

# Incision history of the Black Canyon of Gunnison, Colorado, over the past ~1 Ma inferred from dating of fluvial gravel deposits

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## ABSTRACT

Spatio-temporal variability in fluvial incision rates in bedrock channels provides data regarding uplift and denudation histories of landscapes. The longitudinal profile of the Gunnison River (Colorado), tributary to the Colorado River, contains a prominent knickzone with 800 m of relief across it within the Black Canyon of the Gunnison. Average bedrock incision rates over the last 0.64 Ma surrounding the knickpoint vary from 150 m/Ma (downstream) to 400–550 m/Ma (within) to 90–95 m/Ma (upstream), suggesting it is a transient feature. Lava Creek B ash constrains strath terraces along a paleoprofile of the river. An isochron cosmogenic burial date in the paleo-Bostwick River of  $870 \pm 220$  ka is consistent with the presence of 0.64 Ma Lava Creek B ash in locally derived, stratigraphically younger sediment. With 350 m of incision since deposition, we determine an incision rate of 400–550 m/Ma, reflecting incision through resistant basement rock at 2–3 times regional incision rates. Such contrast is attributed to a wave of transient incision, potentially initiated by downstream base-level fall during abandonment of Unaweep Canyon at ca. 1 Ma. Rate extrapolation indicates that the ~700 m depth of Black Canyon has been eroded since 1.3–1.75 Ma. The Black Canyon knickpoint overlies a strong gradient between low-velocity mantle under the Colorado Rockies and higher-velocity mantle of the Colorado Plateau. We interpret recent reorganization and transient incision of both the Gunnison River

and upper Colorado River systems to be a response to mantle-driven epeirogenic uplift of the southern Rockies in the last 10 Ma.

## INTRODUCTION

Three major orogenic plateaus on Earth include the Tibetan Plateau, the Altiplano-Puna Plateau of South America, and the Colorado Plateau of the western United States. In tectonically active regions such as Tibet and the Andes, the complex interactions between dynamically uplifting plateaus and geomorphic evolution are recorded in deep bedrock gorges commonly located at the edges of these uplifted plateaus (Schildgen et al., 2007). Rivers on the eastern margin of the Tibetan Plateau such as the Yalong, Dadu, and Yangtze rivers and tributaries (Kirby et al., 2003; Ouimet et al., 2010; Kirby and Ouimet, 2011) and exiting the Altiplano (Schildgen et al., 2007) are interpreted to be adjusting to tectonic forcings because of the youthfulness of these mountain belts that give rise to the dramatic landscapes. Spectacular bedrock gorges also exist in the western U.S. associated with the Sierra Nevada (House et al., 2001; Ducea et al., 2003), Hells Canyon and associated Wallowa Mountains uplift (Hales et al., 2005), the edge of the Colorado Plateau in Grand Canyon (Karlstrom et al., 2008), and the Rocky Mountains (Karlstrom et al., 2012). However, in the case of the western U.S., there is ongoing debate about the extent to which these rugged gorges and landscapes are due to active tectonics (Epis and Chapin, 1975; McMillan et al., 2002, 2006; Karlstrom et al., 2008, 2012; Eaton 2009; Aslan et al., 2010) and/or are influ-

enced more by climatic forcing and isostatic adjustments to denudation (Gregory and Chase, 1992, 1994; Pederson et al., 2002; Molnar, 2004; Roy et al., 2004, 2009).

Figure 1 shows comparative profiles of deep bedrock canyons from the areas mentioned above. Compared to other bedrock canyons in the western U.S. and other orogenic plateaus, Black Canyon of the Gunnison is not the widest or deepest, but its depth-to-width ratio is among the highest of the world's bedrock gorges. In the western U.S., Grand Canyon and Hells Canyon, both carved mainly in the last 5–6 Ma due to mantle-driven uplift (Hales et al., 2005; Karlstrom et al., 2008), are much wider overall, but their inner bedrock gorges are shallower and less steeply walled. Yosemite, primarily a glacial valley, is a much broader canyon. Incision rates are anomalously high on rivers that exit the three main orogenic plateaus of the world: Tibetan river gorges incise at rates of 300–500 m/Ma or more (Ouimet et al., 2010; Dortch et al., 2011) and incision in the Bolivian Andes has been measured at 1350 m/Ma (Safran et al., 2005). In the western U.S., Black Canyon incision rates are locally 400–550 m/Ma (Aslan et al., 2008; this paper). These are high incision rates in spite of the fact that the river is carving through resistant Precambrian basement rocks, including the unfoliated and sparsely jointed Vernal Mesa Granite (Hansen, 1965).

The goal of this paper is to integrate new geomorphic, geochronologic, and geophysical data and methodologies to understand the incision history of Black Canyon of the Gunnison. This work builds on the work of Wallace Hansen (1965, 1967, 1971, 1987), who pioneered the

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study of many of the geologic and geomorphic relationships explored here. To this geologic context, we bring several new analyses to this geologic problem, including: (1) analysis of longitudinal profiles of the Gunnison River system (e.g., Wobus et al., 2006; Aslan et al., 2008; Darling et al., 2009a, 2009b; Kirby and Whipple, 2012); (2) synthesis of new and previously published river incision rate data on the Gunnison River and its tributaries; (3) sampling and characterization of a key Lava Creek B ash locality for tephrochronologic identification and confirmation of ages; and (4) mapping and cosmogenic  $^{26}\text{Al}$  and  $^{10}\text{Be}$  dating of terrace deposits associated with the Gunnison River. Collectively, these new observations and data allow us to evaluate possible driving mechanisms for incision of Black Canyon.

## BACKGROUND

The Gunnison River follows the crest of the Laramide anticlinal Gunnison uplift as it flows to the west-northwest across the western slope of the Colorado Rockies (Hansen, 1965). This Laramide uplift is within the broader Pennsylvanian-age Uncompahgre uplift of the Ancestral Rockies. During the Late Cretaceous, these Precambrian-cored uplifts were mantled by ~2 km of sedimentary rocks that became broadly flexed and uplifted into the Gunnison uplift starting ca. 70 Ma (Hansen, 1965). There is little record of the paths of early post-Laramide rivers, but modern river courses seem unaffected by Laramide structures (e.g., Uinta, Uncompahgre, Gunnison uplifts), suggesting that river courses meandered across low-relief surfaces at higher stratigraphic levels and became superimposed on the uplifts during regional exhumation (e.g., Hansen, 1965; Hunt, 1969; Douglas et al., 2009). In contrast, modern rivers flow around Tertiary laccoliths, suggesting the influence of mid-Tertiary volcanic constructional topography (e.g., San Juan volcanic field, Elk and West Elk laccoliths; Hunt, 1969). Hence, the modern drainage system likely initiated with magmatic and tectonic events associated with the Oligocene ignimbrite flare-up (Lipman, 2007) resulting from the detachment of the Farallon flat slab from the base of North America (Humphreys et al., 2003).

A paleo-Gunnison River in about the same location as the modern river emerged in the Oligocene from ca. 35 to 29 Ma (Hansen, 1965), when drainage was constrained between volcanic topography of the West Elk Mountains to the north and the San Juan volcanic field to the south (Fig. 2A; Lipman, 2007). Eruptive sheets from these two volcanic centers thicken into an east-west paleovalley in approximately the same

location as the modern Gunnison River course, pinning drainage between the two constructional edifices (Hansen, 1965). In particular, the thickening of the 28.5 Ma Blue Mesa Tuff in the paleovalley axis, with its base contoured by Hansen (1971), indicates the paleo-Gunnison flowed into an east-west-oriented valley between these volcanic edifices. Figure 3 shows two paleosurfaces for the Oligocene timeframe: the upper profile, modified from Hansen (1971), is based on structure contours at the base of the Oligocene Blue Mesa Tuff dipping upstream (28.5 Ma; Lipman, 2007); the lower profile is created from the elevations of Oligocene West Elk Breccia (29–34 Ma; Coven et al., 1999) at its closest and lowest proximity to the current Gunnison River. Both show that the Oligocene paleo-Gunnison was potentially incising into Precambrian bedrock at modern elevations of 7000–9000 ft (2134–2744 m).

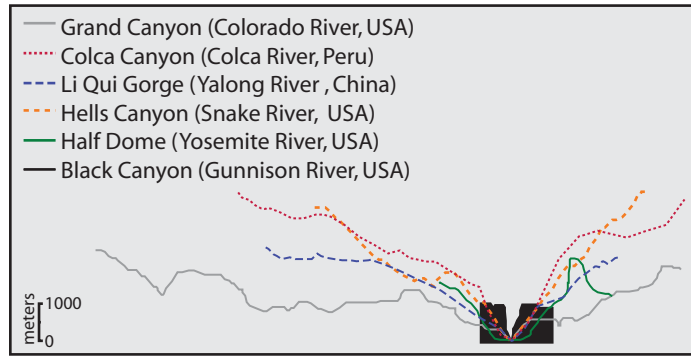
## GUNNISON RIVER PROFILE AND INCISION RATES

### Longitudinal River Profiles

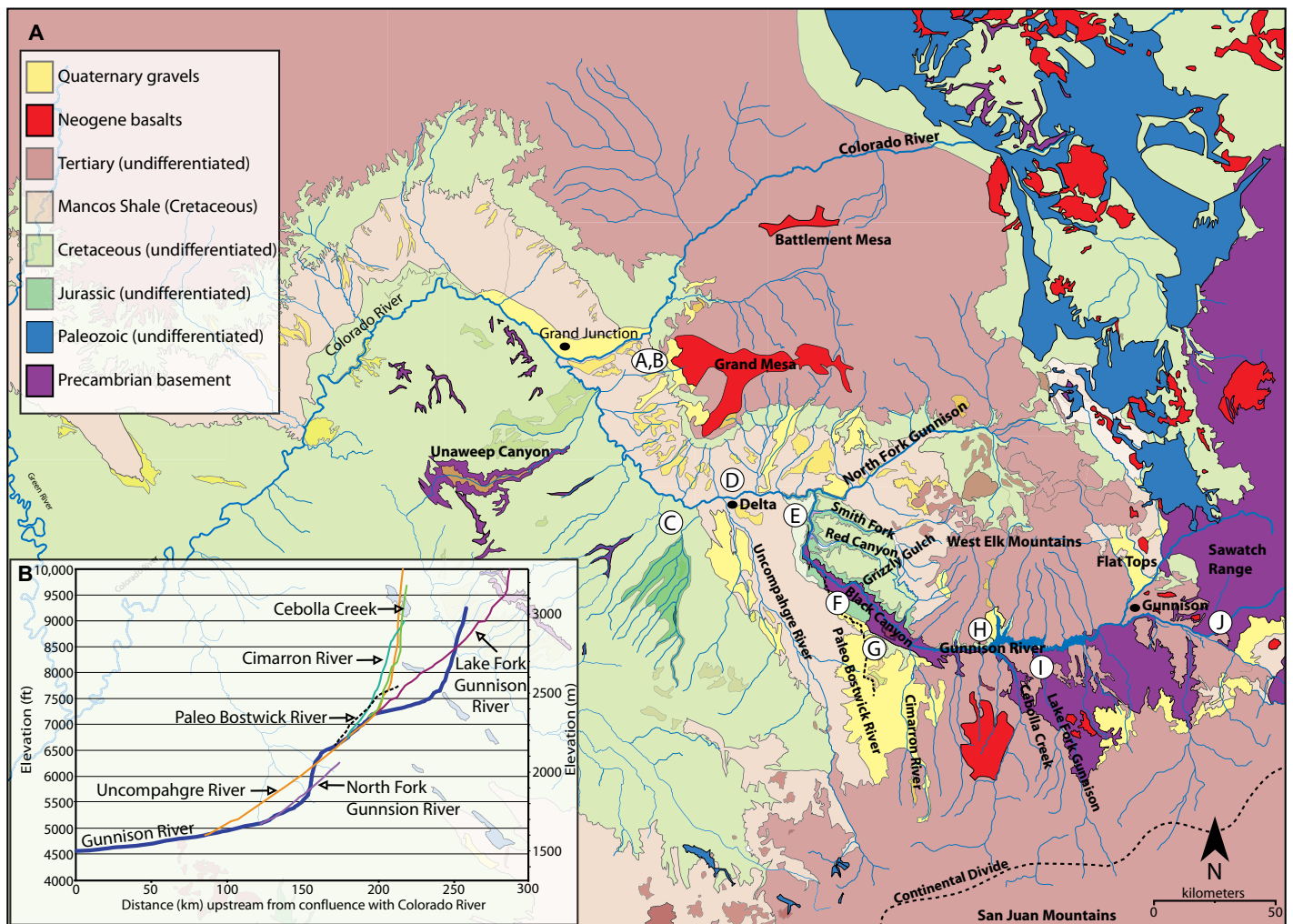
The longitudinal profiles of the Gunnison River and its tributaries are shown in Figure 2B. The modern profile, from headwaters to confluence with the Colorado River, displays a striking convexity associated with the Painted Wall reach of the Black Canyon (Fig. 3). This knickzone is indicative of a disequilibrium river profile (Mackin, 1948) and separates two generally concave portions of the river that have different incision histories. The main features of the Gunnison profile relative to rock type are shown in Figure 3: (1) a low-gradient (1.25 m/km) western reach in erodible Cretaceous and Jurassic rocks, (2) a slight steepening of gradient within basement rocks for ~30 km until the Red Rocks fault zone, (3) a concave river profile inflec-

tion marking where the river leaves the trace of the Red Rocks fault zone and transitions into, (4) the high-gradient (10 m/km) knickpoint in the Painted Wall reach that is partly within the resistant (sparsely jointed and unfoliated) Vernal Mesa Granite (pink stripe in Fig. 3). Above this, the river returns to a lower gradient (5 m/km) above Blue Mesa reservoir while still in Precambrian basement. Finally, the river steepens into the basement-cored Sawatch Range in its high headwaters (as the East River). In summary, while the shallowest reaches are flooded by soft rocks (Mancos Shale) and the steepest partly in basement (Vernal Mesa Granite), there are both steep and gentle reaches that do not correspond to these rock types. Thus, we infer that the profile geometry is only partly attributable to erodibility of the substrate, in keeping with incision rate evidence that the steepest reach is rapidly incising and is likely to be a transient knickpoint.

Modern tributaries to the Gunnison River include the Uncompahgre, North Fork Gunnison, Lake Fork Gunnison, and Cimarron rivers and Cebolla Creek (Figs. 2A, 2B). The Uncompahgre River drains the San Juan Mountains from the vicinity of Ouray, Colorado, and has formed a broad, low-gradient canyon in the Cretaceous rocks flanking the Gunnison uplift. North Fork Gunnison River is the major northern tributary to the Gunnison River, and drains the West Elk Mountains. It is of similar slope to the Uncompahgre River, and upon exiting volcanic strata flows largely on Cretaceous bedrock. The Lake Fork Gunnison and Cimarron rivers and Cebolla Creek are steep tributaries draining the San Juan Mountains. The paleo-Bostwick River, also shown on Figure 2A, is defined by a series of high, grass-covered, low-relief parks underlain by fluvial gravels marking the location of this north-flowing paleotributary to the Gunnison River that had its confluence



**Figure 1. Canyon comparisons showing high depth-to-width ratio of the Black Canyon of the Gunnison (solid black) as compared to many of the world's most iconic bedrock canyons.**



**Figure 2.** (A) Simplified geologic map of the western slope of the Rocky Mountains showing dated sample (Lava Creek B or cosmogenic burial date) locations (letters), Quaternary faults, and other features discussed in text. (B) Nested longitudinal profiles of the Gunnison River system.

with the Black Canyon of the Gunnison in Red Rock Canyon (Hansen, 1987).

Our conceptual framework for drainage evolution in the Black Canyon region utilizes modern drainages as analogs for past drainages. Paleo-tributaries document drainage reorganization due to tectonic (Hansen, 1965; Steven, 1975) and/or geomorphic stream piracy events (Pederson et al., 2002; Schneeflock et al., 2002; Aslan et al., 2008). Stream piracy is considered to be the main mechanism here for rapid abandonment of river reaches and drainage reorganization. Grizzly Gulch Creek (Fig. 2A) is presumed to have been abandoned after head-water capture by Iron Creek (Hansen, 1965), while the paleo-Bostwick River was captured by Cedar Creek of the Uncompahgre system (Figs. 2A, 4A). The modern Lake Fork Gunnison and Cimarron rivers and Cebolla Creek (Fig. 2B), which drain the San Juan volcanic

field and have confluences with the Gunnison River above the knickzone within Black Canyon, are used as proxies for pre-knickpoint gradients. We use these gradients to reconstruct the paleo-Bostwick drainage as a constraint on the former gradient of the Gunnison River.

#### Differential Incision Rate Data

Knickpoints and convexities in river profiles are often attributed to relative base-level lowering within the stream system (Gardner, 1983; Burbank and Anderson, 2001; Whipple, 2004) and/or fluvial response to variable rock strengths or erodibility (Burbank and Anderson, 2001; Berlin and Anderson, 2007). Incision rate data across knickpoints provide an avenue to evaluate the extent to which convexities and knickzones may be due to resistant bedrock versus transient incision pulses that may be impeded by hard

bedrock. If knickpoints are primarily a response of the fluvial profile to resistant bedrock, incision rates should be broadly similar below, within, and above the knickpoint (Gilbert, 1877; Stock and Montgomery, 1999; Phillips et al., 2003; Duvall et al., 2004). Alternatively, in transient knickzones, rates are expected to be highest within the knickzone as the river adjusts and strives to reacquire equilibrium after a change in local base level. Such disequilibrium conditions may be prevalent at the edges of uplifted plateaus or following a change in uplift rate within an active region (Bishop et al., 2005; Goldrick and Bishop, 2007; Whipple, 2004), near a tectonic drop in base level (Karlstrom et al., 2008), or due to drainage reorganization such as stream capture or even bedrock meander cutoff events at small scales (Finnegan and Dietrich, 2011).

Figure 3 (vertical arrows) shows the best-constrained Gunnison River-region incision rates

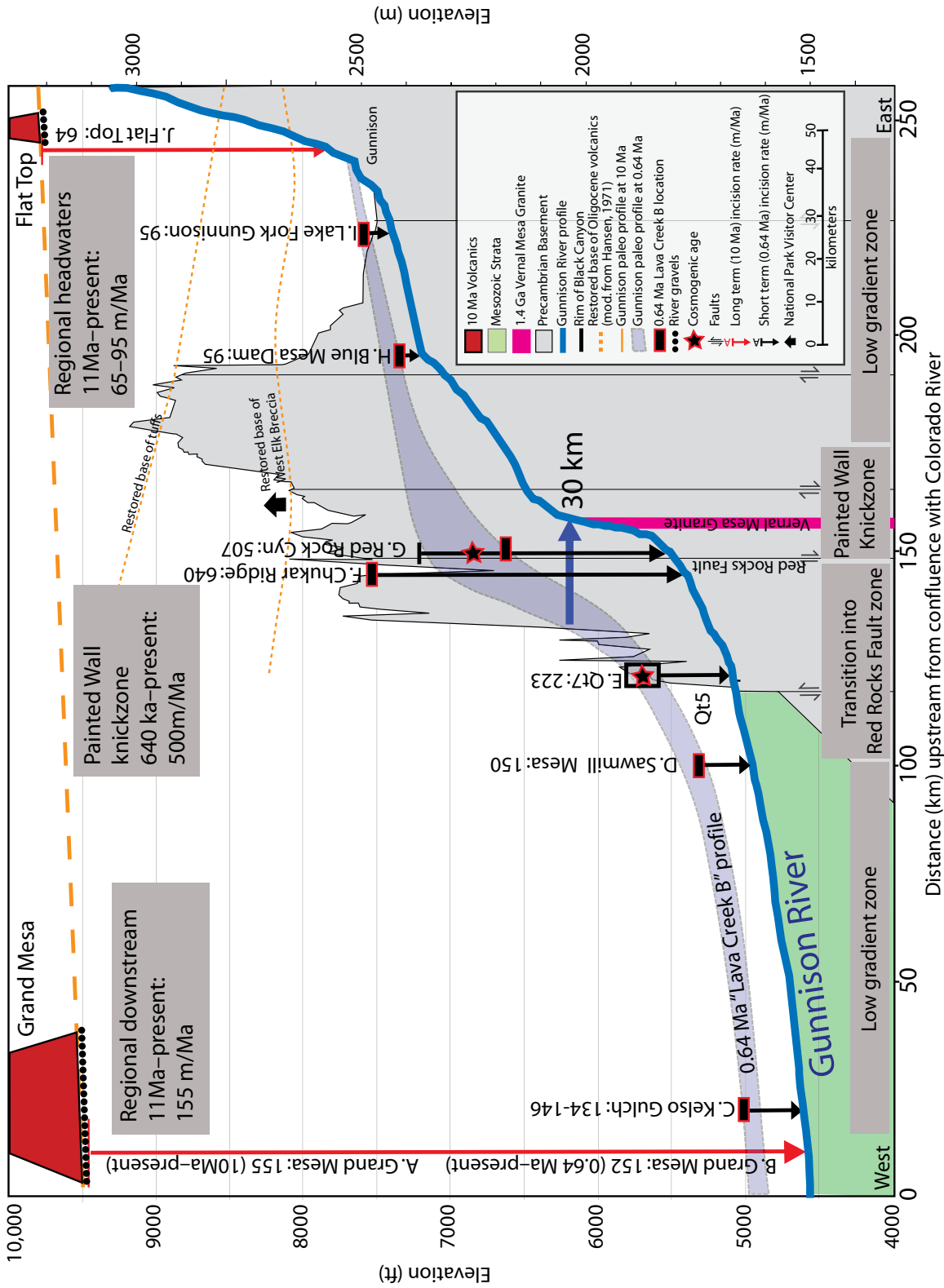


Figure 3. The modern long profile of the Gunnison River from the confluence with the Colorado River at Grand Junction through the Black Canyon of the Gunnison and into its headwaters (thick blue line) upstream from the town of Gunnison with generalized geology and a composite (black line and gray fill below) of the highest points of the north and south rims of the Black Canyon. Primary geologic units are the Precambrian basement (gray) and 1.4 Ga Vernal Mesa Granite (pink). 10–11 Ma basalts are shown in solid red, underlain by river gravels and 10–11 Ma paleoriver strath (long orange dash). Bases of Oligocene volcanics are shown in small orange dash. Black stars with red outline indicate locations of cosmogenic ages; black boxes with red outline indicate Lava Creek B locations. The purple “Lava Creek B” profile swath is constructed to bracket projected Lava Creek B elevations and cosmogenic burial data and analytical error. Letters correspond to incision data points (with incision rates in m/Ma) whose locations are shown in Figure 2. Blue arrow shows 30 km of upstream knickpoint migration in last 0.64 Ma. Gray boxes at the top highlight incision rates for the three main regions (downstream from, within, and above the knickzone) along the Gunnison River profile.

displayed on a longitudinal 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 paleoprofile reconstruction is listed in Table 1, including previously published as well as new data points (new data points in bold).

The best-constrained terrace ages are where the 0.64 Ma Lava Creek B ash has been found in association with strath terraces along the Gunnison River and tributaries (Figs. 2 and 3). Below the Black Canyon knickzone, in the downstream reaches of the Gunnison River, 0.64 Ma Lava Creek B ash is found on erosional pediments near Grand Junction (Figs. 2 and 3, points A, B), at Kelso Gulch (Figs. 2 and 3, point C), and near the modern river at Sawmill Mesa (Figs. 2 and 3, point D). Incision rates from strath terraces constrained by these ash locations are ~130–150 m/Ma, indicating relatively consistent incision throughout this section of the river since ca. 0.64 Ma.

In contrast, in the upstream portions of the Gunnison River and above the central knickzone, Lava Creek B ash is found at the Blue Mesa Dam (Figs. 2 and 3, point H) and the Lake Fork Gunnison–Gunnison River confluence (Figs. 2 and 3, point I). These two locations give relatively slower incision rates of ~95 m/Ma. The interpretation of these low incision rates is that these reaches of the Gunnison River upstream from the modern knickzone have not yet experienced the base-level fall associated with knickpoint migration. A dearth of datable material within the middle concavity between Chasm View and Blue Mesa Dam (1900–2350 m elevation, Fig. 3) leaves incision rates within this reach unconstrained; this paper focuses on the upper and lower reaches of the Gunnison River.

Incision rates within the Black Canyon knickzone area have been inferred by previous workers (Hansen, 1987; Dethier, 2001; Aslan et al., 2008) to be among the highest rates in the Rockies (Dethier, 2001). Hansen (1987) quoted an incision rate based on projection of the Bostwick paleoriver to where it would have joined the Gunnison River near Red Rocks Canyon (400–500 m/Ma; Figs. 2 and 3, point G; Fig. 4C). His age constraints came from the presence of Lava Creek B ash beds overlying gravels of the paleo-Bostwick tributary (Hansen, 1987). The combined data led him to infer that Black Canyon has been carved in the last 1–2 Ma. We concur with this conclusion and refine it based on new data presented below. The elevation of the Chukar Ridge Lava Creek B locality (Table 1) provides the highest calculated incision rate in this study (640 m/Ma; Figs. 2 and 3, point F). This site is associated with river gravels but is difficult to correlate with other terrace heights.

TABLE 1. NEW REGIONAL INCISION RATES

Location	Incision rate (m/Ma)	Age of deposit (Ma)	References
Petrie Mesa	<b>134</b>	0.64	Sandoval (2007)
North Fork Gunnison	<b>221</b>	2.2	Sandoval (2007)
Chukar Ridge	<b>640</b>	0.64	Sandoval (2007)
Painted Wall/Red Rock Canyon	<b>507</b>	0.64	Sandoval (2007)
Blue Mesa Dam	<b>95</b>	0.64	Sandoval (2007)
Lake Fork Gunnison	<b>90</b>	0.64	Sandoval (2007)
Flat Top	<b>55</b>	10	Sandoval (2007)
Flat Top	64	10	Aslan et al. (2008)
Grand Mesa	142	10	Aslan et al. (2008)
Sawmill Mesa	150	0.64	Darling et al. (2009a, 2009b)

### New Tephrochronology

One of the uncertainties in Hansen's calculation of a 1–2 Ma age of Black Canyon stems from uncertainty of the age of post-abandonment deposits that overlie Bostwick paleoriver gravels in Bostwick Park (Fig. 4A). Dickinson (1966) reported two ashes at different stratigraphic levels in a road cut leading up to the south entrance to Black Canyon (Fig. 5). The upper ash was identified as the 0.64 Ma (Lanphere et al., 2002) Yellowstone Lava Creek B ash (Izett and Wilcox, 1982; Hansen, 1987). The lower ash (Fig. 5) was analyzed and reported by Izett and Wilcox (1982) as being similar to the 1.29 Ma Mesa Falls Yellowstone ash (Lanphere et al., 2002), but the correlation was uncertain. Given Hansen's argument that Bostwick paleoriver gravels were graded to an elevation ~350 m down into the depth of the modern Black Canyon, use of the Mesa Falls age as the minimum age on the gravels led to an inferred rate of 325 m/1.29 Ma = 252 m/Ma, necessitating ~2.5 Ma to carve the entire canyon; whereas use of the Lava Creek B age yields a rate of 507 m/Ma and a duration of ~1 Ma for the carving of Black Canyon, assuming steady rates.

We revisited the site and attempted to resample from the location shown in Figure 5. Although an extensive excavation was conducted, no ash layer was found in the stratigraphic position of the lower ash noted by Dickinson (1966). Instead, we obtained the original sample (courtesy of Dickinson) and reanalyzed it. Our reanalysis of the Dickinson "Mesa Falls (?)" ash (Table 2) indicates that while the Mesa Falls correlation is still permissive, there is not a definitive match between the Dickinson ash sample and the Mesa Falls ash (see the Supplemental File<sup>1</sup>). However, there is a positive (>0.95 similarity coefficient) correlation with multiple Lava Creek ash bed samples. The Dickinson

<sup>1</sup>Supplemental File. PDF file of original analyses by Dickinson (1965) of refuted Mesa Falls ash. If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00847.S1> or the full-text article on [www.gsapubs.org](http://www.gsapubs.org) to view Supplemental File 1.

sample exhibited a lower iron concentration level that is more similar to Mesa Falls glass shards than Lava Creek B, as well as the moderate hydration typically seen in older samples. Given that Yellowstone tephra (Huckleberry Ridge, Mesa Falls, and Lava Creek) have overlapping chemistries, the original identification as Mesa Falls ash was likely based on these latter characteristics. Although a Mesa Falls correlation remains possible from the geochemical analysis, new field mapping has failed to reveal a marked unconformity in the few-meters-thick section of fill between the ashes; therefore, the correlation to Lava Creek B ash is supported by stratigraphic context (Aslan et al., 2008). Thus, based on the new analysis (Table 2) and detailed work on the geology at Bostwick Park that suggest post-abandonment deposits are likely close in age to the gravels (Sandoval, 2007; Aslan et al., 2008), we prefer the 0.64 Ma age as a minimum age on the paleo-Bostwick river gravels. We suggest these ashes represent differential erosion and re-deposition of reworked Lava Creek B tephra following abandonment of the paleo-Bostwick paleovalley.

### Cosmogenic Nuclide Dating

To further constrain the age of Bostwick gravels and attain additional new incision rate data, we used cosmogenic nuclides (<sup>10</sup>Be and <sup>26</sup>Al) to determine the depositional ages of gravels sampled from two locations: (1) Bostwick Quarry, and (2) terrace Qt7 (223 m above modern river level) at the North Fork Gunnison–Gunnison River confluence (see Figs. 2 and 4 for locations). We used the isochron burial dating method (Balco and Rovey, 2008) at Bostwick Quarry, and profile dating at terrace Qt7.

### Bostwick Quarry

The depositional history of these gravels was described by Hansen (1987), Sandoval (2007), and Aslan et al. (2008). About 10 m of coarse gravel was deposited in this Gunnison River paleo-tributary, which had its confluence with the Gunnison through Red Rock Canyon (Fig. 4A). Headward cutting of Cedar Creek, a tribu-

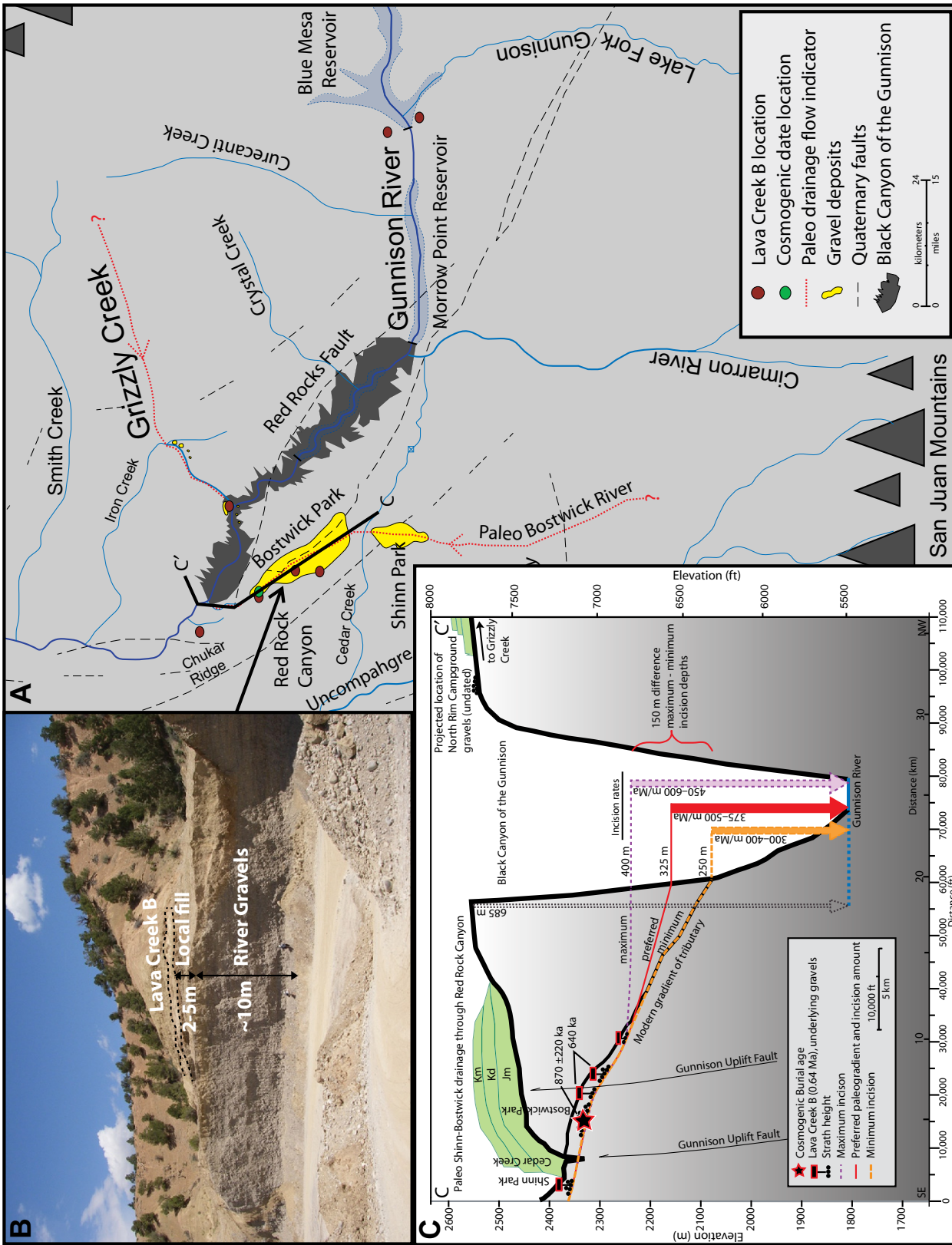
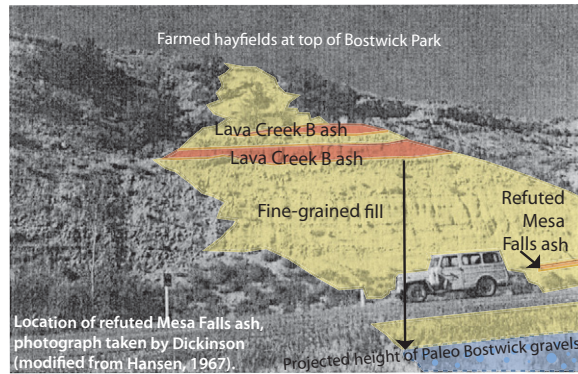


Figure 4. (A) Generalized map of the Black Canyon of the Gunnison region, highlighting the paleo-Bostwick River and Grizzly Creek. (B) River gravel quarry at Bostwick Park, showing gravels overlain by Lava Creek B ash and local fill. (C) Cross-sectional view along the paleo-Bostwick River through Red Rock Canyon into modern Black Canyon. Possible projections (maximum in purple dash, preferred in orange dash, minimum in orange dash) of the tributary into Black Canyon before abandonment of the paleo-Bostwick tributary are shown with resulting incision rates on vertical arrows, bracketing the potential age of Black Canyon. 0.64 Ma Lava Creek B ash and cosmogenic burial age locations are indicated along the length of the paleoprofile.

**Figure 5. Photograph modified from Dickinson (1965) of Lava Creek B and refuted Mesa Falls ash locations at Bostwick Park.**



tary to Uncompahgre River, then captured the paleo-Bostwick drainage, leaving a largely abandoned canyon with an underfit, ephemeral stream draining through Red Rock Canyon into Black Canyon. Abandonment triggered the relatively rapid infilling of the canyon with 5–15 m of locally derived “yellow” alluvium that includes proximal deposits composed of reworked Mancos Shale from nearby hill slopes. As mentioned above, the locally derived sediment interfingers with lenses of reworked Lava Creek B ash that directly overlie the gravel deposit at Bostwick Quarry (Fig. 4B), constraining Bostwick river gravels to be older than 0.64 Ma (Aslan et al., 2008).

Cosmogenic nuclide burial dating provides a more direct constraint on the age of these gravels. We obtained a sample from the base of a >10-m-thick gravel exposure in the recently excavated Bostwick Quarry (Fig. 4B), ~1 km east of the road outcrops shown in Figure 5. Significant shielding (>10 m) in this location allows the burial age to be interpreted as an accurate (although imprecise) depositional age of the gravels.

The cosmogenic burial analysis was from four quartzite clasts that were collected from the base of the quarry face ~10 m stratigraphically below Lava Creek B ash. Post-burial shielding from cosmic radiation was thus at least 10 m (thickness of the gravel) and post-abandonment deposits added an additional 3 m of post-0.64 Ma shielding. Cosmogenic <sup>10</sup>Be and <sup>26</sup>Al were determined for each clast and analyzed using the isochron method for burial dating (Balco and Rovey, 2008). This method

is best executed with clasts collected from the same stratigraphic horizon such that each clast has the same post-burial cosmogenic production history due to similar depth of burial. Each clast has a high probability of having experienced a different exhumation and transport history prior to deposition than the other clasts, such that the initial concentrations of <sup>10</sup>Be and <sup>26</sup>Al vary. Evolution of these different initial ratios due to radioactive decay after deposition forms an isochron that has an age indicated by its slope and post-burial production indicated indirectly by the y-intercept. Since concentrations of <sup>10</sup>Be and <sup>26</sup>Al need to be corrected for the post-burial production experienced due to spallation reactions and muons at depth, age determination is necessarily an iterative process (Balco and Rovey, 2008). The isochron date for deposition of the gravel (Fig. 6) is constrained primarily by one data point, and could be improved with further analyses. The best-fit line yielded an age of 870 ± 220 ka (Fig. 6; Darling et al., 2012), compatible stratigraphically with both the Lava Creek B ash minimum age for the gravels and field relationships that suggest the gravel to be older than but close in age to the Lava Creek B ash. Thus, the time of major depositional activity of Bostwick paleoriver gravels is constrained to between ca. 0.87 and 0.64 Ma.

**North Fork Gunnison River Strath Terraces**

North Fork Gunnison River is the major northern tributary to the Gunnison River, and joins the Gunnison River below Black Canyon (Figs. 2 and 7). This tributary junction has migrated down the dip slope of the underlying

Paleozoic–Mesozoic strata as it has incised, leaving abandoned river drainages (e.g., Smith Fork and Red Canyon) and 11 remnant river terraces abandoned above the present profile (Fig. 7B; Hansen, 1965; Sandoval, 2007). These terrace deposits at the confluence are severely eroded (treads are poorly preserved) and relatively thin (less than several meters), implying they represent strath terraces (Sandoval, 2007). The highest terraces are more than 300 m above the modern Gunnison River (Fig. 7B) in this locality. The confluence of North Fork Gunnison River with the Gunnison River has apparently maintained its general geometry, while the North Fork and the confluence migrated down the dip of the underlying strata and the Cretaceous Dakota escarpment retreated northwards. This is similar to models for streams “sliding down” the dip slopes of the Uncompahgre uplift (Aslan et al., 2008; Darling et al., 2009a) and differs from other locations where rivers become entrenched during superposition across basement-cored uplifts, as was likely to be simultaneously occurring to the east on the Gunnison uplift (Hansen, 1987). The thickest and most widespread of these deposits, Qt7, with a strath at 223 m above the modern river (Fig. 7B), was chosen for trenching by backhoe and collection of a seven-part vertical profile for cosmogenic profile dating.

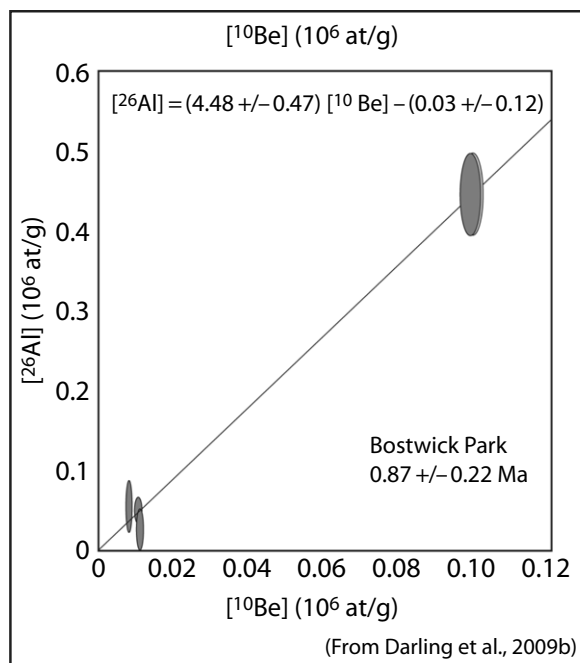
The trench into terrace Qt7/223 m was 6.1 m deep; sample depths ranged from 1.4 to 5.6 m. The stratigraphy included an upper 1.1 m of local fine-grained fill overlying pedogenic carbonate atop the gravels. The top of the gravel was at 1.4 m depth, and continued below the base of the excavation, which was limited by the reach of the backhoe. Gravel exposures on the edge of the terrace nearby were ~6 m thick, suggesting that the bottom of the trench was within 1–2 m of the base of the gravel. The overall stratigraphy seen in the excavation at the confluence is similar to that of Bostwick Quarry, where river gravels are abruptly overlain by fine-grained, yellowish, locally derived colluvium. Five samples consisting of combined mixtures of sand and gravel were analyzed for <sup>10</sup>Be; two of these also yielded meaningful <sup>26</sup>Al results. Cosmogenic data are given in Table 3 and Figure 7C.

The cosmogenic nuclide data for Qt7 were modeled assuming that the fine-grained over-

TABLE 2. U.S. GEOLOGICAL SURVEY (USGS) LABORATORY ANALYSIS OF DICKINSON (1965) BOSTWICK PARK TEPHRA

Sample	Description	Interpretation
K06C03 (suspected Lava Creek B ash)	~95% angular to subangular, lightly to heavily coated (carbonate, organics, clay, and FeO), mostly solid, platy or bw/bwj glass shards	This sample also matches well with a number of the USGS Lab Lava Creek B ash (0.639 Ma, Ar-Ar, sanidine) reference samples. Of specific interest to the investigation could be SL-MM-06-91 (Pop 2), a Lava Creek B ash sample collected by Mike Machette (USGS, Denver, Colorado) from a locality northeast of San Luis, Colorado. In comparison to K06C03, the iron level of SL-MM-06-91 (Pop 2) is slightly higher, and the sodium level is somewhat lower. But the correlation coefficient is still very good at γ 0.98, with and without alkalis.

Note: bw/bwj—bubble walled/bubble walled junction.



**Figure 6.** Isochron plot of  $^{26}\text{Al}/^{10}\text{Be}$  data from Darling et al. (2009b) of Bostwick Park quarry.

burden has been stable or eroding through time, so that the collection depth of each sample is the shallowest depth that it has experienced (e.g., Wolkowsky and Granger, 2004). Because each sample was a combination of many clasts, they are all assumed to have an identical inherited component at the time of deposition consistent with a condition of steady-state erosion in the source area (Repka et al., 1997). The concentration of cosmogenic nuclide  $i$  in each sample is calculated using

$$N_i = N_{i,\text{inh}} e^{-t/\tau_i} + P_i e^{-x/L} \left[ 1 - e^{-(1/\tau_i + \rho E/L)t} \right], \quad (1)$$

where  $N_i$  is the concentration of nuclide  $i$ , inh stands for inherited (referring to the decay of the original nuclides in the quartz when it was deposited),  $P_i$  is the local production rate,  $x$  is depth in cm,  $t$  is time since deposition,  $\tau_i$  is the mean-life of nuclide  $i$ ,  $E$  is the terrace erosion rate,  $\rho$  is the density of the eroding material ( $\text{g}/\text{cm}^3$ ), and  $L$  is the penetration length of secondary cosmic ray neutrons ( $160 \text{ g}/\text{cm}^2$ ). The model is simplified to ignore production by muons, which do not strongly influence the inferred age due to the shallow depth of the profile. While a more complex model including production by muons could be performed (e.g., Granger and Smith, 2000; Hidy et al., 2010), it is not deemed necessary due to the much larger uncertainties in the model associated with terrace erosion.

The model fit to the data is shown in Figure 7C. The best-fit age is  $0.98^{(+0.38/-0.07)}$  Ma for a local production rate of  $12 \text{ at}/\text{g}/\text{yr}$  ( $^{10}\text{Be}$ ) and  $82$

$\text{at}/\text{g}/\text{yr}$  ( $^{26}\text{Al}$ ). The knee in the profile is due to the inherited component that dominates at depth but is overprinted by much higher postdepositional production near the surface. The uncertainty in the fit is strongly asymmetric due to the possibility of terrace erosion that increases the model age. The best-fit value for inheritance corresponds to an erosion rate in the source area of  $60 \text{ m}/\text{Ma}$ . The model describes the data well, with a value for reduced  $\chi^2$  of 0.85.

Using the model profile age of 980 ka for terrace Qt7 yields an incision rate of  $228^{(+17/-64)}$  m/Ma. Assuming that the incision rate has been relatively steady, the lower terrace Qt5 (at an elevation of 190 m) probably correlates with the gravels at Bostwick Quarry and deposition of the Lava Creek B ash at 0.64 Ma. An inferred paleoprofile for this “Lava Creek B” age range is shown as the light purple swath in Figure 3. This relatively well-constrained paleoprofile mimics the modern river profile and suggests that a steep knickzone existed at 0.64 Ma within but farther west in Black Canyon, separating low-gradient upstream and downstream reaches.

## DISCUSSION

### Knickpoints

An examination of the relationship of both the modern and the 0.64 Ma knickpoints to changes in bedrock substrate and to the fault-bounded Gunnison uplift supports the hypothesis that the knickpoint is transient, with an upstream propagation rate that has been slowed in the last

0.64 Ma as the knickzone entered basement rocks. The existence of the modern 10-km-long high-gradient reach may be partly explained by the presence of the Vernal Mesa Granite. However, the knickzone extends upstream and downstream beyond this resistant rock (Fig. 3), suggesting that bedrock is not the only controlling factor. Prior to 0.64 Ma, the knickzone is thought to have moved rapidly through Cretaceous rocks from the Unaweep Canyon area to the Gunnison uplift (Aslan et al., 2008). At 0.64 Ma, the river was just beginning to incise through basement rocks and the top of the steep knickpoint was likely near the Red Rock Canyon confluence.

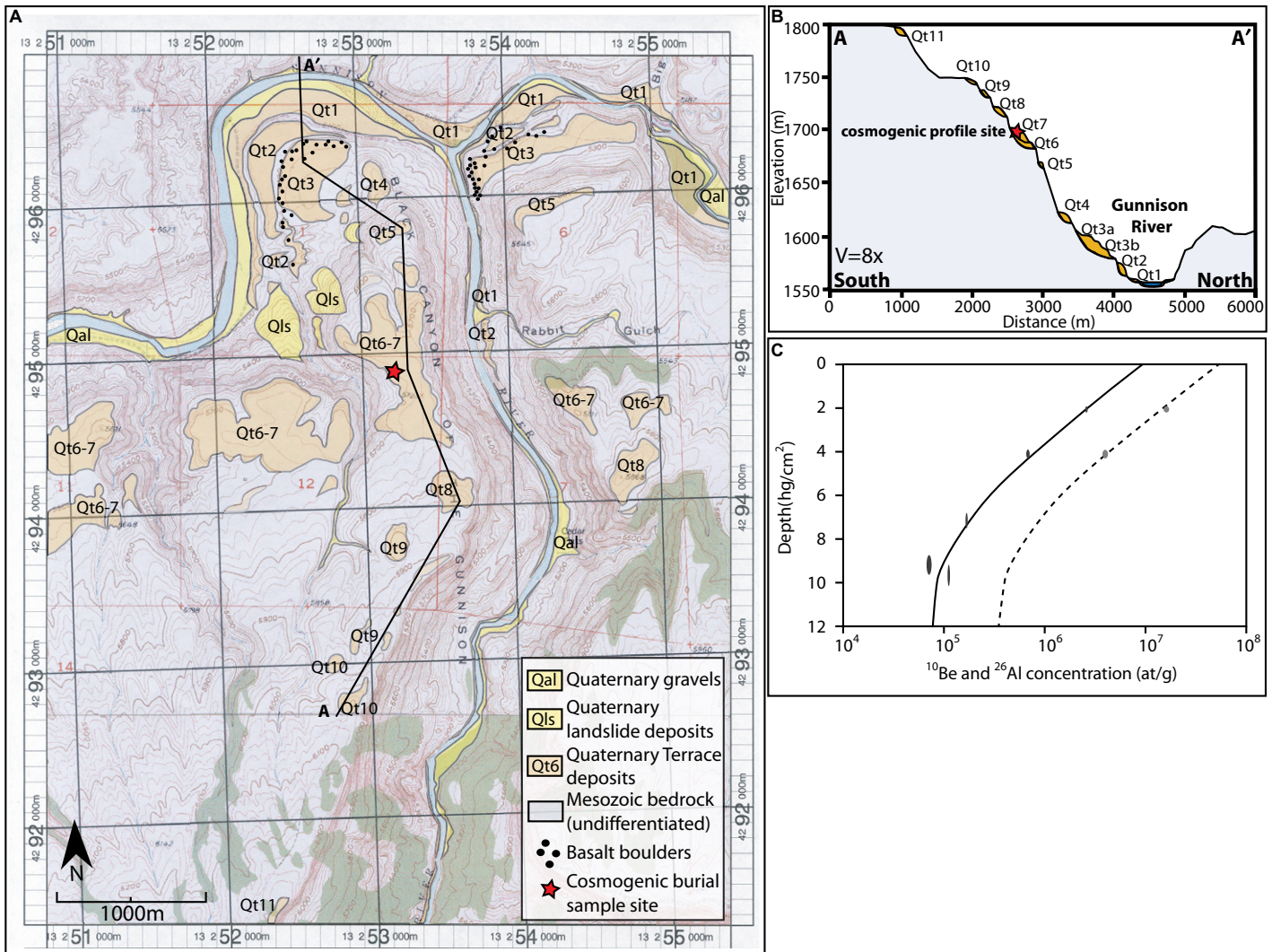
A profile reconstructed from 10 Ma basalts at Grand Mesa and Flat Top Mountain near Almont, Colorado, have ancient gravels beneath them (Fig. 3), and suggest that the late Miocene was characterized by a low-relief landscape with an established westward-draining river system (Hansen, 1971). River gravels containing volcanic and basement clasts are found below and incorporated into the basal basalt flows of Grand Mesa (Aslan et al., 2010). Gravels found beneath the ca. 10 Ma Flat Top Mountain (north of Gunnison) also contain basement clasts. Grand Mesa and Flat Top Mountain, while similar in age and in their preservation of gravels from major paleorivers, have very different calculated long-term incision rates. The Grand Mesa basalt flow is 1503 m above the modern Gunnison–Colorado River confluence, while the Flat Top gravels are 639 m above the headwater regions of the Gunnison River. Thus, post-10 Ma incision by the Gunnison and Colorado rivers in the lower parts of these rivers has removed nearly three times the thickness of rock from the lower reaches of the Gunnison River, with a regional long-term incision rate of  $140 \text{ m}/\text{Ma}$  (Fig. 3, point A; Aslan et al., 2008; Darling et al., 2009a). In contrast, the high-elevation Rocky Mountain headwater regions of the Gunnison River have been incising through the action of small streams in steep, narrow canyons at  $64 \text{ m}/\text{Ma}$  (Fig. 3, point J) over the same time frame. The headwaters region is upstream from the modern knickpoint (Fig. 3) and is adjusted to a local base level of the low-gradient upper section of the Gunnison River. This river reach has yet to feel the effects of events that have modified the lower reaches of the river.

### Models for Drainage Evolution

#### *Abandonment of Unaweep Canyon Instigating Black Canyon Incision*

Unaweep Canyon, a major bedrock gorge now hosting two divergent, underfit streams (Aslan et al., 2008), has been postulated as a





**Figure 7.** (A) Simplified geologic map (UTM Zone 13) with river terraces at the Gunnison River–North Fork Gunnison River confluence, showing Quaternary incision and confluence migration. Red star with black outline indicates cosmogenic isochron age location. (B) Cross sectional view of A–A' through river terraces. V—vertical exaggeration. (C) Depth versus concentration plot from terrace Qt7/223 m ( $^{10}\text{Be}$ —solid black line;  $^{26}\text{Al}$ —dashed line).

possible early path for the Gunnison River as it flowed northwest downstream of the present Black Canyon (Hansen, 1965, 1967). The abandonment of Unaweep Canyon at ca. 1 Ma (Aslan et al., 2008) shows clear evidence of drainage reorganization, probably through stream piracy

rerouting the Gunnison River through the Grand Valley. One possibility is that this piracy set off an incision pulse that is now expressed as the Black Canyon knickzone. Darling et al. (2009b) noted that such a transient knickzone would have passed rapidly upstream through

the weak Mancos Shale, and then more slowly once it encountered Precambrian bedrock of the Gunnison uplift.

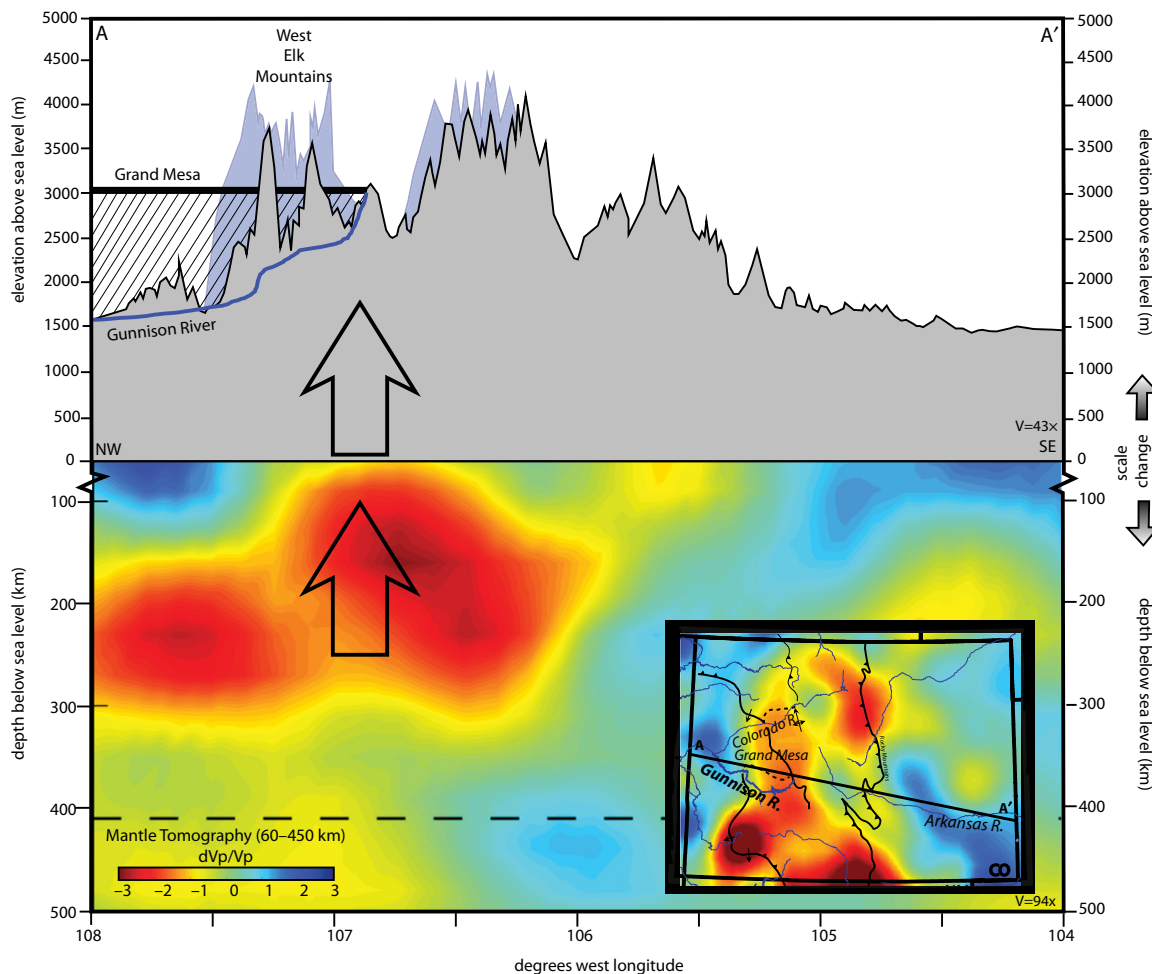
**Model for Mantle Processes Driving Both Drainage Reorganization and Rapid Bedrock Incision of Black Canyon**

Recent tomographic images indicate complex patterns in mantle velocity structure below the Gunnison River (Fig. 8; Karlstrom et al., 2012). Of particular interest, the transition from the low-velocity mantle domain beneath the headwaters to higher velocities in the lower reaches of the Gunnison River suggests that buoyant mantle may be driving differential uplift in the Rocky Mountains, and may also

**TABLE 3. COSMOGENIC NUCLIDE DATA FOR TERRACE QT7/223 M (UTM ZONE 13 253122E, 4295012N)**

Sample	Depth (m)	Depth* (g/cm <sup>2</sup> )	[ <sup>10</sup> Be] <sup>†</sup> (10 <sup>9</sup> at/g)	[ <sup>26</sup> Al] <sup>†</sup> (10 <sup>9</sup> at/g)
MS-06-18	1.4	205 ± 10	2.635 ± 0.040	15.99 ± 1.05
MS-06-13	2.4	410 ± 20	0.691 ± 0.022	3.95 ± 0.27
MS-06-14	4.0	720 ± 36	0.170 ± 0.003	—
MS-06-15g	4.9	920 ± 46	0.072 ± 0.004	—
MS-06-21g	5.6	970 ± 50	0.112 ± 0.005	—

\*Depth calculated for density 1.5 g/cm<sup>3</sup> (0–1.4 m), 1.8 g/cm<sup>3</sup> (1.4–2.75 m), and 1.5 g/cm<sup>3</sup> (>2.75 m).  
<sup>†</sup> $^{10}\text{Be}$  and  $^{26}\text{Al}$  measured at PRIME Lab, (Purdue University, West Lafayette, Indiana), against standards prepared by Nishiizumi.  $^{10}\text{Be}$  was calibrated to values reported in Nishiizumi et al. (2007).



**Figure 8.** Cross sectional view of tomography beneath the general trend of the Gunnison River (A–A’ on inset), showing the possible influence of buoyant mantle (red areas) affecting topographic behavior in the Gunnison region. Blue line represents the Gunnison River longitudinal profile from headwaters to confluence with the Colorado River. Thick black line is at the elevation of Grand Mesa (black oval on inset); hatched area indicates material removed through erosion since the eruption of Grand Mesa basalts. Inset map shows tomography at 90 km depth. Large arrows show the area undergoing mantle-driven uplift. V—vertical exaggeration.

be influencing the longitudinal profile of the Gunnison River (Schmandt and Humphreys, 2010). The hypothesis of young uplift in the headwater region of the Gunnison River is supported by apatite fission-track and apatite helium cooling ages, which show <10 Ma AHe cooling ages in the San Juan Mountains to the south (McKeon, 2009) and the West Elk and Elk Mountain Ranges to the north (Garcia, 2011) of Black Canyon. This suggests that more than 1 km of material has been eroded off the headwater regions of the Gunnison River in the last 10 Ma. Our hypothesis is that low-velocity mantle under these recently exhumed areas may have driven headwater uplift resulting in higher gradients for the Gunnison River, which then facilitated drainage reorganization and upstream knickpoint migration.

An important and often overlooked component of the uplift story involves flexural isostatic rebound driven by erosional denudation of the Rocky Mountain–Colorado Plateau region. Lazear et al. (2013) presented calculations of isostatically driven rebound applied to the Gunnison River region that suggest that independent of any tectonic surface uplift, there has been ~200 m of differential isostatically driven rock uplift of the Gunnison knickpoint region relative to both the Colorado–Gunnison confluence and the headwater regions, including Grand Mesa.

**CONCLUSIONS**

Our data suggest a very young river system responding to multiple forcings, including downstream drainage reorganization, differen-

tial isostatic rock uplift, and possible mantle-driven headwater uplift. New data conclusions are as follows.

(1) *Differential incision across a transient knickzone:* Incision rates downstream from the modern knickpoint are higher (130–150 m/Ma over 0.64 Ma and 140 m/Ma over 10 Ma) in comparison to upstream rates (90–100 m/Ma over 0.64 Ma and ~60 m/Ma over 10 Ma). Incision rates within the 10-km-long Painted Wall knickzone are strikingly higher at ~500 m/Ma over 0.64 Ma (Fig. 3, Table 1). This variation in incision rate within a relatively small lateral distance (100 km) and within the hardest rocks in the region (Fig. 3) argues that this feature is the transient expression of a stream system adjusting to a downstream drainage reorganization and related regional base level fall and/or headwater

uplift. Our model also indicates ~30 km of upstream knickpoint migration through basement from 1.0 to 0.64 Ma (0.36 Ma). This documents the importance of bedrock erodibility on knickpoint propagation rates.

(2) *Incision history of Black Canyon of the Gunnison*: Projection of the abandoned paleo-Bostwick tributary, that deposited the 0.64 Ma Lava Creek B-associated river gravels, to its intersection with the Gunnison at Red Canyon is presently the best constraint on the age and rate of incision of Black Canyon. At this location, ~350 m of the roughly 700 m total depth of Black Canyon has been incised in the last 0.64–0.87 Ma. We use the Cimarron gradient as a proxy for the paleo-Bostwick to extrapolate preserved and dated straths to their inferred confluence with the river at 350 m above the river. The result is that over the past 0.87–0.64 k.y., incision has occurred at the high average rate of 400–550 m/Ma. If one assumes steady incision rates, this implies the spectacular bedrock Black Canyon was carved within the last 1.3–1.75 Ma. However, given that these high rates are only likely to have been active in the Black Canyon reach once the incision transient from Unaweep abandonment arrived near Red Canyon after 1 Ma, rates may have been higher and carving of the entire bedrock canyon in the last ~1 Ma seems most likely.

(3) *New incision rates from tephrochronology and cosmogenic burial dating of gravels*: Our new data suggest that the previously reported 1.2 Ma Mesa Falls tuff locality in the Shinn-Bostwick drainages is likely to be the 0.64 Ma Lava Creek B. The new age of the paleo-Bostwick gravels below the ash of 870 ± 220 ka precludes this ash being Mesa Falls. This reassignment is also supported by stratigraphic relations, indicating no major unconformity between the two exposed ashes. Cosmogenic dating indicates that terrace QT7/223 m at the North Fork Gunnison–Gunnison River confluence is 0.98 (+0.38/-0.07) Ma, yielding an incision rate there of 228 (+17/-64) m/Ma.

(4) *Persistent differential incision in the early Gunnison River*: Incision rates calculated from 10 Ma basalts show the same long-term differential incision as seen in the younger profiles and suggests that either (a) the knickpoint was already in existence at 10 Ma or (b) that post-3 Ma incision has created the differential incision rates (our favored hypothesis). The Oligocene profile is near the modern profile in the upper reaches of the Gunnison system, suggesting zero long-term incision—presumably due to a combination of aggradation and surface uplift following the construction of Oligocene-age volcanics. Erosionally driven isostatic rebound of the region may also have helped drive incision of the Black Canyon of the Gunnison.

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#### REFERENCES CITED

- Aslan, A., and 13 others, 2008, River incision histories of the Black Canyon of the Gunnison and Unaweep Canyon: Interplay between late Cenozoic tectonism, climate change, and drainage integration in the western Rocky Mountains, in Reynolds, R.G. ed., *Roaming the Rocky Mountains and Environs: Geological Field Trips: Geological Society of America Field Guide 10*, p. 175–202.
- Aslan, A., Karlstrom, K.E., Crossey, L.J., Kelley, S., Cole, R., Lazear, G., and Darling, A., 2010, Late Cenozoic evolution of the Colorado Rockies: Evidence for Neogene uplift and drainage integration, in Morgan, L.A., and Quane, S.L., eds., *Through the Generations: Geologic and Anthropogenic Field Excursions in the Rocky Mountains from Modern to Ancient: Geological Society of America Field Guide 18*, p. 21–54.
- Balco, G., and Rovey, C.W., 2008, An isochron method for cosmogenic nuclide dating of buried soils and sediments: *American Journal of Science*, v. 308, p. 1083–1114, doi:10.2475/10.2008.02.
- Berlin, M.M., and Anderson, R.S., 2007, Modeling of knickpoint retreat on the Roan Plateau, western Colorado: *Journal of Geophysical Research*, v. 112, F03S06, doi: 10.1029/2006JF000553.
- Bishop, P., Honey, T.B., Jansen, J.D., and Artza, I.L., 2005, Knickpoint recession rate and catchment area: The case of uplifted rivers in Eastern Scotland: *Earth Surface Processes and Landforms*, v. 30, p. 767–778, doi:10.1002/esp.1191.
- Burbank, D.W., and Anderson, R.S., 2001, *Tectonic Geomorphology*: Malden, Massachusetts, Blackwell Publishing, 161 p.
- Coven, B., Panter, K., and Stork, A., 1999, Ar/Ar age of the West Elk Volcano, Gunnison and Delta Counties, Colorado: *Geological Society of America Abstracts with Programs*, v. 31, no. 7, p. 478.
- Darling, A., Aslan, A., Cole, R., Karlstrom, K., Betton, C., and Wan, E., 2009a, Late Quaternary incision rates and drainage evolution of the Uncompahgre and Gunnison Rivers calibrated by Lava Creek B ash: *Western Colorado: Rocky Mountain Geology*, v. 44, p. 71–83, doi:10.2113/gsrrocky.44.1.71.
- Darling, A., Karlstrom, K., Kirby, E., and Ouimet, W., 2009b, Comparison of the modern profiles and discharge of the Green and Colorado Rivers and implications for epeirogenic uplift of the Colorado Plateau and Rocky Mountains: *Geological Society of America Abstracts with Programs*, v. 41, no. 7, p. 306–307.
- Darling, A.L., Karlstrom, K.E., Granger, D.E., Aslan, A., Kirby, E., Ouimet, W.B., Lazear, G.D., Coblenz, D.D., and Cole, R.D., 2012, New incision rates along the Colorado River system based on cosmogenic burial dating of terraces: Implications for regional controls on Quaternary incision: *Geosphere*, v. 8, p. 1020–1041, doi:10.1130/GES00724.1.
- Dethier, D.P., 2001, Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra: *Geology*, v. 29, p. 783–786, doi:10.1130/0091-7613(2001)029<0783:PIRITW>2.0.CO;2.
- Dickinson, R.G., 1966, *Geology of the Cerro Summit quadrangle, Montrose County, Colorado* [Ph.D. Dissertation]: Tucson, University of Arizona.
- Dortch, J.M., Dietsch, C., Owen, L.A., Caffee, M.W., and Ruppert, K., 2011, 2011, Episodic fluvial incision of

- rivers and rock uplift in the Himalaya and Transhimalaya: *Journal of the Geological Society*, v. 168, p. 783–804, doi:10.1144/0016-76492009-158.
- Douglas, J., Meek, N., Dorn, R., and Schmeekle, M., 2009, A criteria-based methodology for determining the mechanism of transverse drainage development, with application to the southwestern United States: *Geological Society of America Bulletin*, v. 121, p. 586–598, doi: 10.1130/B26131.1.
- Ducea, M.N., Kidder, S., and Zandt, G., 2003, 2003, Arc composition at mid-crustal depths: Insights from the Coast Ridge Belt, Santa Lucia Mountains, California: *Geophysical Research Letters*, v. 30, 1703, doi: 10.1029/2002GL016297.
- Duvall, R.A., Kirby, E., and Burbank, B., 2004, Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California: *Journal of Geophysical Research*, v. 109, F03002, doi:10.1029/2003JF000086.
- Eaton, G.P., 2009, Epeirogeny in the Southern Rocky Mountains region: Evidence and origin: *Geosphere*, v. 5, p. 408, doi:10.1130/GES00149.1.
- Epis, R., and Chapin, C., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the Southern Rocky Mountains, in Curtis, B.F., ed., *Cenozoic History of the Southern Rocky Mountains: Geological Society of America Memoir 144*, p. 45–74.
- Finnegan, N.J., and Dietrich, W.E., 2011, Episodic bedrock strath terrace formation due to meander migration and cutoff: *Geology*, v. 39, p. 143–146, doi:10.1130/G31716.1.
- Garcia, R.V., 2011, *Cenozoic intrusive and exhumation history of the Elk and West Elk Mountain plutons, southwest Colorado* [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 160 p.
- Gardner, T.W., 1983, Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material: *Geological Society of America Bulletin*, v. 94, p. 664–672, doi:10.1130/0016-7606(1983)94<664:ESOKAL>2.0.CO;2.
- Gilbert, G.K., 1877, Report on the geology of the Henry Mountains, in Powell J.W., ed., *United States Geographical and Geological Survey of the Rocky Mountains Region*: Washington, D.C., U.S. Government Printing Office, p. 160.
- Goldrick, G., and Bishop, P., 2007, Regional analysis of bedrock stream long profiles: Evaluation of Hack's SL form, and formulation and assessment of an alternative (the DS form): *Earth Surface Processes and Landforms*, v. 32, p. 649–671, doi:10.1002/esp.1413.
- Granger, D.E., and Smith, A.L., 2000, Dating buried sediments using radioactive decay and muogenic production of <sup>26</sup>Al and <sup>10</sup>Be: *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, v. 172, p. 822–826, doi:10.1016/S0168-583X(00)00087-2.
- Gregory, K.M., and Chase, G.C., 1992, Tectonic significance of paleobotanically estimated climate and altitude of the late Eocene erosion surface, Colorado: *Geology*, v. 20, p. 581–585, doi:10.1130/0091-7613(1992)020<0581:TSOPEC>2.3.CO;2.
- Gregory, K.M., and Chase, C.G., 1994, Tectonic and climatic significance of a late Eocene low-relief, high-level geomorphic surface, Colorado: *Journal of Geophysical Research*, v. 99, p. 20,141–20,160, doi:10.1029/94JB00132.
- Hales, T.C., Abt, D.L., Humphreys, E.D., and Roering, J.J., 2005, A lithospheric instability origin for Columbia River flood basalts and Wallowa Mountains uplift in northeast Oregon: *Nature*, v. 438, p. 842–845, doi: 10.1038/nature04313.
- Hansen, W.R., 1965, *The Black Canyon of the Gunnison: Today and yesterday*: U.S. Geological Survey Bulletin 1191, 76 p.
- Hansen, W.R., 1967, *The lower Black Canyon of the Gunnison*: *National Parks Magazine*, v. 41, no. 238, p. 14–19.
- Hansen, W.R., 1971, *Geologic map of the Black Canyon of the Gunnison River and vicinity, western Colorado*: U.S. Geological Survey Miscellaneous Geological Investigations Map I-584, scale 1:31,680, 1 map on 2 sheets.
- Hansen, W.R., 1987, *The Black Canyon of the Gunnison, Colorado*, in Bues, S., ed., *Centennial Field Guide:*

- Boulder, Colorado, Geological Society of America, Rocky Mountain Section, v. 2, p. 321–324.
- Hidy, A.J., Gosse, J.C., Pederson, J.L., Mattern, J.P., Finkel, R.C., 2010, A geologically constrained Monte Carlo approach to modeling exposure ages from profiles of cosmogenic nuclides: An example from Lees Ferry, Arizona: *Geochemistry, Geophysics, Geosystems*, v. 11, Q0AA10, doi:10.1029/2010GC003084.
- House, M.A., Wernicke, B.P., and Farley, K.A., 2001, Paleogeomorphology of the Sierra Nevada, California, from (U-Th)/He ages in apatite: *American Journal of Science*, v. 301, p. 77–102, doi:10.2475/ajs.301.2.77.
- Humphreys, E., Hessler, E., Dueker, K., Farmer, G.L., Erslev, E., and Atwater, T., 2003, How Laramide-age hydration of North American lithosphere by the Farallon slab controlled subsequent activity in the western United States: *International Geology Review*, v. 45, p. 575–595, doi:10.2747/0020-6814.45.7.575.
- Hunt, C.B., 1969, Geologic history of the Colorado River, in *The Colorado River Region and John Wesley Powell*: U.S. Geological Survey Professional Paper 669, p. 59–130.
- Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distributions of Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the Western United States and southern Canada: U.S. Geological Survey Miscellaneous Investigations Map I-1325, scale 1:4,000,000, 1 sheet.
- Karlstrom, K.E., Crow, R., Crossey, L., Coblenz, D., and Van Wijk, J., 2008, Model for tectonically driven incision of the younger than 6 Ma Grand Canyon: *Geology*, v. 36, p. 835–838, doi:10.1130/G25032A.1.
- Karlstrom, K.E., and 14 others, and CREST working group, 2012, Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis: *Lithosphere*, v. 4, p. 3–22, doi:10.1130/L150.1.
- Kirby, E., and Ouimet, W., 2011, Tectonic geomorphology along the eastern margin of Tibet: Insights into the pattern and processes of active deformation adjacent to the Sichuan Basin, in *Gloaguen, R., and Ratschbacher, L., eds., Growth and Collapse of the Tibetan Plateau*: Geological Society of London Special Publication 353, p. 165–188, doi:10.1144/SP353.9.
- Kirby, E., and Whipple, K.X., 2012, Expression of active tectonics in erosional landscapes: *Journal of Structural Geology*, v. 44, p. 54–75, doi:10.1016/j.jsg.2012.07.009.
- Kirby, E., Whipple, K.X., Tang, W., and Chen, Z., 2003, Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: Inferences from bedrock channel longitudinal profiles: *Journal of Geophysical Research*, v. 108, 2217, doi:10.1029/2001JB000861.
- Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovich, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field: Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: *Geological Society of America Bulletin*, v. 114, p. 559–568, doi:10.1130/0016-7606(2002)114<0559:RAFTOT>2.0.CO;2.
- Lazar, G., Karlstrom, K., Aslan, A., and Kelley, S., 2013, Denudation and flexural isostatic response of the Colorado Plateau and Southern Rocky Mountains region since 10 Ma: *Geosphere*, v. 9, doi:10.1130/GES00836.1.
- Lipman, P.W., 2007, Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field: *Geosphere*, v. 3, p. 42–70, doi:10.1130/GES00061.1.
- Mackin, J.H., 1948, Concept of the graded river: *Geological Society of America Bulletin*, v. 59, p. 463–511, doi:10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2.
- McKeon, R.E., 2009, The interaction between tectonics, topography, and climate in the San Juan Mountains, Southwestern Colorado [M.S. Thesis]: Bozeman, Montana State University, 86 p.
- McMillan, M.E., Angevine, C.L., and Heller, P.L., 2002, Postdepositional tilt of the Miocene–Pliocene Ogallala Group on the western Great Plains: Evidence of late Cenozoic uplift of the Rocky Mountains: *Geology*, v. 30, p. 63–66, doi:10.1130/0091-7613(2002)030<0063:PTOTMP>2.0.CO;2.
- McMillan, M.E., Heller, P.L., and Wing, S.L., 2006, History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau: *Geological Society of America Bulletin*, v. 118, p. 393–405, doi:10.1130/B25712.1.
- Molnar, P., 2004, Late Cenozoic increase in accumulation rates of terrestrial sediment: How might climate change have affected erosion rates?: *Annual Review of Earth and Planetary Science*, v. 32, p. 67–89, doi:10.1146/annurev.earth.32.091003.143456.
- Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., and McAninch, J., 2007, Absolute calibration of <sup>10</sup>Be AMS standards: Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, v. 258, p. 403–413, doi:10.1016/j.nimb.2007.01.297.
- Ouimet, W., Whipple, K.X., Royden, L., Reiners, P., Hodges, K., and Pringle, M., 2010, Regional incision of the eastern margin of the Tibetan Plateau: *Lithosphere*, v. 2, p. 50–63, doi:10.1130/L57.1.
- Pederson, J.L., Mackley, R.D., and Eddleman, J.L., 2002, Colorado Plateau uplift and erosion evaluated using GIS: *GSA Today*, v. 12, no. 8, p. 4–10, doi:10.1130/1052-5173(2002)012<0004:CPUAEE>2.0.CO;2.
- Phillips, W.M., Commins, D.C., and Gupta, S., 2003, Rates of knickpoint migration and bedrock erosion from cosmogenic <sup>10</sup>Be in a landscape of active normal faulting: *Geological Society of America Abstracts with Programs*, v. 35, no. 6, p. 63.
- Repka, J.L., Anderson, R.S., and Finkel, R.C., 1997, Cosmogenic dating of fluvial terraces, Fremont River, Utah: *Earth and Planetary Science Letters*, v. 152, p. 59–73, doi:10.1016/S0012-821X(97)00149-0.
- Roy, M., Kelley, S.A., Pazzaglia, F., Cather, S., and House, M., 2004, Middle Tertiary buoyancy modification and its relationship to rock exhumation, cooling, and subsequent extension at the eastern margin of the Colorado Plateau: *Geology*, v. 32, p. 925–928, doi:10.1130/G20561.1.
- Roy, M., Jordan, T.H., and Pederson, J., 2009, Cenozoic magmatism and rock uplift of the Colorado Plateau by warming of chemically buoyant lithosphere: *Nature*, v. 459, p. 978–982, doi:10.1038/nature08052.
- Safran, E.B., Bierman, P.R., Aalto, R., Dunne, T., Whipple, K.X., and Caffee, M., 2005, Erosion rates driven by channel network incision in the Bolivian Andes: *Earth Surface Processes and Landforms*, v. 30, p. 1007–1024, doi:10.1002/esp.1259.
- Sandoval, M.M., 2007, Quaternary incision history of the Black Canyon of the Gunnison, Colorado [M.S. thesis]: Albuquerque, University of New Mexico, 120 p.
- Schildgen, T.F., Hodges, K.V., Whipple, K.X., Reiners, P.W., and Pringle, M.S., 2007, Uplift of the western margin of the Andean plateau revealed from canyon incision history, southern Peru: *Geology*, v. 35, p. 523–526, doi:10.1130/G23532A.1.
- Schmandt, B., and Humphreys, E.D., 2010, Complex subduction and small-scale convection revealed by body wave tomography of the western U.S. upper mantle: *Earth and Planetary Science Letters*, v. 297, p. 435–445, doi:10.1016/j.epsl.2010.06.047.
- Schneeflock, F., Meyer, G., Karlstrom, K., and Wagner, S., 2002, Quaternary drainage development and incision history in the Black Canyon of the Gunnison area, Colorado: *Geological Society of America Abstracts with Programs*, v. 34, no. 6, p. 472.
- Steven, T.A., 1975, Middle Tertiary volcanic field in the Southern Rocky Mountains, in *Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains*: Geological Society of America Memoir 144, p. 75–94.
- Stock, J.D., and Montgomery, D.R., 1999, Geologic constraints on bedrock river incision using the stream power law: *Journal of Geophysical Research*, v. 104, p. 4983–4994, doi:10.1029/98JB02139.
- Whipple, K.X., 2004, Bedrock rivers and the geomorphology of active orogens: *Annual Review of Earth and Planetary Sciences*, v. 32, p. 151–185, doi:10.1146/annurev.earth.32.101802.120356.
- Wobus, C.W., Crosby, B.T., and Whipple, K.X., 2006, Hanging valleys in fluvial systems: Controls on occurrence and implications for landscape evolution: *Journal of Geophysical Research*, v. 111, F02017, doi:10.1029/2005JF000406.
- Wolkowinsky, A.J., and Granger, D.E., 2004, Early Pleistocene incision of the San Juan River, Utah, dated with <sup>26</sup>Al and <sup>10</sup>Be: *Geology*, v. 32, p. 749–752, doi:10.1130/G20541.1.