood period of denudation of the peaks and aggradation in the surrounding areas likely ensued from ~30-10 Ma as these highlands were eroded.

In the upstream portions of the Gunnison, Lava Creek B is found at the Blue Mesa Dam (H), and the confluence of the Lake Fork Gunnison tributary (I). These two locations show a low incision rates of 95 and 90m/Ma, respectively. Following the river profile, this consistent occurrence of low incision rates indicates that the river assumes it is near equilibrium, incising evenly through the length of this low-gradient reach. The interpretation of these lowered incision rates is that they remain low because the upper reaches of the Gunnison (above the knickpoint) have not yet felt the base level fall that has influenced downstream events.
Discussion of Driving Forces and Processes—Tectonics and Climate

NEOTECTONIC LINKAGES

Numerous studies have addressed the incision of river systems into elevated plateaus such as in Tibet and the South American Altiplano (Clark et al., 2005; Rogers et al., 2006). River response to downstream adjustments whilst undergoing headward modification leaves a depositional signature distinct from that of a river system at equilibrium (Burbank and Anderson, 2001).

Disturbances (i.e., base-level drop, uplift in the headwaters) to a river “at equilibrium” will cause adjustments that will be reflected throughout the river system in the creation or destruction of river straths, terraces, depositional units and patterns. Such adjustments are generally manifested rapidly on a geologic scale (Whipple and Tucker, 1999) and might include an acceleration or deceleration in erosion or deposition, headward cutting, or stream capture. The effect is to produce knickpoints that separate downstream zones that have seen the lowered base level and elevated low gradient reaches (i.e., hanging valleys) that have not (Howard et al., 1994; Clark et al., 2005; Dorsey and Roering, 2006). This pattern is also seen across the Black Canyon knickpoint. Uplift rates are rapid (>500m/Ma) and result in the formation of the concave up river profile we see today because of the excess of stream power despite present incision and bedload transport. In order to release some excess energy in the river system, the river moves laterally (as it can) and
produces strath terraces and sometimes flood plains (Bull, 1979; Pazzaglia et al., 1998).

The same river geometry can result from uplift of the surface of the plateau region (e.g. Tibet) or the base level fall and integration of drainages towards a previously elevated region (Formento-Trigilio and Pazzaglia, 1998; Pazzaglia, 1998; de Broekert and Sandiford, 2005). Hence the pattern of terrace and incision rates observed in Black Canyon region is ambiguous in terms of driving forces. There seems little doubt that the drainage system is young and still adjusting to base level fall, but less clear the extent to which this is due to neotectonics uplift at local scale (faulting), surface uplift at regional scale (epirogeny), and/or relief generation due to drainage integration, accelerated incision, and isostatic response to incision and denudation. Support for each of these driving forces operating in the Black canyon region is presented below.

Mantle driven epirogeny: The Aspen Anomaly hypothesis involves the contemporary epeirogenic uplift of the Rocky Mountains as a result of upwelling buoyant mantle as evidenced by measured mantle low velocity domains (Dueker, 2001; Morgan, 2003). The area of interest lies at the intersection of several major structural and temporal features spanning Proterozoic structural suture zones, Laramide tectonism and associated magmatism in the Colorado Mineral Belt, Oligocene volcanic activity in the San Juan region and Neogene volcanism embodied by the Rio Grande Rift (Figure 6). A radial drainage pattern - of which the Gunnison and Colorado Rivers are members of - has been established on this high-elevation region. Incision rates from these two rivers will help to assess the
magnitude of neotectonic uplift in the Rocky Mountains (McMillan et al., 2002; McMillan et al., 2006). The suggested presence of buoyant mantle as a contributor to the continuous and modern uplift of the Rocky Mountains will be recorded by the relatively rapid adjustments made by a river system in response to disequilibrium settings and tectonic forcing (Burbank et al., 1996; Humphrey and Konrad, 2000; Snyder et al., 2000; Williams et al., 2000; Karlstrom et al., 2006; VanLaningham et al., 2006; Whittaker et al., 2007).

Local neotectonics (faulting and microseismicity): Fault networks may be recording upper crustal adjustments to addition of mantle buoyancy via reactivation of older fault systems and compositional heterogeneities in the lithosphere. Quaternary faults in the Gunnison River region indicate an ongoing tectonic presence in this region (Figure 18). Many of the structural blocks seen today were created during and shortly following the Laramide Orogeny, and took advantage of inherited weaknesses associated with Paleozoic faults, fractures, and/or suture lines (Karlstrom, 2005).

**CLIMATE EXPLANATIONS – NO UPLIFT NEEDED?**

Changes in local and global climates are reflected in topography. The high elevation of these structures rendered the landscape highly susceptible to erosion. Rapid erosion and exhumation of the landscape by a progressively more integrated drainage system has likely contributed some component of isostatic uplift to the elevation of the Rocky Mountains (Pazzalgia and Kelley, 1998). Erosion rates, sedimentation rates, vegetative ground cover all reflect the gross climate. A global
(Molnar and England, 1990) to regional (Dethier et al., 2001; McMillan, 2005) change to flashier climate in the last 3.5 Ma may have been a mechanism for increased relief production in the Rockies (Molnar and England, 1990; Dethier, 2001; Zaprowski, 2001). Increased precipitation and unstable vegetation facilitates rapid canyon cutting and an increase in topographic denudation as streams become better integrated from the exposed highlands to increasingly lower base levels (Pazzaglia and Kelley, 1998).

Allowing for both neotectonic and climatic contributions to the shaping of the Rocky Mountain topography is viable (Jones et al., 1999; Leonard, 2002). One such fusion involves the incising Gunnison River affected by local and regional neotectonic adjustments in the context of regional climate change. In all of the models, shorter temporal scale climatic changes have induced cyclic aggradation and incision events superposed on the longer-term bedrock incision history (Dethier, 2001; Pederson et al., 2002; Sharp et al., 2003). The Black Canyon of the Gunnison, initiated at ~2Ma as shown in this study is in line with the local (Rocky Mountain and western US) increase in incision since ~3Ma. The non-incisional - or even aggradational - foundation upon which the Gunnison River sat from Oligocene time was rapidly removed in this pulse of incision. The pace of incision was so great that rivers in this setting incised downward at a very rapid pace; trunk rivers dissected the landscape cutting narrow gorges without taking the “effort” to clear the traditionally broad, v-shaped valleys. Tributaries were rapidly abandoned as the precipitous rate of downcutting provided a setting for rapid stream capture events, rerouting and rewriting of drainages as the landscape swiftly evolved.
Figure 18. Quaternary faults superimposed on DEM of Colorado. Gunnison and Colorado Rivers for reference, the major Red Rocks and Cimarron faults are indicated. (modified from the Colorado Survey).
Summary and Conclusions

The Gunnison River is the major tributary of the Colorado River that drains some of the highest and most rugged topography of the Colorado Rocky Mountains. As such, the river provides a sensitive record for the interaction of tectonic, geomorphic, and climatic processes in shaping the modern relief and high elevations of the Rockies. Our data suggest a very young river system responding to multiple forcings.

Paleo river profiles at 640ka, Ma, ~1.4 Ma, ~ 2.4 Ma, 10Ma, and ~35Ma provide benchmarks, admittedly of variable quality, to understand the long-term incision history of the Black Canyon. Comparison of these to the modern profile offers insight into long-term incision history.

1) The modern profile: Working backwards, we use the modern Gunnison River profile to understand effects of variable bedrock and gradients of modern tributaries. The profile displays a prominent knickpoint between Painted Wall and Chasm View. The existence of this ~10km-long high-gradient reach may be partly explained by the presence of the Vernal Mesa Granite; however, the knickpoint extends across and through this resistant rock, suggesting it is not the only controlling factor on the placement of this knickpoint (Wohl, 1993; Young and McDougall, 1993, Seidl et al., 1997). Incision rates downstream of the knickpoint are higher (130-150m/Ma over 640 ka and ~ 160m/Ma over 10 Ma) in comparison to upstream rates (90-100m/Ma over 640 ka and ~ 60m/Ma over 10 Ma). Incision rates within the knickpoint reach are >500m/Ma over 640 ka. This variance in incision rate within a relatively small distance argues that this feature is a transient expression of stream system
adjustments to a downstream base level lowering or drainage reorganization event. Incision rates in the nearby reaches of the Colorado River since 1-3 Ma are distinctly higher than those in the time periods of ~30 Ma- present and 10 Ma-present. This leads us to infer that rapid incision was not established in the Gunnison region until post ca. 3 Ma. A knickpoint similar to that seen in the modern profile is present in the reconstructed 640ka profile, reinforcing the transient character and implying upstream migration of the knickpoint of 25km in the past 640 ka. Modern tributary drainages are steep consequent streams, and we have used these as models in recreating the paleo-tributaries within the Gunnison River system.

2) Lava Creek B-- Projection of the ~ 640 ka river gravels in the abandoned Shinn-Bostwick tributary to its intersection with the Gunnison at Red Canyon is presently the best constraint on the age of incision; here, ~400m of its ~700m total depth in the Black Canyon has been incised in the last 640 ka. we use the Cimarron gradient as a proxy for the Bostwick (paleo Uncompahgre) to extrapolate preserved and dated straths to their inferred confluence with the river at 325m, and have incised at a rate of 507m/Ma.

New tephrochronology indicates that the paleo Gunnison river system has undergone significant reorganization in the last 640 ka. Locations of interbedded ashes and river gravels allow for the age assignment of drainages throughout the Gunnison region as well as the comparison of cosmogenic and tephrochronologic dating methods. This study refutes the existence of a reported Mesa Falls tuff locality in the Shinn-Bostwick drainages.
3) 1 Ma -- New cosmogenic burial dating indicates that terraces at the North Fork-Gunnison River confluence are older than expected. 1 Ma Qt7 terranes give rate of 221 m/Ma.

4) 1.4 and @.4 Ma pseudo constraints – These profiles are constructed based off of a single reference point (the confluences of Red Rocks Canyon and Grizzley Gulch, respectively) and are created by mimicking the modern and well-constrained 640 ka river profiles.

5) 10 Ma profile shows the same long term differential incision as the younger profiles and suggests that either (a) the knickpoint was already in existence at 10 Ma (not favored) or (b) post- 3 Ma incision has created the differential incision rates.

6) Oligocene profile is near the modern profile in upper reaches suggesting zero long-term incision—presumably due to a combination of aggradation that elevated the land surface after construction of Oligocene volcanoes 35 Ma.

The southern Rocky Mountains and the rivers sourced from this region are influenced by multiple drivers, including climate oscillations, local Quaternary faulting and microseismicity, and possibly regional epeirogeny and underlying mantle buoyancy. Integrated geomorphic, geophysical, and structural studies are needed to continue to resolve relative importance and magnitudes of these different forcings.
Appendix A: Unaweep Story and Relationships to Evolution of the Colorado River

The current courses of the Gunnison and Colorado Rivers have changed dramatically through a series of basin reorganization, stream capture and tectonic events. Early explorers such as the Hayden Survey (1869), Peale (1877) and Ganett (1882) noted this high-elevation, abandoned canyon and researchers since then have puzzled over its creation. Hypotheses currently considered are expanded on in the following and summarized in Table 2.

Lohman (1961) hypothesizes that both the excavation and abandonment of Unaweep Canyon is a result of two major stream capture events followed by later tectonic uplift and a final minor stream reorganization. Superpositioning of the drainages of both the Colorado and Gunnison Rivers onto Tertiary volcanic rocks during subsequent tectonic uplift caused the entrenchment of these drainages and initiated the formation of Unaweep Canyon as the rivers flowed southwest across the underlying Uncompahgre arch. Incision was retarded upon encountering of crystalline basement rocks and the Ancestral Colorado River cut headward to capture it’s own upper reaches, leaving only the ancestral Gunnison River to continue its course through Unaweep Canyon.

Cater (1966) attributes the excavation of Unaweep Canyon to the ancestral Gunnison River but not having ever been the course of the Colorado River. His conclusions are primarily based on the volcaniclectic nature of river gravels sourced
from the Elk Mountains, observed topography uncharacteristic of a large river, and incision on tributaries and the trunk stream since abandonment of Unaweep Canyon. Cater proposed that a sequence of tectonic adjustment events prompted the migration from a paleo-river course to present-day conditions include: 1) original river courses of the westward-draining Colorado River with a tributary from the SE joining near Grand Junction were separated from the drainage of the ancestral Gunnison River, which flowed roughly WNW before turning abruptly SW across the Uncompahgre Uplift upon arrival at Cactus Park; 2) The upper portion of the major Colorado River tributary eroded headward, capturing the upper reaches of the Ancestral Gunnison River drainage, diverting it to the NW and greatly reducing the flow to Unaweep Canyon; 3) continued water capture from the Elk Mountains and Sawatch Ranges into the approximately present-day course of the Gunnison River and the Colorado River drainage network; as well as (4) continued activity of the Uncompahgre Uplift prompting the reversal of westerly flow through the active Unaweep Canyon to an easterly drainage toward the Gunnison River via East Creek.

Steven (2002) has a slightly different version for the formation of Unaweep Canyon, which involves the evolution of the Uncompahgre Plateau to involve two distinct phases of tectonic and geomorphic activity. Laramide tectonic activity (along Proterozoic boundaries) formed a low-relief regional topography upon which drainages were set. Renewed uplift and tilting during the late Miocene to early Pliocene provided impetus for the incision of deep, narrow canyons throughout the
region. Unawep Canyon is thus an artifact of antecedent incision by the major crosscutting stream across the rapidly uplifting Uncompahgre structural block.

**Appendix Table 1**: Unaweep Canyon: Hypotheses of formation

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hypothesis</th>
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</thead>
<tbody>
<tr>
<td>Lohman, 1961</td>
<td>Stream capture, tectonic uplift, drainage reorganization. Superposed paleo-Colorado and Gunnison river was entrenched, encountered geologic structures, and drainages were later pirated by Colorado River, which had cut headward through softer rock.</td>
</tr>
<tr>
<td>Cater, 1966</td>
<td>Gunnison River only through Unaweep. Multiple (small) stream capture events in a tectonically modifying environment</td>
</tr>
<tr>
<td>Steven, 2002</td>
<td>Antecedence: a 2-phase evolution: a) low-relief Laramide surface develops drainage patterns and is b) tectonism in late Miocene-Pliocene, which encourages accelerated incision.</td>
</tr>
</tbody>
</table>
Appendix B: Cosmogenic Radionuclide Decay Dating

A suite of nine gravel and sand samples from Qt7 were collected for cosmogenic radionuclide decay dating. Samples MS-06-13, MS-06-14, MS-06-15sand, MS-06-15gravel, MS-06-16, MS-06-17, MS-06-18, MS-06-21sand, MS-06-21gravel were collected from a variety of depths from two pits dug in close proximity on the terrace. Optimal sample material is pure quartzite, my samples consisted of a mixture of quartzite, granites, and other quartz-rich rock material picked from the specified depth. Sample material consisted of hand-picked quartzite, granite, and other quartz-rich rock material.

These samples were wire-brushed to remove caliche and other concretions, hand washed and dried. Each sample was then separately crushed first in a jaw-crusher, and then a mill-grinder to <1mm size at the New Mexico Tech facility. The sample was then sieved to obtain the optimal grain size of 0.5-0.25mm. All three size fractions (>0.50mm, 0.50-0.25mm, <0.25mm) of material were separated and kept in case of possible augmentation to an insufficient mass of optimally-sized material. These three size fractions were subsequently packed and shipped to the Purdue Rare Isotope Measurement Laboratory (PRIME lab) at Purdue University, West Lafayette, IN.

Under supervision of Dr. Darryl Granger (PRIME lab), will be separated in order to identify two cosmogenic nuclides preserved within the quartz structure. The isotopes of particular interest to this study are beryllium-10 (10Be) and aluminum-26.
(26Al). These nuclides are produced by the interaction of cosmic rays with the nucleus of the atom of interest. The half-lives of 10Be and 26Al radionuclides are 1500ka and 730ka, respectively.

To wholly separate the quartz and eventually the aluminum and beryllium nuclides, a series of physical separations, cleansings, and chemical routines are completed. Each sample is individually treated to the same chemical routines.

The first chemical cleansing is a “aqua regia” bath: the sample is placed in a glass beaker. Deionized water is added to just cover the sample. Nitric acid (HNO3) is added (~half volume of sample + deionized water) to beaker. An approximately equal volume of hydrochloric acid (HCl) is added to beaker. Sample is covered for 24 hours. Acid is drained from sample, which is then rinsed a minimum of 15 times with deionized water. Sample is then transferred to a new beaker and dried in oven.

Froth floatation is conducted to separate particles of feldspar and micas from the quartz sample. This is done with a soda carbonator and a mixture of 1ml/L acetic acid and 1 g/L lauryl amine (to keep pH~5) in 1L pure water; this mixture is then mixed with 10L pure water and carbonated. The quartz is pre-treated for one hour with 1% solution of hydrofluoric acid (HF). The HF solution changes the surface chemistry of the feldspar and mica and quartz so that the feldspars and micas are hydrophobic and quartz is hydrophilic. After pre-treatment, the HF is drained off the sample, which is poured into a large metal salad bowl. Three-four drops of pine- or eucalyptus oil are added to mineral mixture; the addition of the oil promotes the formation of bubbles and the eventual formation of a foamy “head” which will trap the
feldspar and mica particles. Carbonate the mixture; allow minerals to settle; pour off feldspar and mica bubbles. The remaining material is the quartz and other heavy minerals. Repeat if needed. Biotite mica needs to be separated magnetically, as it will not float properly. Collect, rinse, and dry the quartz and heavy mineral section.

Initial leaching on hotdog rollers is done to separate quartz from its host mineral through chemical and physical abrasion. Each sample of approximately 60-80g is added to a massed HDPE Nalgene bottle, labeled with sample name and HF/HNO3 leach in blue permanent ink. Each bottle is filled to 75% full with 5% HF/HNO3 solution and sealed tightly. The Nalgene bottles are then placed on hotdog rollers and heated for 24 hours. Acid is then drained from sample, and rinsed 3-4 times with pure water. This 24-hr hot leaching and rinse step is repeated, for a total of 2 days on the rollers. The sample is then rinsed 3-4 more times with pure water and Nalgene bottle with sample is placed uncapped in oven to dry overnight.

Magnetic separation can be done either before or after the initial leaching. For my samples, it was done after initial leaching in an effort to retain as much quartz as possible from a rather small original sample volume. The dried sample is poured through the magnetic separator creating “magnetic” and “nonmagnetic” portions of sample.

The nonmagnetic sample is now ready for separation by heavy liquids. Suspend a separation funnel over a flask with ceramic filter funnel. Place a coffee filter in the filter funnel to catch the drippings. Close the stopcock and fill the separation funnel ~2/3 full with 2.7 density heavy liquid (LST). Pour ~60g of sample into separator funnel. Let funnel stand until all gain motion has stopped: heavy grains (>2.7
density) will collect at bottom, while lighter grains remain suspended in liquid. Settling time may range from 15 minutes to several hours; smaller grains tend to remain suspended longer. Drain heavy minerals out through stopcock, collecting in coffee filter below. Shake capped separation funnel and repeat until no more heavy grains are readily settling out. Add 15 drops of pure water and cap tightly. Shake the funnel vigorously, loosen cap and return funnel to position over the collecting funnel. By now, most of the heavy minerals will have dropped out. Drain heavies out onto coffee filter. Repeat addition of 15 water drops, recording total drops of water added on funnel with a sharpie. Add more drops of water in increments of 2-3 drops, shaking funnel after each addition. Remove “heavies” coffee filter, label it, and replace it with a “quartz” coffee filter. By now the quartz will have dropped down due to the change in density of the heavy liquid created by the addition of water. Carefully drain out the quartz that has collected in the bottom of the funnel. Draining the quartz may take several attempts and you may have to re-shake and allow quartz to resettle. Rinse quartz (in coffee filter) generously with pure water to remove any heavy liquid. Place quartz in a clean, labeled PP Nalgene bottle in preparation for ultrasonic leach.

Ultrasonic leaching is done to further clean the quartz sample. The PP Nalgene bottle is filled to about 75% full with 1% HF/HNO₃ solution, capped tightly, and placed in ultrasonic tank for ~12-24 hours (“overnight”). Acid is drained from sample, rinsed 3 times with pure water, and refilled with 1% HF/HNO₃ acid solution and returned to the ultrasonic tank for ~12-24 hours (“overnight”). Sample is then rinsed with 3L of
pure water and placed in oven to dry. This sample is of considered clean, pure quartz, and is ready for the aluminum and beryllium extraction process.

Further work is done in Darryl’s chemistry lab. Here, strict lab etiquette applies. All lab ware is triple-washed in pure (18ohm) water prior to use each day. All lab ware is acid cleaned in a solution of 50% HNO3 at 70º for a minimum of 2 hours or overnight at room temperature, rinsed, and dried in an oven before putting away.

An initial aluminum assay is done to assess whether the aluminum concentration in the quartz is low enough to consider further chemistry viable. If the aluminum levels are too high, then the sample is abandoned.

In the case that there is an appropriate aluminum concentration within the sample to justify further separation, the next step is to “spike” the massed sample with beryllium.

The quartz sample is transferred to a Nalgene bottle and a volumetrically proportional solution of HF/HNO3 (~5xquartz mass/1xquartz mass) solution is added. This bottled solution is then heated in a water bath (attended up to 80º, unattended up to 70º) for a minimum of 24 hours, and until sample is entirely dissolved (usually ~2-3 days) and orange fumes form. This solution is then poured into a Teflon beaker, placed on hotplate at 100º(?) and allowed to evaporate to 1” volume, usually about 2 days.

The volume of HF/HNO3 and dissolved quartz is then separated into a ~200µfg Al solution to beaker for final aliquot solution, and the remaining solution is carefully evaporated and eventually drained into a platinum dish for fluoride fuming.
The final aluminum assay is done to assess the aluminum concentration within the quartz.

Fluoride fuming is done using the concentrated HF/HNO3 + dissolved quartz sample. Once the sample is in the platinum dish, it is rinsed with HNO3 and dried down three times. Sulfuric acid is then added and allowed to dry completely through 3 cycles. The residue is then dissolved in HCl and transferred to centrifuge tube. The pH of the solution is then adjusted with ammonia (NH4OH) to obtain pH 8, and then dried.

Aluminum and beryllium are then ready to be separated from the prepared samples through a series of column chemistry routines. First both anion and cation columns are prepared and stacked cation above anion. Oxalic acid is run first through both columns. The columns are then split and the beryllium sample and rinses are collected individually from the cation columns. Similarly, an anion sample and rinse are collected from the anion columns. The columns are then reconditioned, the anion and cation sludge are collected and the columns are cleaned.

The aluminum sample is combined with H2O2, dried down, and then dissolved in 2ml of 1:1 HCl and transferred to a centrifuge tube. Pure water is added to create 6ml of solution. Beryllium and aluminum are then precipitated with the addition of ammonia. Precipitation is aided by use of a centrifuge. The centrifuged precipitate is rinsed in pure water and water level is returned to 6ml volume. This centrifuging and rinsing is repeated three times.
The aluminum and beryllium samples are then transferred from centrifuge tubes to acid-washed quartz vials and dried. This dried aluminum sample then is prepared for loading into the AMS. An ~equal amount of powdered silver is carefully added to the speck of Al and crushed until thoroughly combined. This mixture is then transferred and packed into pellet holder which will be run through the accelerator.
Tables
Table 1: Summarized incision rates for the Gunnison River, as indicated on Figure 5.
Table 2: North Fork – Gunnison River confluence terraces: heights and thicknesses.

<table>
<thead>
<tr>
<th>Terrace Number</th>
<th>Maximum Thickness</th>
<th>Height above river (m)</th>
<th>Height above river (ft)</th>
</tr>
</thead>
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<td>16.72</td>
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<tr>
<td>4b</td>
<td>9.14</td>
<td>108</td>
<td>354</td>
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<tr>
<td>4a</td>
<td>7.6</td>
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<tr>
<td>3c</td>
<td>6.08</td>
<td>76</td>
<td>249</td>
</tr>
<tr>
<td>3b</td>
<td>12.16</td>
<td>49</td>
<td>160</td>
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<td>3a</td>
<td>9.12</td>
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Table 3: North Fork cosmogenic samples, description and status in processing.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Date</th>
<th>UTM (Elevation)</th>
<th>UTM (Elevation)</th>
<th>Elevation (m)</th>
<th>Elevation (ft)</th>
<th>Comments/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-06-10</td>
<td>6/23/06</td>
<td>13S262475E (38.499772°N)</td>
<td>4264349N (107.723586°W)</td>
<td>6870</td>
<td>2093.976</td>
<td>Bostwick Park, Gray Pit #1. Lava Creek B ash layer which overlies the main gravel quarry. Collected from main ash layer.</td>
</tr>
<tr>
<td>MS-06-11</td>
<td>6/23/06</td>
<td>13S262475E (38.499772°N)</td>
<td>4264349N (107.723586°W)</td>
<td>6863</td>
<td>2091.8424</td>
<td>Bostwick Park, Gray Pit #1. Top of gravel directly underlying the ash layer of MS-06-10. Clast composition:</td>
</tr>
<tr>
<td>MS-06-12</td>
<td>6/23/06</td>
<td>13S262482E (38.497563°N)</td>
<td>4264331N (107.72498°W)</td>
<td>6842</td>
<td>2085.4416</td>
<td>Qt7 hole #1. Quartzite sample. Also did clast compositional survey from region ±1m (vertical) from horizon from which quartzite was sampled. Sample of 56 clasts total w/in 1m vertical range. Mafic volcanics = 2, 355.71%; Silicic volcanics = 32, 57.14%; Total granitic rocks = 7, 12.50%; Pegmatite = 0, 0.00%; Schists and metamorphics =9, 16.07%; Quartzite = 6, 10.71%.</td>
</tr>
<tr>
<td>MS-06-13</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>0</td>
<td>Qt7 hole #1. At 13-14.5’ depth from surface. Collect quartzites, quartz, pegmatites underlying a white caliche-cemented layer. By hand-picking from wall.</td>
</tr>
<tr>
<td>MS-06-14</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>0</td>
<td>Qt7 hole #1. At 13-14.5’ depth from surface. Collect quartzites, quartz, pegmatites underlying a white caliche-cemented layer. &quot;Bucket sample&quot; was a scoop from the backhoe bucket in generally the same depth as MS-06-13.</td>
</tr>
<tr>
<td>MS-06-15grav el</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>0</td>
<td>Qt7 hole #1. From very base of pit at 16’ depth. Taken 10’ below the top of gravel-base of &quot;dirt&quot;/colluvial cover. Sample was separated into gravel section and sand section.</td>
</tr>
<tr>
<td>MS-06-15sand</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>0</td>
<td>Qt7 hole #1. From very base of pit at 16’ depth. Taken 10’ below the top of gravel-base of &quot;dirt&quot;/colluvial cover. Sample was separated into gravel section and sand section.</td>
</tr>
<tr>
<td>MS-06-16</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>Qt7 hole #1. Loose layer of uncemented pebbles and sand under a thin gypsum horizon and overlying a strongly cemented gravel layer at base of pit.</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------</td>
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<td>MS-06-17</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
<td>0</td>
<td>Qt7 hole #1. At 7'2&quot; from gravel-colluvium contact. Taken from horizon ±10cm from original clast at 7'2&quot; depth. Overlies a horizon with ash-like appearance.</td>
<td></td>
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<tr>
<td>MS-06-18</td>
<td>8/5/06</td>
<td>13S0253328E</td>
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<td>Qt7 hole #1. At 4'6&quot; from gravel-colluvium contact in a large pebble-cobble horizon.</td>
<td></td>
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<tr>
<td>MS-06-19</td>
<td>8/5/06</td>
<td>13S0253328E</td>
<td>4294883N</td>
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<td>Qt7 hole #1. Colluvium sample for calculating bulk composition and density of overlying sediment. Approximately 7.5cc's of sand and fines from ~1m depth from surface.</td>
<td></td>
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<tr>
<td>MS-06-20</td>
<td>8/6/06</td>
<td>13S0262537E</td>
<td>4264344</td>
<td>0</td>
<td>Bostwick Quarry (Gray Pit #1). Quartzite 4' from base of quarry. Sampled on horizontal ±1m from original clast.</td>
<td></td>
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<tr>
<td>MS-06-21gravel</td>
<td>8/6/06</td>
<td>13S0253103</td>
<td>4294966</td>
<td>0</td>
<td>Qt7 hole #2. At 18.7' depth. Hole is further laterally from hole #1, but displays similar stratigraphy throughout. Think of this deeper hole as the extended bottom of hole #1. Sample taken from very base gravel on Qt7. Sample was separated into gravel section and sand section.</td>
<td></td>
</tr>
<tr>
<td>MS-06-21sand</td>
<td>8/6/06</td>
<td>13S0253103</td>
<td>4294966</td>
<td>0</td>
<td>Qt7 hole #2. At 18.7' depth. Hole is further laterally from hole #1, but displays similar stratigraphy throughout. Think of this deeper hole as the extended bottom of hole #1. Sample taken from very base gravel on Qt7. Sample was separated into gravel section and sand section.</td>
<td></td>
</tr>
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</table>
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