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ABANDONMENT OF UNAWEEP CANYON (1.4 TO 0.8 MA), WESTERN COLORADO: EFFECTS OF STREAM CAPTURE AND ANOMALOUSLY RAPID PLEISTOCENE RIVER INCISION

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ABSTRACT

Cosmogenic-burial and U-series dating, identification of fluvial terraces and lacustrine deposits, and river-profile reconstructions show that capture of the Gunnison River by the Colorado River and abandonment of Unaweep Canyon occurred between 1.4-0.8 Ma. This event led to a rapid pulse of incision unlike any documented in the Rocky Mountains. Following abandonment of Unaweep Canyon by the ancestral Gunnison River, a wave of incision propagated upvalley rapidly through Mancos Shale at rates of ~90-440 km/Ma. The Gunnison River removed 400-500 km^3 of erodible Mancos Shale and incised up to 360 m deep in 0.17-0.76

My (incision rates of ~470-2250 m/Ma). Prior to canyon abandonment, long-term (~11-1 Ma) Gunnison River incision averaged ~100 m/Ma.

The wave of incision also caused the subsequent capture of the Bostwick-Shinn Park River by the ancestral Uncompahgre River ca. 0.87-0.64 Ma, at a location ~70 km upvalley from Unaweep Canyon. This event led to similarly rapid (up to ~500 m/Ma) but localized river incision. As regional river incision progressed, the juxtaposition of resistant Precambrian bedrock and erodible Mancos Shale within watersheds favored the development of significant relief between adjacent stream segments, which led to stream piracy. The response of rivers to the abandonment of Unaweep Canyon illustrates how the mode and tempo of long-term fluvial incision are punctuated by short-term geomorphic events such as stream piracy. These short-term events can trigger significant landscape changes, but the effects are more localized relative to regional climatically- or tectonically-driven events.

INTRODUCTION

Stream capture is a well-known process, but our understanding of its effects on rates and magnitudes of fluvial incision is hampered by poor preservation of associated landforms, and uncertainties involving the timing of capture events (Prince et al., 2011). Whereas tectonism and climate are known to drive landscape change (e.g., Hoffman and Grotzinger, 1993; Harkins et al., 2007; Bonnet, 2009), the effects of autocyclic processes such as stream capture have received considerably less attention (Hasbargen and Paola, 2000; Prince et al., 2011). Although tectonic and climatic events set the stage for stream capture, stream piracy's effects on spatial and temporal patterns of fluvial erosion must be evaluated carefully in order to formulate accurate interpretations of landscape evolution.

Unaweep Canyon is the most spectacular example of stream piracy resulting in canyon abandonment in the upper Colorado River system (Hunt, 1969, p. 78) (**Fig. 1**). The present canyon is 40-km-long, 5-km-wide, up to 700-m-deep, and is cut mostly through resistant Precambrian bedrock (**Fig. 2**). It has no major river at its base, and is currently drained by two underfit streams, East and West Creeks, which drain the northeast and southwest ends of the canyon, respectively. Starting with the Hayden Survey, geologists recognized Unaweep as an abandoned canyon that was once occupied by the Gunnison River (Peale, 1877; Cater, 1966; 1970), the Colorado River (Gannett, 1882), or both (Lohman, 1965, 1981; Sinnock, 1983; Aslan et al., 2008a; Hood, 2011). Subsequent debate has focused on which river(s) cut the canyon, over what time period incision occurred, the timing and causes of abandonment, and the amount of fill in the valley. There has also been debate over whether or not Unaweep Canyon has both a Quaternary and Paleozoic component to its history (Soreghan et al., 2007). Recent drilling has resolved the thickness of fill to be at least 320 m locally (Soreghan et al., 2007; as predicted by Oesleby, 1983; 2005a). This result demonstrates that Unaweep is at least a 1-km-deep, partially filled bedrock canyon that rivals Black Canyon of the Gunnison and the inner gorge of Grand Canyon in depth (Donahue et al., 2013).

The purpose of this paper is to document the context, timing, and geomorphic effects of Unaweep's abandonment. Specifically, this paper describes how canyon abandonment initiated a wave of fluvial incision that propagated upstream along the Gunnison River system, triggered at least one additional stream capture event, and produced anomalously rapid short-term river incision rates. The rates and magnitudes of landscape change brought about by this single event are compared with longer-term fluvial incision governed by tectonic processes that have operated over the last ~10 Ma in the upper Colorado River basin (Aslan et al., 2010; Karlstrom et al., 2012).

METHODS

Fieldwork included mapping of ancient river gravels and lacustrine deposits in Cactus Park, and reconnaissance studies near Gateway. Two shallow (<50 m deep) hollow-stem-auger drillholes were completed in Cactus Park to provide core samples of lake beds and cuttings of buried Gunnison River gravels. Beige sandstone fragments from the lowermost sample from one of the cores were dated by $^{26}Al/^{10}Be$ burial dating at PRIME lab (Purdue University) to determine the timing of abandonment (Table 1). Sand samples were collected at 5 locations for detrital zircon analysis at the University of Arizona's LaserChron lab to evaluate provenance of ancient river drainages (**Fig. 2,** Supplemental Table 1). Additional examination of Colorado and Gunnison River terraces that post-date Unaweep Canyon's abandonment were also completed in the vicinity of Grand Junction. At key locations, clast counts (100 to 200 clasts at each site) of representative gravel deposits were used to characterize gravel compositions. Sparry calcite-cemented gravels acquired from gravel pits of the oldest Colorado River terraces that post-date Unaweep Canyon abandonment were subsampled for U-series age dating, which was carried out at the University of New Mexico (Table 2, Supplemental Table 2).

Proterozoic Taylor Ranch and Vernal Mesa granite (Williams, 1964) were sampled near Unaweep Divide and Gateway, respectively, for apatite-fission-track analysis to better constrain the long-term exhumation history of the area (Table 3) (**Fig. 3**). Apatite fission-track dates were determined following procedures outlined in Kelley et al. (1992). Thermal history models were extracted from the age and track length data using the HeFTy model of Ketchum (2005) and the annealing equations of Ketchum et al. (1999). No apatite chemistry or (U-Th)/He data are currently available for the samples. Dpar values of 1.2-1.5 µm are consistent with a fluorapatite composition. A mean annual modern surface temperature of 11°C was used in the thermal history modeling, based on data for nearby Grand Junction.

Together, this diverse suite of data allows us to improve our understanding of the timing of Unaweep Canyon abandonment, and evaluate its influence on drainage evolution along the western slope of the Colorado Rockies.

POST-CRETACEOUS EXHUMATION IN THE VICINITY OF UNAWEEP CANYON

The geologic record in the vicinity of Unaweep Canyon provides clues about the exhumation and burial history of the Uncompahgre Uplift. The Cutler Formation laps onto the south flank of this Ancestral Rocky Mountain uplift, placing the Proterozoic rocks that form the core of the uplift at the surface at ca. 300 Ma. The Proterozoic basement was subsequently buried by ca. 350 m of Mesozoic rocks (Triassic Moenkopi to Cretaceous Burro Canyon) that were deposited in eolian and fluvial environments prior to the incursion of the Western Interior Seaway at ca. 110 Ma (Nuccio and Roberts, 2003). Marine deposition in this area gave way to marginal marine and fluvial deposition of the Mesaverde Group. Cretaceous deposition ended at ca. 66 Ma (Nuccio and Roberts, 2003). According to Nuccio and Roberts (2003), the average thickness of Cretaceous rocks in the Piceance Basin north of the Uncompahgre uplift is 3000 to 3400 m; 1500 to 1700 m of the section is composed of Mancos Shale.

New apatite-fission-track (AFT) cooling ages were determined help to constrain the timing of the post-Cretaceous exhumation of the northern Uncompahgre Plateau. Two samples were acquired from Proterozoic granitic rocks located 1) along the south rim of the canyon at Unaweep Divide (elev. 2130 m) and 2) at the lowermost outcrop (elev. 1550 m) of Proterozoic rocks on the west side of Unaweep Canyon near Gateway, Colorado (**Fig. 3**). A geologic cross-section that shows the context of the samples is shown in **Fig. 4A.** The two samples are separated by about 1 km of vertical relief. The samples have AFT cooling ages of 22 to 38 Ma and mean track lengths of 12.7-12.9 μm (Table 3), indicative of slow cooling during mid-Cenozoic time.

HeFTy was used to construct twenty thermal histories using the geologic constraints outlined above; two sets of models were run without geologic constraints for comparison. Four representative thermal histories are illustrated in **Figure 4B**. Note that the curves for the constrained and the unconstrained models are quite similar within and below the apatite partial annealing zone (PAZ), suggesting that the data and not the constraints are controlling the calculated histories. The youthful nature of the AFT apparent ages does little to constrain the Cretaceous burial history of the region, as indicated by the wide zones of "good-fit" prior to 40 Ma. The thermal blanketing effects of the 1.5 to 1.7 km-thick, low thermal conductivity shales, which can have interval gradients of 40 to 60°C/km, even in terrains with average heat flow (Kelley and Chapin, 2004), was sufficient to totally reset the fission-track system in the basement rocks during late Cretaceous time. The sampled portion of the Uncompahgre Uplift was not strongly exhumed by Laramide deformation, although faulting of Laramide age has been recognized.   Instead, this area was exhumed beginning in Eocene to Oligocene time. Erosion through the sedimentary cover of the Uncompahgre Uplift eventually exposed resistant Precambrian rocks in the vicinity of present-day Unaweep Canyon at elevations of 2.5-2.8 km. Continued exhumation and the presence of these resistant rocks set the stage for the subsequent development and abandonment of Unaweep Canyon. The AFT data suggest a couple of pulses of exhumation or cooling, one at 45 to 40 Ma that was recorded by the shallower sample and another at 25 to 30 Ma recorded by the deeper sample; the latter event could be related to relaxation of isotherms as activity in the San Juan volcanic field waned. An apparent pulse of accelerated exhumation during the last 10 Ma is shown in the thermal history of the deeper of the two samples and needs to be tested with (U-Th)/He dating.

SUMMARY OF EVENTS LEADING UP TO ABANDONMENT OF UNAWEEP CANYON

Onset of Canyon Cutting and Stages of Unaweep Canyon Abandonment

The connection of Unaweep Canyon with the upper Colorado River drainage probably began in the late Miocene. This interpretation is based on the presence of ancestral Colorado River gravels located beneath ~11 Ma Grand Mesa basalts that are at an elevation of ~2.9 km (Aslan et al., 2011) (**Fig. 2**). The flows are located 10-15 km east of Unaweep Canyon, and their elevation is similar to the highest bedrock walls of Unaweep Canyon (Hood, 2011). These observations, coupled with the distribution of younger fluvial gravels, suggest that the combined ancestral Colorado-Gunnison River flowed southwest across the Uncompahgre Plateau at a present-day elevation of ~2.9 km, and established the position of Unaweep Canyon in the late Miocene (Cater, 1966; Hood, 2011) (**Fig. 5A**).

Abandonment of the canyon likely occurred in two stages (Lohman, 1961; Cater, 1966; Sinnock, 1978; 1981; Aslan et al., 2008a; Hood, 2011). Stage one of canyon abandonment was the capture of the ancestral Colorado River and its re-location near the northern edge of the Uncompahgre Plateau (**Fig. 5B**). The timing and cause of this stream capture event is poorly known, but it is reasonable to assume that a stream eroding headward along the northern edge of the Uncompahgre Plateau through Mancos Shale (**Fig. 5A**) facilitated the capture (Lohman, 1961; 1965; Sinnock, 1981).

The second event leading to complete abandonment of Unaweep Canyon was the capture of the Gunnison River (**Fig. 5C**). This event may have been associated with a large landslide (Oesleby, 2005b) that blocked the ancestral Gunnison River, and formed a lake within the western end of Unaweep Canyon ca. 1.4-1.3 Ma (Soreghan et al., 2007; Balco et al., 2013). Balco et al. (2013) suggest that the presence of lacustrine sediment in western Unaweep Canyon marks abandonment of Unaweep at ca. 1.4 Ma. While it is possible that the formation of the landslide dam and lake triggered complete abandonment of Unaweep Canyon, it is also possible that the Gunnison River continued to occupy the upstream portion of the canyon for a significant interval of time following lake formation. Additional information that supports this latter hypothesis follows herein, and a more thorough discussion of causes of abandonment, including lake spillover scenarios, is presented in Hood et al. (2014).

FLUVIAL AND LACUSTRINE DEPOSITS RELATED TO UNAWEEP CANYON ABANDONMENT

Soreghan et al. (2007) interpret interbedded sand and mud exposed within a drill core of Unaweep Canyon valley-fill (**Fig. 3**) as deposits of an ancient lake that existed in western Unaweep Canyon by ca. 1.4 Ma (Balco et al., 2013). Other than this subsurface data, however, ancient river gravel and lacustrine deposits have not been documented within Unaweep Canyon proper, due to the presence of thick Pleistocene valley fill. However, important fluvial and lacustrine records are preserved in nearby Cactus Park and at Gateway, Colorado. These deposits provide important constraints on pre- and post-abandonment geomorphic events associated with Unaweep Canyon.

Cactus Park River Gravels

Cactus Park is a fluvial paleovalley that joins Unaweep Canyon at the east (upstream) end of the canyon (**Fig. 6**). River gravels are found throughout Cactus Park and are typically represented by 2-4-m-thick accumulations of well-rounded pebbles and cobbles that overlie Jurassic sandstone or shale. These gravel accumulations are interpreted as eroded remnants of strath terraces based on gravel thicknesses and the concordance of strath elevations (Aslan et al., 2008a). Strath elevations range from 1870 to 1980 m. Mapping of the Cactus Park gravels, combined with compositional data, shows that the ancestral Gunnison River in this area flowed northwest before entering Unaweep Canyon. At the junction with Unaweep Canyon, the river turned southwest and flowed across the Uncompahgre Plateau (**Figs. 3 and 6**).

The gravels are composed largely of intermediate volcanic clasts derived from Oligocene volcanic rocks of the San Juan and West Elk Mountains as well as small percentages (3-5 %) of granitic clasts (**Figs. 7 and 8**), which were possibly eroded from the Gunnison Uplift and Sawatch Range. Alternatively, a portion of the granitic clasts could be reworked from Oligocene Telluride Conglomerate that crops out along the flanks of the San Juan Mountains. Clast counts comparing modern Gunnison and Uncompahgre River gravels with those found in Cactus Park show that both Gunnison River and Cactus Park gravels are dominated by intermediate volcanic lithologies, and have small but significant granitic components (**Fig. 8**). In contrast, the modern Uncompahgre River gravel lacks granitic clasts. Based on these considerations, it seems likely that the Cactus Park gravel represent deposits of the combined ancestral Gunnison and Uncompahgre Rivers rather than the ancestral Uncompahgre River alone (Steven, 2002).

Detrital-Zircon Provenance Data

U-Pb age spectra of detrital zircons of modern Gunnison and Uncompahgre River and Cactus Park samples further support a Gunnison River interpretation for Cactus Park river gravels (**Fig. 9**). The Cactus Park zircon-age population of grains <600 Ma resembles the modern Gunnison River in 1) the presence of ca. 25-30 Ma grains (San Juan volcanic field), 2) the presence of ca. 60-75 Ma (Laramide-aged) grains, 3) the presence of ca. 95-105 Ma and ca. 160-180 Ma grains (Cordilleran magmatic arc activity), and 4) the paucity of ca. 250-600 Ma grains. The same grain populations are also found in the modern Uncompahgre River sample. However, ca. 250-500 Ma grains are much more abundant in the Uncompahgre River sample compared to the Cactus Park sample. This difference could represent dilution of Uncompahgre River detrital zircons at locations downstream of the Gunnison-Uncompahgre River confluence. The modern Gunnison River has a significantly greater discharge and sediment load than the Uncompahgre River, and assuming this condition existed in the past, then a dilution of ancient Uncompahgre River zircons at locations downstream of the paleo-confluence would be expected. In summary, the detrital zircon age population for the Cactus Park sample supports the idea that Cactus Park fluvial sediments represent a mixture of the Gunnison and Uncompahgre Rivers.

Gateway River Gravels

At the west end of Unaweep Canyon near Gateway, Colorado, there are at least two levels of fluvial gravels, referred to as the Gateway gravels (Cater, 1955; Kaplan, 2006). The gravels contain boulders of subrounded Precambrian granite and angular Mesozoic sandstone, as well as appreciable quantities of rounded, cobble-sized intermediate volcanic clasts similar to those found in Cactus Park. In addition, the gravels contain uncommon but distinctive red, rounded fine-grained sandstone and siltstone cobbles that could be derived from the Pennsylvanian Maroon Formation (Hood, 2011). The Gateway gravels are broadly correlative with those in Cactus Park, and have been interpreted as deposits of the ancestral Gunnison River (Cater, 1955, Kaplan, 2006) and/or the ancestral Colorado River (Hood, 2011).

Detrital-Zircon Provenance Data

U-Pb age spectra of detrital zircons of modern Gunnison and Colorado River and Gateway samples can be used to provide additional insight on the provenance of the Gateway Gravels (**Fig. 9**). The Gateway Gravel zircon-age population resembles the modern Gunnison River in 1) the presence of ca. 25-30 Ma grains (San Juan volcanic field), 2) the presence of ca. 60-75 Ma (Laramide-aged) grains, 3) the presence of (ca. 95-105 Ma) and (ca. 160-180 Ma) grains derived from Cordilleran magmatic arc activity, 4) the paucity of ca. 250-600 Ma grains, and 5) the presence of a few ca. 390 Ma-aged grains. Similar to the Cactus Park gravels, some of the detrital-zircon peaks in the Gateway Gravels could also reflect minor contributions from the Uncompahgre River. The ca. 79 to 88 Ma peaks in the Gateway Gravel sample are not easily explained by comparisons with the modern rivers. Perhaps some of these grains could reflect a contribution by the Colorado River, which has a ca. 92 Ma peak. In addition, the ca. 547-566 Ma peak in the Gateway Gravels matches the ca. 564 Ma peak in the Colorado River. In summary, the detrital zircon age population for the Gateway Gravels clearly contains a Gunnison

River signature with probable contributions from the Uncompahgre River. Whether or not this deposit represents contributions from the ancestral Colorado River, however, is not clear.

Cactus Park Lake Beds

The lowest Cactus Park river gravels are buried by yellow to beige, thinly bedded and laminated, alternating clay and silt, which has a maximum preserved thickness of 67 m (**Figs. 10 and 11**). Based on the fine-grained texture and bedding structure, and the presence of underlying river gravel, these clay and silt deposits are interpreted as lacustrine sediments that accumulated following Gunnison River abandonment of Cactus Park, and by inference, Unaweep Canyon. At no location do river gravels overlie lake beds. Lake beds crop out for about 6 km to the southeast of the Cactus Park gravel pit (**Fig. 6**). The original extent of the lake is poorly constrained. The uppermost lake beds in Cactus Park are at an elevation of 1928 m while the lake beds in western Unaweep are present at an elevation of ~1830 m (Soreghan et al., 2007).

While is it plausible that the lake in western Unaweep Canyon reported on by Balco et al (2013) extended as far upstream as Cactus Park, there are several noteworthy differences between the lacustrine deposits. Cactus Park lake beds contain sparse pollen and Cretaceous microfossils (reworked foraminifera, coccolith fragments), and are geochemically and mineralogically similar to Cretaceous Mancos Shale (Aslan et al., 2008a; Hood et al., 2014). The similarity between the composition of lake beds and Mancos Shale indicates that the lake filled primarily with locally derived sediments. Currently there is no evidence to show that the ancestral Gunnison River supplied sediment to the lake in Cactus Park. In contrast, the lake sediments in Unaweep Canyon contain volcanic rock fragments in sand fractions, which indicates that the ancestral Gunnison River was still flowing into the canyon (Marra et al., 2010) while the lake sediments accumulated (ca. 1.4-1.3 Ma) (Balco et al., 2013). In summary, Cactus Park lake sediments are younger than those in western Unaweep Canyon and probably accumulated after the Gunnison River had already abandoned Unaweep Canyon. A more detailed discussion of the relationship between lakes in Unaweep Canyon and Cactus Park are discussed in Hood et al., (2014).

COSMOGENIC BURIAL DATING AND TIMING OF UNAWEEP CANYON ABANDONMENT

Cores and cuttings of Cactus Park lacustrine sediments and underlying Gunnison River gravels were recovered from a drillhole, which bottomed in Jurassic bedrock (**Figs. 6** and **11**). Fragments of Gunnison River gravels from a depth of 49.9 to 51.2 m included common volcanic and sandstone clasts. Two samples of drill cuttings consisting of fragments of sandstone clasts from the same 49.9 to 51.2 m interval were analyzed. The resulting burial-age estimates (sample CP3 = 0.92 +/- 031 Ma; sample CP3A = 0.62 +/- 0.39 Ma) average to ~0.80 +/- 0.24 Ma (**Table 1**). These are strictly minimum ages, as they ignore post-burial production by muons (negligible at 50 m depth) and assume rapid burial, which is supported by relatively low radionuclide concentrations.

Balco et al. (2013) dated similar sediments in the western part of Unaweep Canyon and obtained a considerably older age of 1.41 ± 0.19 Ma at the base of lake sediments from the deep Oklahoma drillhole (**Fig. 3**). It is worth noting that their cosmogenic nuclide concentrations are somewhat higher than ours, but we see no analytical discrepancies that might lead to such an age difference. We interpret our 0.80 +/- 0.24 Ma burial age as the minimum age for abandonment of Cactus Park and by inference, Unaweep Canyon. We view the ca. 1.4 Ma Unaweep abandonment age estimate of Balco et al. (2013) as a maximum.

In summary, we suggest that river flow through Unaweep Canyon was dammed ca. 1.4-1.3 Ma but continued to supply sediment to the lake in western Unaweep Canyon. Farther upstream in Cactus Park, river incision would have ended with the formation of the lake in western Unaweep Canyon. By ca. 0.8 Ma, lacustrine sedimentation began to bury the lowermost Gunnison River strath terraces in Cactus Park, but the Gunnison River was not supplying sediment to this younger lake system, as suggested by the absence of volcanic inputs to the lacustrine sediments in Cactus Park (Hood et al., 2014). Thus abandoment of Unaweep Canyon by the ancestral Gunnison River occurred between ca 1.4 and 0.8 Ma.

STREAM CAPTURE AND EFFECTS OF UNAWEEP CANYON ABANDONMENT

The capture of the ancestral Gunnison River created a remarkable series of events. Ancient river gravels clearly show that the ancestral Gunnison River flowed on resistant Precambrian bedrock within Unaweep Canyon at the time of capture. Concurrently, the ancestral Colorado River flowed through Mancos Shale badlands along the north flank of the Uncompahgre Plateau (Lohman, 1961; 1965, 1981; Sinnock, 1981) (**Fig. 5B**). It is likely that ancient Colorado River tributaries flowing on Mancos Shale badlands northeast of Cactus Park facilitated the eventual capture of the ancestral Gunnison River as envisioned by previous workers (Sinnock, 1981; Hood et al., 2014) (**Figs. 5B-C**). Although the exact location(s) of the capture of the ancestral Gunnison River is not precisely known, Star Mesa, located several kilometers upstream of Cactus Park, contains ancient Gunnison River gravels that are present at lower elevations (1857 m) than the lowest (1870 m) and therefore youngest Gunnison River gravels in Cactus Park (**Figs. 5C** and **6**). This observation indicates that the ancestral Gunnison River was captured south of Cactus Park, possibly in the vicinity of Star Mesa, and subsequently established a new course parallel to and northeast of Cactus Park (Aslan et al., 2008a; Hood et al., 2014) (**Fig. 12**). Following its capture, the ancestral Gunnison River probably joined the ancestral Colorado River near Grand Junction.

Long Profile Reconstruction and Post-Abandonment River Incision Estimates

Gunnison River Profile at ~1.4 Ma

Balco et al. (2013) used geophysical data of Oesleby (2005a), a drillhole completed by the University of Oklahoma in western Unaweep Canyon (Soreghan et al., 2007), and broadly correlative gravel outcrops at Cactus Park and Gateway (Kaplan, 2006), along with burial ages from the Oklahoma drillhole and Gateway gravels to construct a ca. 1.4 Ma Gunnison River profile (**Fig. 13**). The gradient of the ancestral Gunnison River as it flowed across Precambrian rocks in Unaweep Canyon was ~7 m/km (Oesleby, 2005b). While steep, this gradient is less than the gradient of the modern Gunnison River (~16 m/km) as it flows across Precambrian rocks of the Black Canyon of the Gunnison. Geologic mapping shows that the top of the Precambrian bedrock at the upper end of Unaweep Canyon is at an elevation of ~1850 m (Williams, 1964). Upstream of this point, the ancestral Gunnison River flowed across Jurassic mudstones and sandstones. Field relations among the lowest straths (elevation ~1870 m) of the ancestral Gunnison River show that its slope was ~1.1 m/km through Cactus Park. This slope is almost identical to the slope of the Gunnison River between Delta and Grand Junction, Colorado, which flows across similar Jurassic sedimentary rocks.

Gunnison River Profile at ~0.64 Ma

Gunnison River deposits associated with the ca. 0.64 Ma Lava Creek B tephra are used to reconstruct the profile of the river at this time (**Fig. 13**). At Kelso Gulch near Delta, Colorado, Lava Creek B tephra is interbedded with fine-grained sediments that overlie mainstem river gravels, which correlate to the 100-m Gunnison River terrace (Darling et al., 2009). Lava Creek B tephra localities also constrain the elevation of the ca. 0.64 Ma Gunnison River further upstream near Red Canyon and Blue Mesa Reservoir (**Fig. 13**), and the context of these localities is described more fully elsewhere (Aslan et al., 2008a; Donahue et al., 2013). The ca. 0.64 Ma profile is further constrained by U-series dating of 100-m Colorado River terrace gravels near Grand Junction (**Fig. 12,** black square). Although this terrace is of Colorado and not Gunnison River origin, field relationships show that the 100-m terrace of both rivers converge (Scott et al., 2002) and are therefore of similar age. The 100-m Colorado River terrace (elev. 1500 m) near Grand Junction has a U/Th age of 581 +129/-68 ka based on a sample of sparry calcite cement at the base of a 4- to 5-m-thick deposit of imbricated gravel (**Table 2**). The U-series data represents a minimum age for the gravel. Because the height of the 100-m Colorado River terrace is the same as the height of the ca. 0.64 Ma Gunnison River terrace at Kelso Gulch, we use the 100-m Colorado River terrace at Grand Junction, and its convergence with the 100-m Gunnison River terrace, to constrain the ca. 0.64 Ma Gunnison River profile.

River Incision Estimates

Comparisons between the ca. 1.4 Ma and modern profiles of the Gunnison River can be used to calculate the amount and rate of river incision following stream capture (**Fig. 13**). Using the elevation of Cactus Park (1870 m) and the elevation of the modern Gunnison River at

Whitewater (1410 m), as much as ~460 m of river incision has occurred since abandonment over a time interval ranging from a maximum of ca. 1.4 My to a minimum of 0.80 My. Using this range of age estimates, the long-term incision rate since abandonment at Cactus Park is ~330 to 600 m/Ma. Assuming that the combined Colorado-Gunnison River has incised ~1500 m over the past ca. 11 Ma based on the data for Grand Mesa, then ~1040 m (1500 m – 460 m) of Gunnison River incision occurred between ~11 and 1 Ma, which represents an incision rate of ~100 m/Ma.

Comparing the ca. 1.4 and 0.64 Ma profiles suggests that ~360 m of river incision occurred in the vicinity of Cactus Park over 0.76 to 0.16 My, depending on which age assignment (1.4 – 0.8 Ma) is used for canyon abandonment. Using the maximum and minimum time interval (0.76 to 0.16 My) for post-abandonment incision, Gunnison River incision rates ranged from ~470-2250 m/Ma.

Relief between the ancestral Colorado and Gunnison Rivers at the time of stream capture

At the time of the Gunnison River's capture by the ancestral Colorado there could have been several hundred meters of relief, perhaps as much as ~300 m, separating the two rivers near Grand Junction. This is possible because prior to the capture event, the confluence of the two rivers was probably located ~150 km downstream of Grand Junction near the present-day confluence between the Colorado and Dolores Rivers (Sinnock, 1981). Two observations support the possibility that there were several hundred meters of relief between the two rivers near Grand Junction. First, ancient Colorado River gravels located upstream of Unaweep Canyon near Rifle, Colorado are older than the Gunnison River gravels at Cactus Park, but occupy a lower elevation relative to the modern-day river. A cosmogenic-burial age for

Colorado River gravels beneath Grass Mesa, located ~100 km upstream of Unaweep Canyon near Rifle, Colorado, produced a minimum burial age of ~1.8 Ma (Berlin et al., 2008). These gravels are located ~170 m above the modern Colorado River. By comparison, ca. 1.4 Ma Gunnison River gravels at Cactus Park are 460 m above the Gunnison and Colorado Rivers. These observations support the idea that at the time of stream capture ca. 1.4-0.80 Ma, the Colorado River was at an elevation <200 m higher than the modern river near Rifle, and by extension, Grand Junction. At roughly the same time, the ancestral Gunnison River was ~460 m above the modern river.

Second, age estimates and strath heights of the oldest Colorado and Gunnison River terraces near Grand Junction that post-date abandonment of Unaweep Canyon support the idea of rapid incision by the ancestral Gunnison River in response to stream capture. The locations of these terraces are shown as black triangles on Figure 12. The oldest post-abandonment Gunnison River terraces are located at an elevation of 1560 m, which is 160 m higher than the modern river and ~310 m lower than Cactus Park river gravels. These terraces are undated but they broadly correlate with the 160-m Colorado River terrace (elev. 1575 m), which has been dated using U-series methods.

U-series samples from the highest and therefore oldest Colorado River terraces (140 to 160-m Colorado River terraces; Scott et al., 2002) near Grand Junction are outside the upper limit of U/Th dating range (i.e. > 600 ka), and yields a ^{234}U-model age (Edwards, 1987) between 0.72 and 1.21 Ma, based on assumed initial δ^{234}U values of 1000 to 4000 ‰ (**Table 2, DR Table 2**). These assumed initial values are based on the range of δ^{234}Ui values from successful U/Th ages, which range from 1031 to 3105 ‰ based on results presented here (**DR Table 2)** and by

Polyak et al. (2013). 4 other samples outside of U/Th dating range showed evidence of open-system behavior as the analyses plotted well below the asymptote of a ($^{234}U/^{238}U$) vs. ($^{230}U/^{238}U$) evolution plot; those data were disregarded. The elevation (1575 m) of the oldest terrace is shown on Figure 13. Extrapolation of incision rates based on the height and age of the 100-m terrace (Hood et al., 2002), and the ^{234}U-model ages for the 146-m terrace suggest that these oldest, post-abandonment river gravels are younger than 1.2 Ma. Although the modeled ^{234}U ages are imprecise, they are generally consistent with the age assignment of ca. 1.4-0.8 for Unaweep Canyon abandonment.

In summary, based on the heights (elev. 1560-1575 m) and age estimates (<1.2 Ma) for the oldest post-abandonment Gunnison and Colorado River terraces, and the elevation (~1870 m) of pre-abandonment Gunnison River gravel in Cactus Park, it is reasonable to infer that there was ~300 m of relief separating the ancestral Gunnison and Colorado Rivers in the vicinity of Grand Junction at the time of stream capture.

Stream Capture and Abandonment of Bostwick-Shinn Park Paleovalley

Spatial relationships and additional age dating of fluvial gravels suggests that the capture of the ancestral Gunnison River and abandonment of Unaweep Canyon led to at least one additional stream capture event upstream. Evidence supporting this interpretation comes from Bostwick-Shinn Park (**Figs. 2 and 12**). Prior to ca. 640 ka, a tributary of the ancestral Gunnison River flowed north from the San Juan Mountains through Bostwick-Shinn Park, and joined the Gunnison River via Red Canyon along the south flank of the Black Canyon (**Fig. 14**).

Similar to Cactus Park, Bostwick-Shinn Park records an episode of stream capture and valley abandonment, followed by valley filling and rapid, but localized river incision. The base of the Bostwick-Shinn Park valley fill is comprised of ~6 m of river gravel dominated by volcanic lithologies derived from the San Juan Mountains (Donahue et al., 2013) (**Fig. 15A**). A cosmogenic-burial-isochron age on quartzite clasts from the basal gravel produced an age of 0.87+/- 0.22 Ma (Darling et al., 2012). Bostwick-Shinn Park river gravels are overlain by ~50 m of fine-grained alluvial and colluvial valley-fill deposits that include the 0.64 Ma Lava Creek B tephra in the lowermost 1-2 m of the fill (Hudson et al., 2007; Aslan et al., 2008a) (**Fig. 15B)**. The valley fill consists primarily of silt and clay reworked from nearby Mancos Shale, which forms the floor and uplands of the Bostwick-Shinn Park paleovalley. Far-traveled gravel clasts are rare in the fill. The lack of paleosol features at the base of the fill and the similarity in the age estimates for the basal river gravels and overlying Lava Creek B tephra, suggests that filling commenced soon after the ancestral Bostwick-Shinn Park River ceased to flow through this area. We interpret this transition from fluvial gravel deposition to fine-grained aggradation to have been caused by stream capture and valley abandonment, which promoted side-stream aggradation rather than mainstem river erosion.

Correlative valley-fill deposits located south of Bostwick-Shinn Park also contain Lava Creek B tephra overlying basal, volcanic-rich river gravel. The distribution of the terrace remnants demonstrates that the ancestral Bostwick-Shinn Park River flowed north towards the Black Canyon of the Gunnison (**Fig. 16**). The ancestral Uncompahgre River flowed northwest along the Dakota Sandstone dipslope of the Uncompahgre Plateau prior to and following the abandonment of Unaweep Canyon (Sinnock, 1978). In this scenario, the ancestral Uncompahgre and Bostwick-Shinn Park Rivers flowed northwest and north, respectively, in separate valleys cut into Mancos Shale, and were probably separated by a Mancos Shale divide. Based on the proximity between the modern Uncompahgre River and the terrace remnants of the ancestral Bostwick-Shinn Park River, it is likely that the ancestral Uncompahgre River captured the Bostwick-Shinn Park River. The cosmogenic age date on river gravels at Bostwick Park and the presence of the overlying Lava Creek B tephra constrains the timing of this stream capture to ca. 0.87-0.64 Ma.

The abandonment of Unaweep Canyon and the Bostwick-Shinn Park paleovalley share several notable similarities. In both examples, the pirated river's gradient was locally influenced by the presence of resistant Precambrian bedrock (Hudson et al., 2007; Donahue et al., 2013). We suggest that the thief river (e.g., the ancestral Uncompahgre River) lacked Precambrian knickpoints and thus incised more rapidly through Mancos Shale.

By comparing the elevations of the ancestral Bostwick-Shinn Park river gravels and the modern Uncompahgre River (**Fig. 17**), the amount of post-0.64 Ma incision can be calculated. At the Bostwick Park gravel pit and Ewing Hill, the ancestral Bostwick-Shinn Park river gravels are ~360 m and ~200 m above the modern river. This relief translates to an incision rate of 564 m/Ma and 308 m/Ma, respectively (**Fig. 17**).

In summary, the timing of Unaweep Canyon abandonment ca. 1.4-0.8 Ma, and Bostwick–Shinn Park abandonment ca. 0.87-0.64 Ma, coupled with the spatial patterns of river incision reported here, suggest that the initial capture of the ancestral Gunnison River triggered a second significant stream capture event upstream, which resulted in a similar episode of valley abandonment and subsequent filling. The thick Pleistocene fills in Unaweep Canyon (Soreghan et al., 2007) and Bostwick-Shinn Park (Hudson et al., 2007; Aslan et al., 2008a) are anomalous in the region and record significant fluvial events, namely stream capture. Furthermore, the thick fill sequences in Unaweep Canyon and the Bostwick paleovalley demonstrate that river canyons in areas of rugged topography and, in the absence of a major river, do not remain unfilled for long following stream capture. Rapid filling is attributable to a combination of tributary debris-fan and colluvial deposition, and the absence of significant mainstem river sediment transport.

COLORADO RIVER INCISION RELATED TO UNAWEEP CANYON ABANDONMENT

Based on the Gunnison River incision history, it is reasonable to assume that the capture of the ancestral Colorado River during the initial stage of canyon abandonment might be similarly associated with several hundred meters of rapid river incision. The sparse data that exist show mixed support for this assumed pulse of rapid incision along the course of the ancestral Colorado River upstream of Unaweep Canyon. ^{234}U-model ages for speleothems in caves at the west end of Glenwood Canyon, located approximately 150 km upstream from Unaweep Canyon, suggest that there has been ~375 m of river incision over the past 1.36-1.72 Ma (Polyak et al., 2013). In contrast, cosmogenic dating of Colorado River gravel at Rifle, ~100 km upstream from Unaweep Canyon, suggests that there has been only ~170 m of river incision over the past ~1.8 Ma (Berlin et al., 2008). By comparison, the Cactus Park data shows that the Gunnison River incised ~480 m over the past ~1.4-0.8 Ma.

The observations at Rifle could suggest that abandonment of Unaweep Canyon by the ancestral Colorado River occurred prior to ~1.8 Ma, which would explain the absence of evidence for more than ~170 m of river incision near Rifle within the past ~1.8 My. Alternatively, Hood (2011) argues that the ancestral Colorado River was present in Unaweep Canyon until the time represented by the Gateway Gravels, the youngest of which have been dated to ~1.4 Ma (Balco et al., 2013). If this latter interpretation is correct, then the observations at Rifle would suggest that the abandonment of Unaweep Canyon by the ancestral Colorado River occurred within the past 1.4 Ma, but did not produce hundreds of meters of bedrock incision as did Gunnison River abandonment. To resolve this question, additional constraints on the timing and magnitude of Colorado River incision upstream of Unaweep Canyon will be required.

CONTROLS ON RATES AND MAGNITUDES OF RIVER INCISION AND KNICKPOINT PROPAGATION

Rates and Magnitudes of River Incision

How anomalous are the river incision rates associated with the abandonment of Unaweep Canyon? A compilation of regional incision rates shows that incision rates are generally <180 m/Ma, and are as low as ~50 m/Ma when measured over the past ~1 My (Dethier, 2001; Aslan et al., 2010; Darling et al., 2012) (**Fig. 18**). In contrast, incision rates measured over approximately the same time interval at Cactus Park and in the vicinity of Bostwick-Shinn Park are ~300-600 m/Ma (Donahue et al., 2013). Moreover, incision rates immediately following abandonment of Unaweep Canyon were ~470-2250 m/Ma. Clearly, the abandonment of Unaweep Canyon by the ancestral Gunnison River produced anomalously rapid river incision.

These observations, along with bedrock geology and profile geometries of the ancestral Gunnison and Bostwick-Shinn Park River systems point to a critical factor necessary to explain the magnitudes (up to 360 m) and extraordinary rates (~470-2250 m/Ma) recorded by the Gunnison River abandonment of Unaweep Canyon. In the case of both Unaweep Canyon and Bostwick-Shinn Park abandonment, large-magnitude, rapid river incision involved the development of significant relief between the thief stream and the pirated river, prior to stream capture. As noted previously, there was probably as much as 250-300 m of relief separating adjacent channel segments of the ancestral Gunnison and Colorado Rivers in the vicinity of Grand Junction at the time of capture ca. 1.4-0.8 Ma. In the example of ancestral Bostwick-Shinn Park River and its thief stream (i.e., the ancestral Uncompahgre River), there was on the order of ~250 meters relief between the rivers at the latitude of the Bostwick Park gravel pit (**Fig. 17**). This interpretation is based on the elevation of the ca. 0.64 Ma profile for ancestral Bostwick-Shinn Park River at the gravel pit (**Fig. 17**, elevation ~2250; appx. 350 m above the Uncompahgre River), and the correlative profile of the ca. 0.64 Ma Gunnison River at Kelso Gulch located just downstream of Bostwick Park, which is only 100 m above the modern river (Darling et al., 2009).

The reason significant relief developed between adjacent river segments in these two examples is the localized, but strategic position of resistant Precambrian bedrock within the drainage basin. The downstream portions of the flattest channel gradients for both the ancestral Gunnison River in Unaweep Canyon (**Fig. 13**) and ancestral Bostwick-Shinn Park River (**Fig. 17**) correspond with the transition from sedimentary to Precambrian bedrock. This observation suggests that Precambrian bedrock locally inhibited river incision upstream of these resistant rocks, which allowed contemporaneous thief streams eroding through Mancos Shale to steepen their gradients with respect to the pirated streams. Ultimately these conditions led to stream piracy.

Rates of Knickpoint Propagation

The rate at which the erosional effects of Unaweep Canyon's abandonment were translated upstream is constrained by three key areas. Kelso Gulch is located 24 km upstream from Unaweep Canyon along the Gunnison River (**Fig. 12**). The age of the 100-m Gunnison River terrace at this site is ~0.64 Ma based on the presence of the Lava Creek B tephra (Darling et al., 2009), and the post-0.64 Ma incision rate at this site is ~150 m/Ma. This rate is roughly 2-4 times slower than the incision rate of the Gunnison River at Cactus Park measured over the past 1.4-0.8 Ma. Based on these observations, the wave of incision triggered by the capture of the Gunnison River had passed south of Kelso Gulch by ~0.64 Ma.

A second important area is Ridgway, Colorado, which is located ~70 km upstream from Unaweep Canyon along the Uncompahgre River (**Fig. 16**). This location represents the approximate point of stream capture of ancestral Bostwick Creek by the Uncompahgre River ca. 0.87-0.64 Ma. The timing of this stream piracy event confirms that the wave of erosion triggered by Unaweep Canyon abandonment had passed south of Ridgway by ~0.64 Ma.

Lastly, the lower reaches in the Black Canyon of the Gunnison knickzone are floored by both sedimentary and resistant Precambrian bedrock (Donahue et al., 2013). This observation suggests that the transient knickpoint associated with Unaweep Canyon abandonment eroded through sedimentary rocks and a portion of the resistant Precambrian rock, approximately 80 km upstream from Unaweep Canyon.

Rates of knickpoint migration can be estimated using the distances described above and the minimum (0.8 Ma) and maximum (1.4 Ma) ages for Unaweep Canyon's abandonment. Based on the distance upstream (70 km) from Ridgway and the preceding discussion, knickpoint migration rates ranged between ~90-440 km/Ma between the time of Unaweep Canyon abandonment and ca. 0.64 Ma.

What factors influenced these estimated rates of knickpoint migration? Clearly, the magnitude of base level fall (~300 m) associated with the capture of the ancestral Gunnison River is important. The other key factor is the areal extent of Mancos Shale in the region. While it is true that rivers such as the Colorado and Gunnison can incise through resistant bedrock as seen in Black Canyon of the Gunnison and Glenwood Canyon, erosion of sedimentary rocks such as Mancos Shale leads to large volumes of sediment removal and formation of broad valleys. For example, **Figure 12** shows the narrow incision made by rivers through resistant Precambrian rocks of Unaweep Canyon and the Black Canyon of the Gunnison. In contrast, the Grand Valley near Grand Junction and the Uncompahgre River valley were once filled by thick sequences of Mancos Shale. In the case of the abandonment of Unaweep Canyon, we estimate that the affected area is roughly 65 km long and as much as 15 to 20 km wide. Excavation of ~400 m of material means 400 to 500 km^3 of shale was removed in no more than ~1.4 Ma, and perhaps as little as 0.8 Ma.

CONCLUSIONS

1. Unaweep Canyon is the most spectacular example of stream capture in the upper Colorado River system. The canyon was probably carved by both the ancestral Colorado and Gunnison Rivers, although the early stages of the canyon's history are poorly known due to the presence of thick Pleistocene valley fill that accumulated following canyon abandonment.

2. Capture of the ancestral Gunnison River by the Colorado River ca. 1.4-0.8 Ma represents the final stage of Unaweep Canyon abandonment. Lake beds that overlie a flight of buried Gunnison River strath terraces in Cactus Park record this final stage.

3. Abandonment of Unaweep Canyon triggered a series of major fluvial adjustments and rapid and widespread erosion in the Gunnison River system. Specific adjustments include ~460 m of post-abandonment incision by the ancestral Gunnison River with the majority of the incision occurring prior to ca. 0.64 Ma. Rates of post-abandonment incision range from 470 to 2250 m/Ma, which are significantly faster than the long-term incision rate (140 m/Ma) for the region. By comparison, a total of ~1000 m of river incision occurred ~10-1 Ma in the Gunnison River system (~100 m/Ma). Abandonment of Unaweep Canyon is directly responsible for this variable rate of long-term river incision.

4. Fluvial adjustments to a new base level included upvalley propagation of a transient knickpoint at rates of 90 to 440 km/Ma. The wave of incision propagated readily through Mancos Shale, but it also produced significant erosion of resistant Precambrian rocks in the lower reaches of the Black Canyon of the Gunnison.

5. Transient knickpoint migration triggered the subsequent capture of the ancestral Bostwick-Shinn Park River by the ancestral Uncompahgre River ca. 0.87-0.64 Ma. This separate event was also associated with anomalously rapid rates of post-abandonment incision (up to 564 m/Ma).

6. In both instances of stream capture, the location of resistant Precambrian bedrock within the watershed of the pirated rivers, coupled with the widespread presence of erodible Mancos

Shale in the watershed of the thief streams, set the stage for the development of significant relief (200-300 m) between adjacent stream segments, which ultimately led to stream capture.

7. Spatial variability in the magnitude of incision rates demonstrated in this paper clearly illustrates the importance of the distinction between local short-term river incision events such as described here or in epigenetic canyons (cf, Ouimet et al., 2009) from spatial patterns associated with regional long-term incision driven by climatic or tectonic events.

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FIGURE CAPTIONS

Figure 1. Map showing the location of the study area in Colorado (inset map) and the upper Colorado River basin region (30-m DEM base) including locations of the Colorado and Green Rivers and Unaweep Canyon. Locations of Figure 2 and 5 are also shown.

Figure 2. Geologic map of study area showing locations of the modern Colorado, Gunnison, and Uncompahgre Rivers, and important areas including Unaweep Canyon, Cactus Park, Grand Mesa,and Black Canyon of the Gunnison. Location of Figure 3 is also shown. Modified from Williams (1964).

Figure 3. Digital elevation model (30-m DEM base) of the Uncompahgre Plateau extending from Whitewater, Colorado (northeast) to Gateway, Colorado (southwest). Locations of Unaweep Canyon, Cactus Park, and important sample sites are shown. OK core = Univ. of Oklahoma drillhole (Marra et al., 2008). 22 Ma AFT cooling age at Unaweep Divide is from a sample of Taylor Ranch granite sampled at an elevation of 2130 m. 38 Ma AFT cooling age near Gateway is from a sample of Vernal Mesa granite sampled at an elevation of 1550 m. Location of Figure 6 is also shown.

Figure 4. A. Geological cross section showing Laramide structural relief and faulting. The line of section parallels Unaweep Canyon between Whitewater and Gateway, Colorado. Modified from Aslan et al. (2008a). B. Thermal history plot for the AFT samples at Unaweep Divide (07UNI01, blue) and near Gateway (07UNI02, red). Geological constraints for the models depicted by the solid lines are: (1) the basement was near the surface at ca. 100 Ma at the time of Dakota Sandstone deposition; (2) the area attained maximum burial at ca. 66 Ma at the end of Mesaverde deposition; (3) the basement is now at 11°C. Only constraint 3 was used for the models depicted by the dashed lines. See text for further discussion.

Figure 5. Maps summarizing the two-stage abandonment of Unaweep Canyon. A. Ancestral Colorado and Gunnison Rivers flow through Unaweep Canyon. B. Ancestral Colorado River is captured by tributary eroding headward through Mancos Shale badlands along northern edge of the Uncompahgre Plateau. C. Ancestral Gunnison River captured by Colorado River tributary eroding heardward through Mancos Shale badlands southeast of Grand Junction. Dotted lines represent abandoned courses. Black arrows indicate flow directions. GJ – Grand Junction, Colorado.

Figure 6. Aerial photograph showing the distribution of ancient river gravel and lake bed localities in Cactus Park, the locations of the Cactus Park gravel pit and drillhole, and the inferred course of the ancestral Gunnison River prior to Unaweep Canyon abandonment.

Figure 7. Photograph of representative Cactus Park river gravels including quartzite (Q), volcanic (V), conglomeratic (C), and granitic(G) clasts. Lens cap (5 cm diameter) is for scale.

Figure 8. Histogram comparing compositions of river gravel from the modern Colorado, Gunnison, and Uncompahgre Rivers with Cactus Park river gravels. The percentages of felsic and intermediate clasts in the Cactus Park river gravels are generally similar to those observed in the modern Gunnison River. N is the number of clasts analyzed.

Figure 9. Stacked normalized probability-density plot of U-Pb detrital zircon spectra for samples from the modern Gunnison, Uncompahgre, and Colorado Rivers, and ancient fluvial sands from the Cactus Park gravel pit and a recent backhoe exposure at Gateway, Colorado (see Figure 3). Data is shown only for grains <600 Ma to highlight major differences among the samples. Numbers represent the age of peaks and N = number of grains analyzed. Note that the modern

rivers were sampled upstream of their confluence with one another. See text for further discussion. All the U-Pb zircon ages for each of the samples are contained in Data Repository Table 1.

Figure 10. Photograph showing rhythmically interbedded silt and clay in Cactus Park. The beds dip gently to the northeast, and the view is to the west. The texture and bedding characteristics strongly suggest that these deposits are lacustrine in origin. Outcrop exposure is 2.5 m tall, and the field notebook is for scale.

Figure 11. Generalized stratigraphic cross section of Cactus Park showing the late Quaternary paleovalley. The valley fill is inset into Jurassic bedrock and consists of gravels of probable Gunnison River origin, overlying lake beds, and surficial deposits. The Cactus Park drillhole (see Figure 6 for location) penetrated a thick sequence of lake beds, overlying river gravels, and bottomed in bedrock. Vertical exaggeration is 200x.

Figure 12. Diagram comparing locations of modern river courses (blue) with ancient river courses (red, black) including abandoned segments in Unaweep Canyon/Cactus Park and Bostwick Park. The oldest Gunnison and Colorado River terraces (~160- to 170-m above the modern rivers) are also shown (black triangles). The 100-m Colorado and Gunnison River terraces converge just south of Grand Junction (black square). BM=Blue Mesa, BP=Bostwick Park, CP=Cactus Park, EH=Ewing Hill, G=Gateway, KG=Kelso Gulch, and RC=Red Canyon. See text for detailed discussion.

Figure 13. Long profiles of the modern Colorado (light blue) and Gunnison (navy blue) Rivers, and reconstructed profiles of the ca. 0.64 Ma (black) and 1.4 Ma (red) Gunnison/Uncompahgre

River. The position of the oldest (160 m) Colorado and Gunnison River terraces (black triangles) and the 100-m Colorado River terrace (black square; ca. 0.6 Ma U-series age) is also shown. Locations of the reconstructed profiles are provided by place name abbreviations in Figure 12. Data for the 0.64 Ma profile come from Aslan et al. (2008a), Darling et al., (2009), and Sandoval et al. (2013). Data for the 1.4 Ma profile come from Oesleby (1983; 2005), Aslan et al. (2008a), Marra et al. (2008), and Balco et al. (2013).

Figure 14. Photograph showing remnants of the Bostwick-Shinn Park paleovalley and the inferred course (yellow dashed line) of this ancient Gunnison River tributary. View is towards the Black Canyon of the Gunnison (north). The modern Uncompahgre River is located to the left (west) of the field of view, and is 300-400 m lower in elevation than the top of the Bostwick Park paleovalley fill. Photograph by Grant Meyer.

Figure 15. Photographs of A. Bostwick Park gravel pit showing ~6 m of ancient Bostwick Creek river gravels overlain by Lava Creek B tephra and beige, fine-grained valley-fill deposits. B. close-up view of the ca. 640 ka Lava Creek B tephra (50 cm thick) first reported on by Dickinson (1965) in this region.

Figure 16. Map showing course of ca. 0.64 Ma Bostwick Creek and modern Uncompahgre River. White dots are locations of selected elevations used in Figure 17 to estimate post-0.64 Ma rates of river incision following piracy of Bostwick Creek by the ancestral Uncompahgre River.

Figure 17. Long profiles of the Uncompahgre River and ca. 0.64 Bostwick Creek between the latitudes of Ridgway Reservoir (south) and Delta, Colorado (north). Locations of the profiles are shown in Figure 16. Note that both rivers flow/flowed across erodible Mancos Shale. The

dramatic difference in gradient between these two Gunnison River tributaries cannot be attributed to differences in bedrock. Instead, the gradient differences are consistent with base-level fall downstream, probably related to the abandonment of Unaweep Canyon. See text for further discussion.

Figure 18. Map showing regional river incision rates in western Colorado, eastern Utah, and southwestern, Wyoming measured over past ca. 0.6 to 3.0 Ma. Numeric values in the figure refer to incision rates measured in m/Ma. The rates are based primarily on the presence of Lava Creek B tephra, similar to Dethier (2001). Additional rates are based on $^{40}Ar/^{39}Ar$ dating of lava flows and cosmogenic-burial dating. Sites are characterized by slow (<90 m/Ma; yellow dots), intermediate (90-170 m/Ma; blue dots), and fast (>300 m/Ma; red dots) incision rates. Data are from Larsen et al. (1975), Izett and Wilcox (1985), Willis (1999), Lange et al. (2000), Kunk et al., (2002), Counts (2005), Hudson et al. (2006), Kelley et al. (2007), Aslan et al. (2008b; 2010), Berlin et al. (2008), Darling et al. (2009; 2012), and Balco et al. (2013).

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Figure 1

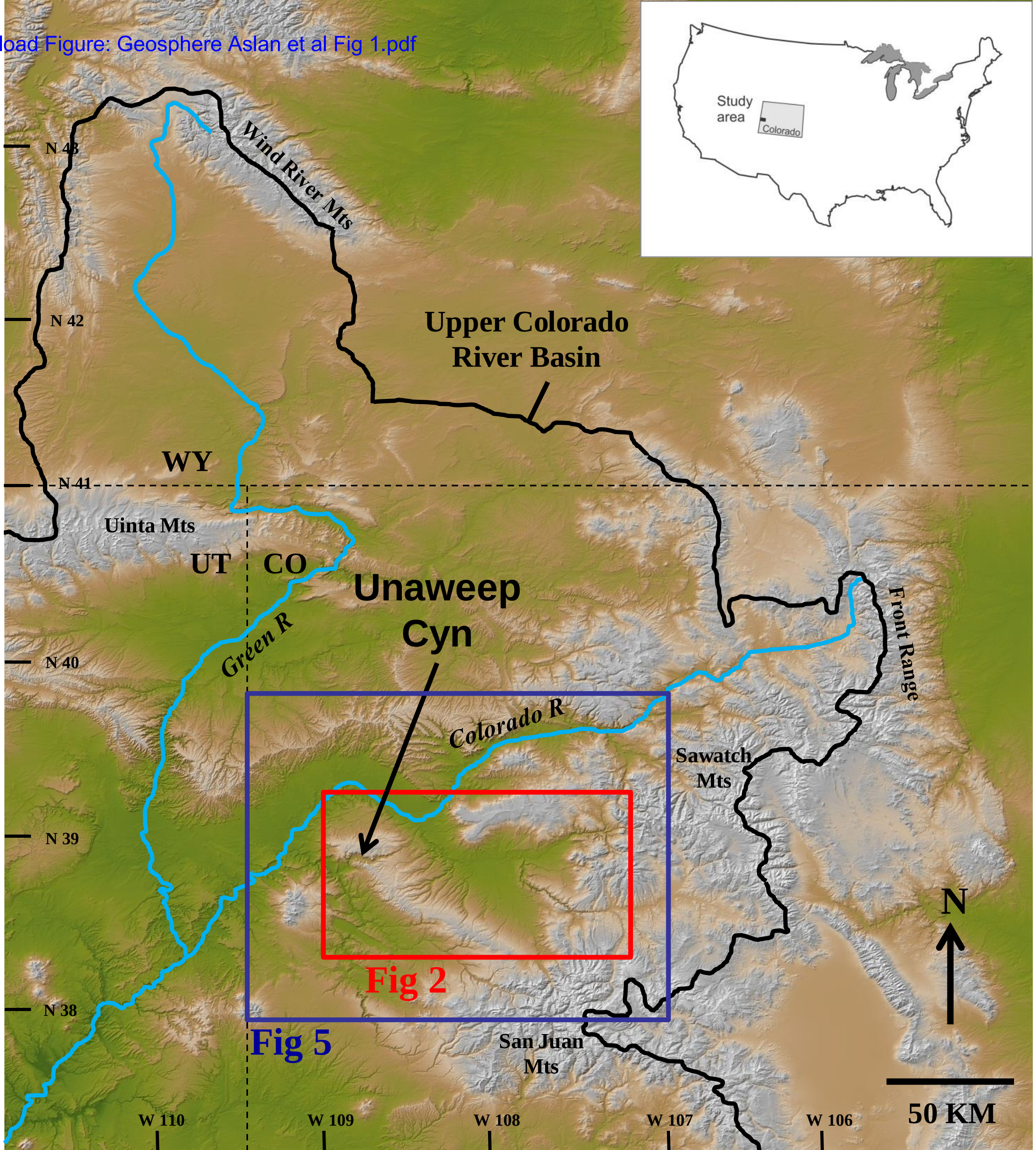
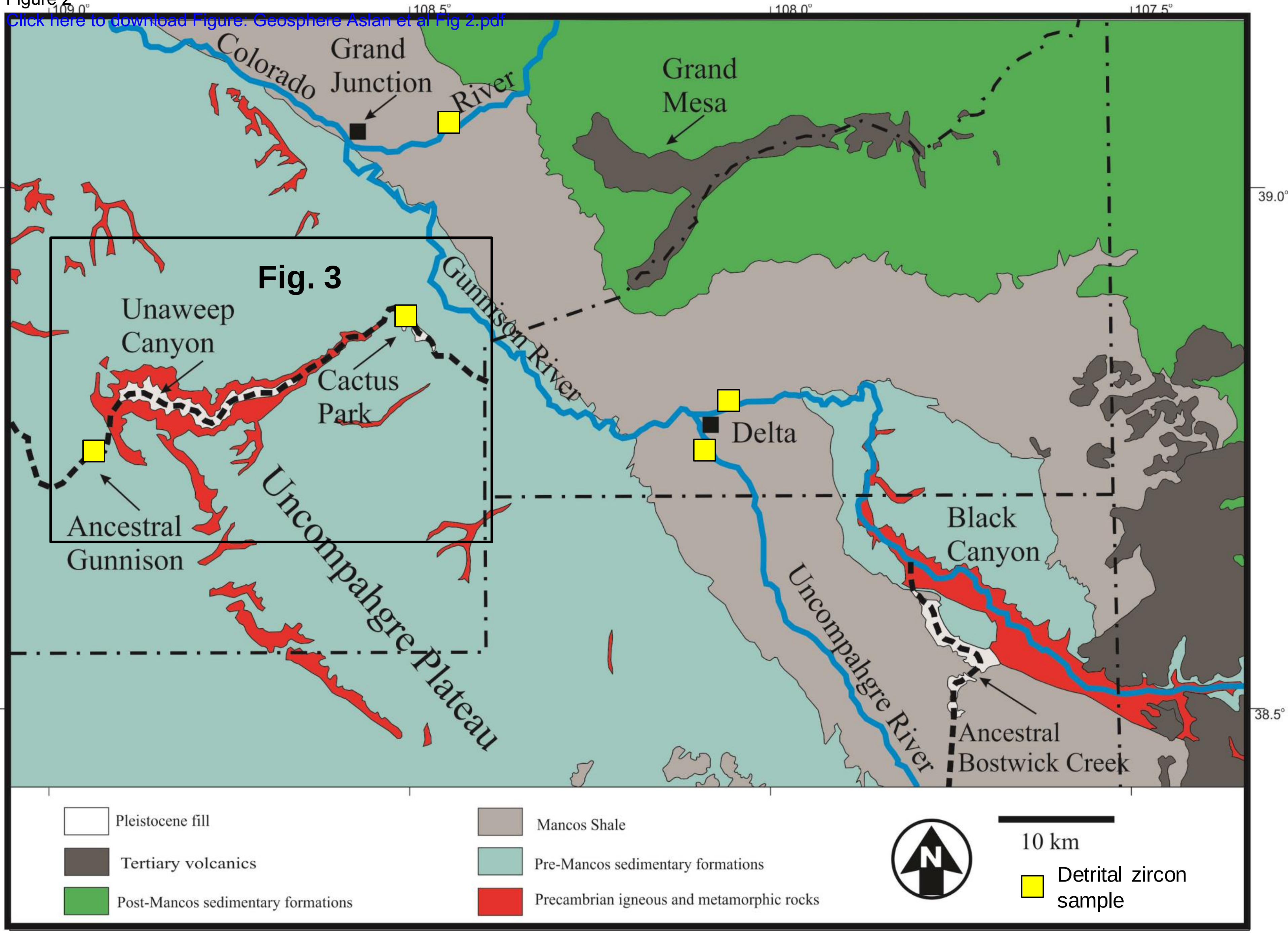

Study area
Colorado
Wind River Mts
Upper Colorado River Basin
N 43
N 42
N 41
N 40
N 39
N 38
WY
Uinta Mts
UT
CO
Unaweep Cyn
Green R
Colorado R
Front Range
Sawatch Mts
Fig 2
Fig 5
San Juan Mts
N
50 KM
W 110
W 109
W 108
W 107
W 106

Figure 2


109.0°
108.5°
108.0°
107.5°
39.0°
38.5°
Colorado River
Grand Junction
Grand Mesa
Gunnison River
Fig. 3
Unaweep Canyon
Cactus Park
Ancestral Gunnison
Uncompahgre Plateau
Delta
Uncompahgre River
Black Canyon
Ancestral Bostwick Creek
Pleistocene fill
Tertiary volcanics
Post-Mancos sedimentary formations
Mancos Shale
Pre-Mancos sedimentary formations
Precambrian igneous and metamorphic rocks
N
10 km
Detrital zircon sample

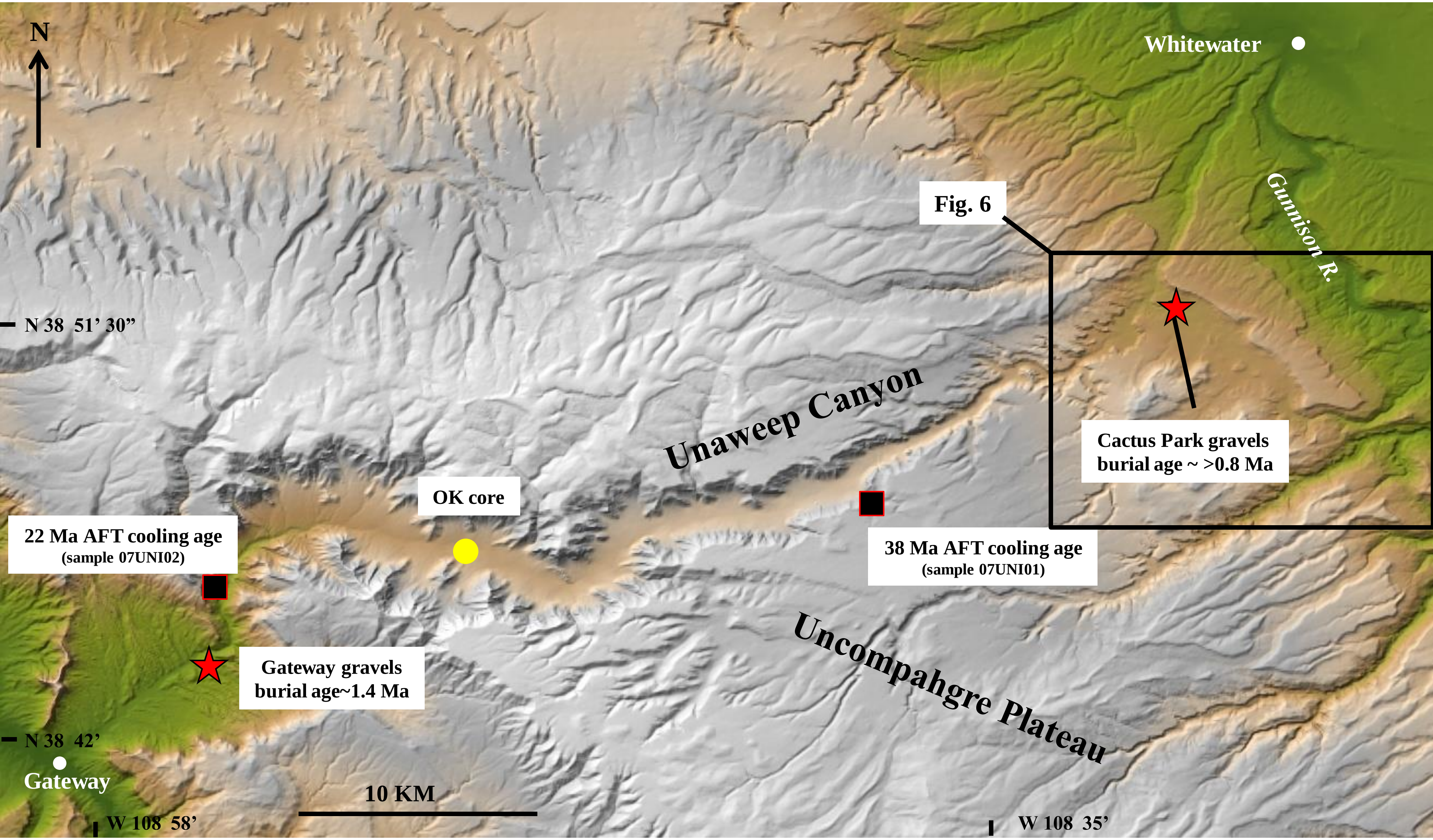
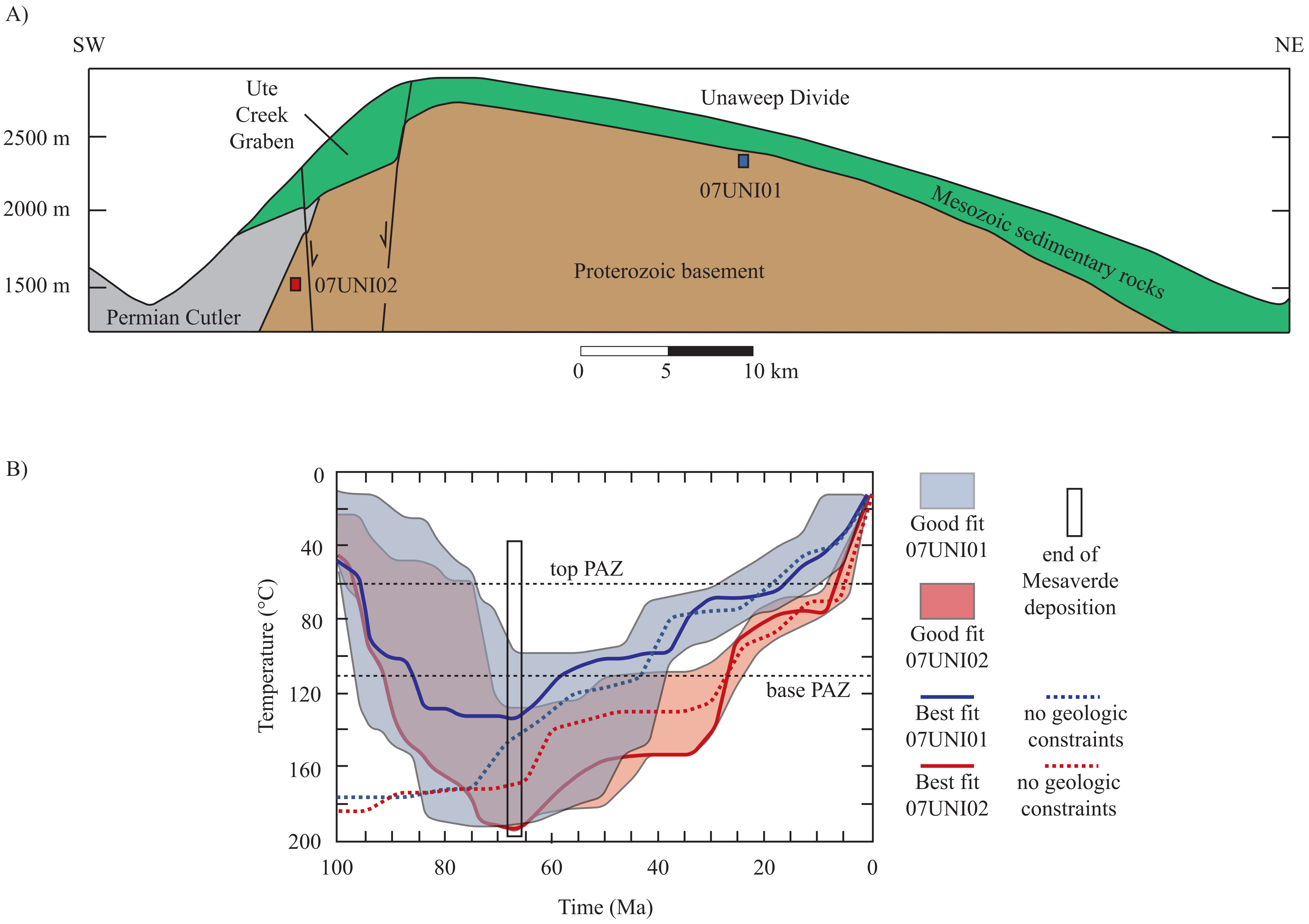

N
Whitewater
Fig. 6
Gunnison R.
N 38 51’ 30”
Unaweep Canyon
Cactus Park gravels
burial age ~ >0.8 Ma
OK core
22 Ma AFT cooling age
(sample 07UNI02)
38 Ma AFT cooling age
(sample 07UNI01)
Uncompahgre Plateau
Gateway gravels
burial age~1.4 Ma
N 38 42’
Gateway
10 KM
W 108 58’
W 108 35’

Figure 4


A)
SW
NE
Ute
Creek
Graben
Unaweep Divide
2500 m
2000 m
1500 m
07UNI01
Mesozoic sedimentary rocks
07UNI02
Proterozoic basement
Permian Cutler
0
5
10 km
B)
0
40
80
120
160
200
Temperature (°C)
top PAZ
base PAZ
100
80
60
40
20
0
Time (Ma)
Good fit 07UNI01
Good fit 07UNI02
end of Mesaverde deposition
Best fit 07UNI01
no geologic constraints
Best fit 07UNI02
no geologic constraints

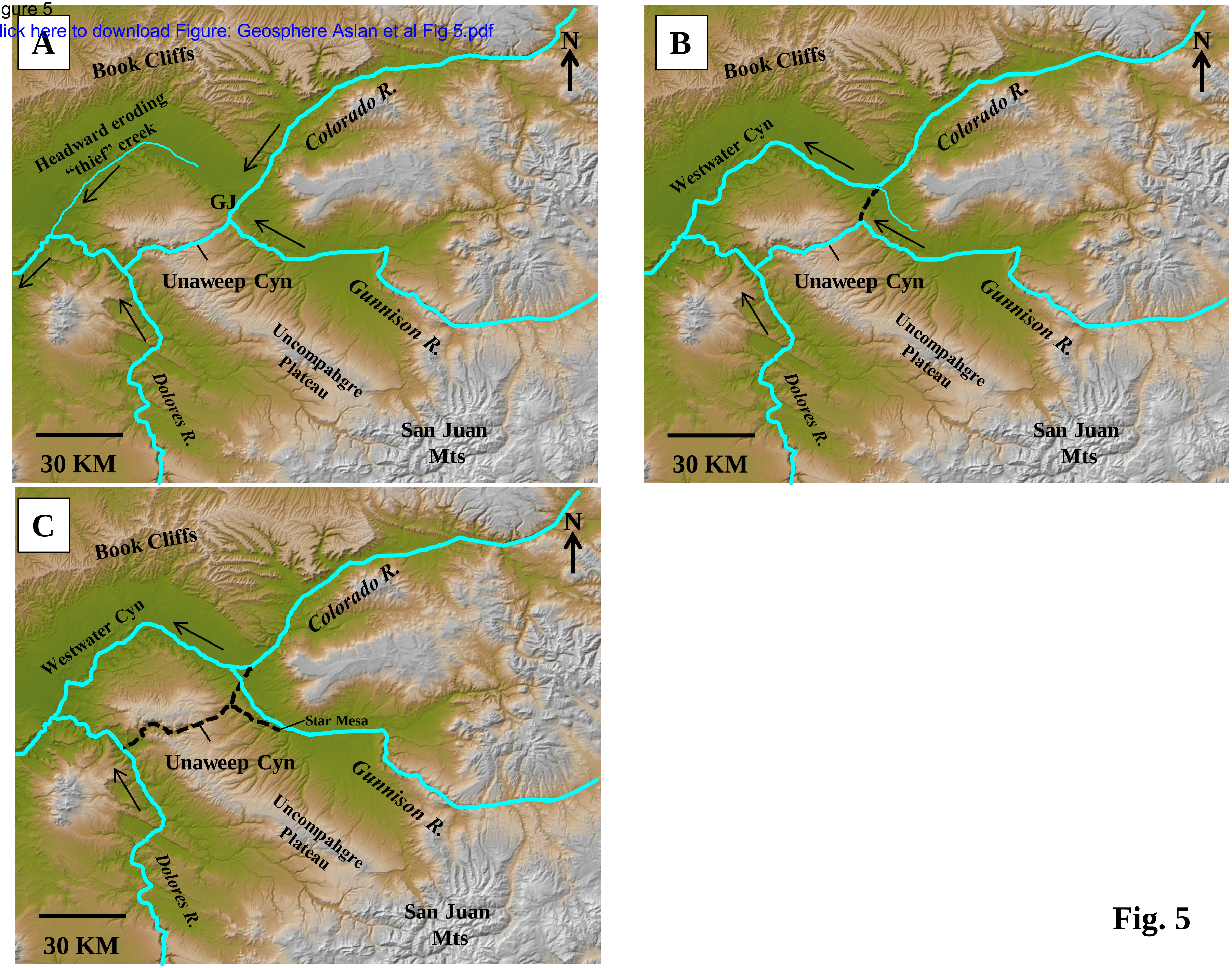
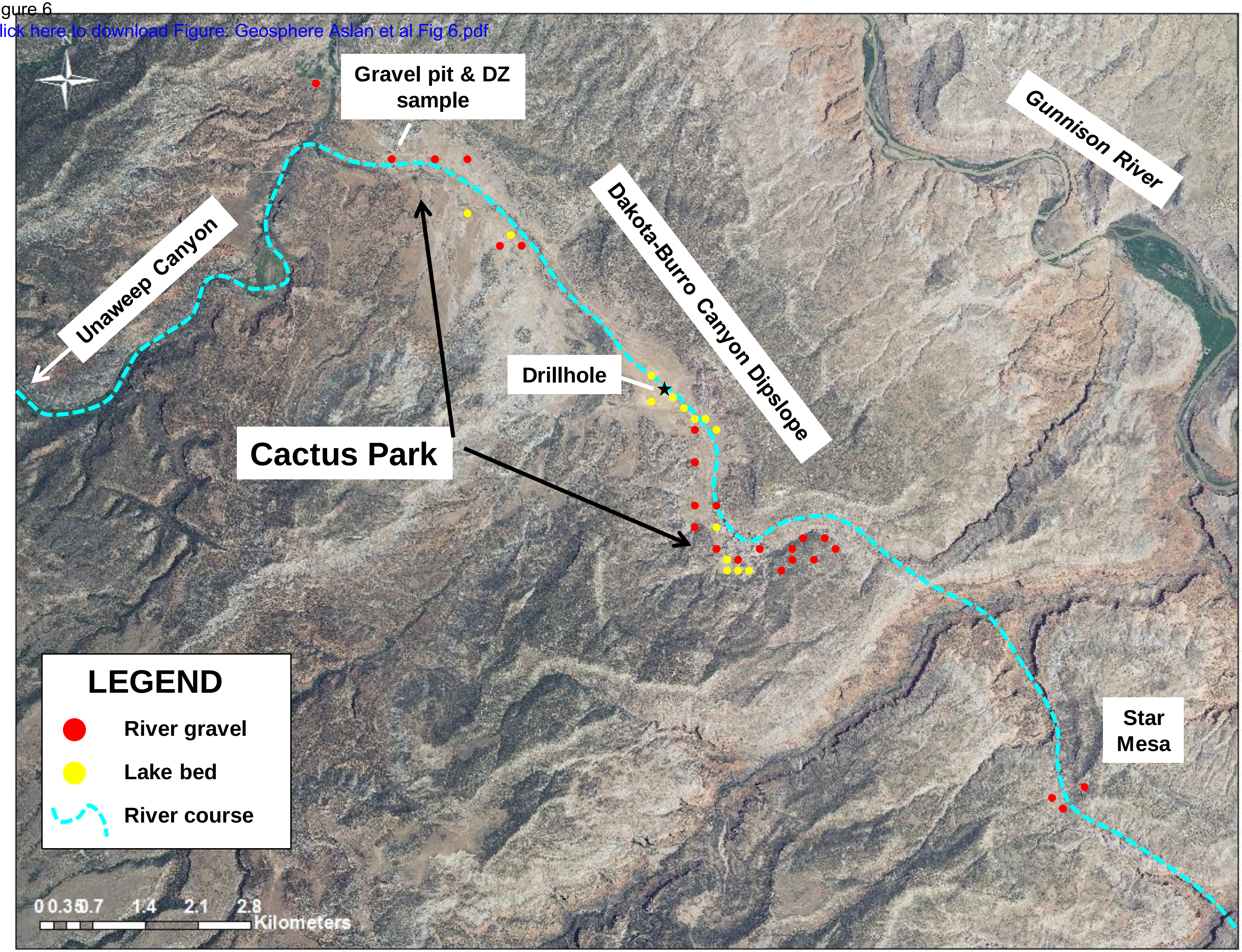

A
Book Cliffs
N
Headward eroding
"thief" creek
Colorado R.
GJ
Unaweep Cyn
Gunnison R.
Uncompahgre
Plateau
Dolores R.
San Juan
Mts
30 KM
B
Book Cliffs
N
Westwater Cyn
Colorado R.
Unaweep Cyn
Gunnison R.
Uncompahgre
Plateau
Dolores R.
San Juan
Mts
30 KM
C
Book Cliffs
N
Colorado R.
Westwater Cyn
Star Mesa
Unaweep Cyn
Gunnison R.
Uncompahgre
Plateau
Dolores R.
San Juan
Mts
30 KM

Fig. 5

Figure 6


Gravel pit & DZ sample
Gunnison River
Unaweep Canyon
Dakota-Burro Canyon Dipslope
Drillhole
Cactus Park
Star Mesa
LEGEND
River gravel
Lake bed
River course
0 0.35 0.7 1.4 2.1 2.8
Kilometers

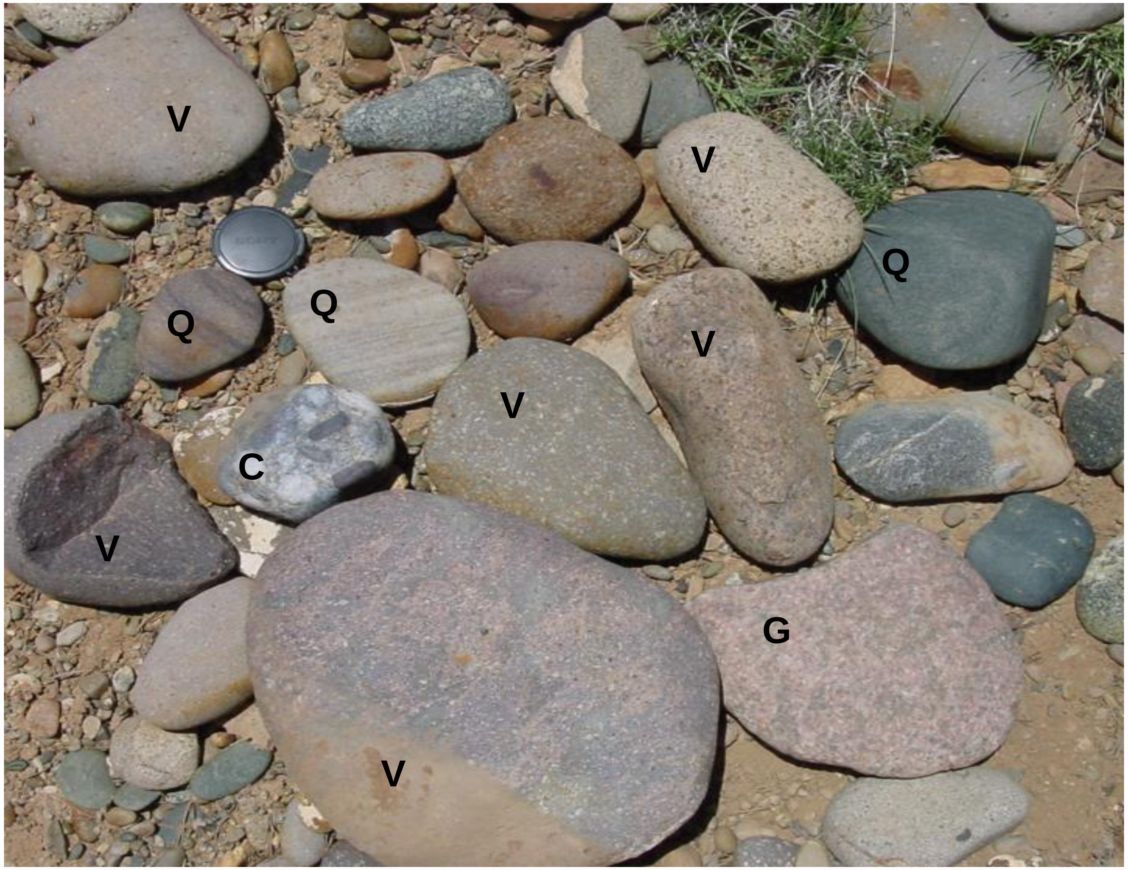
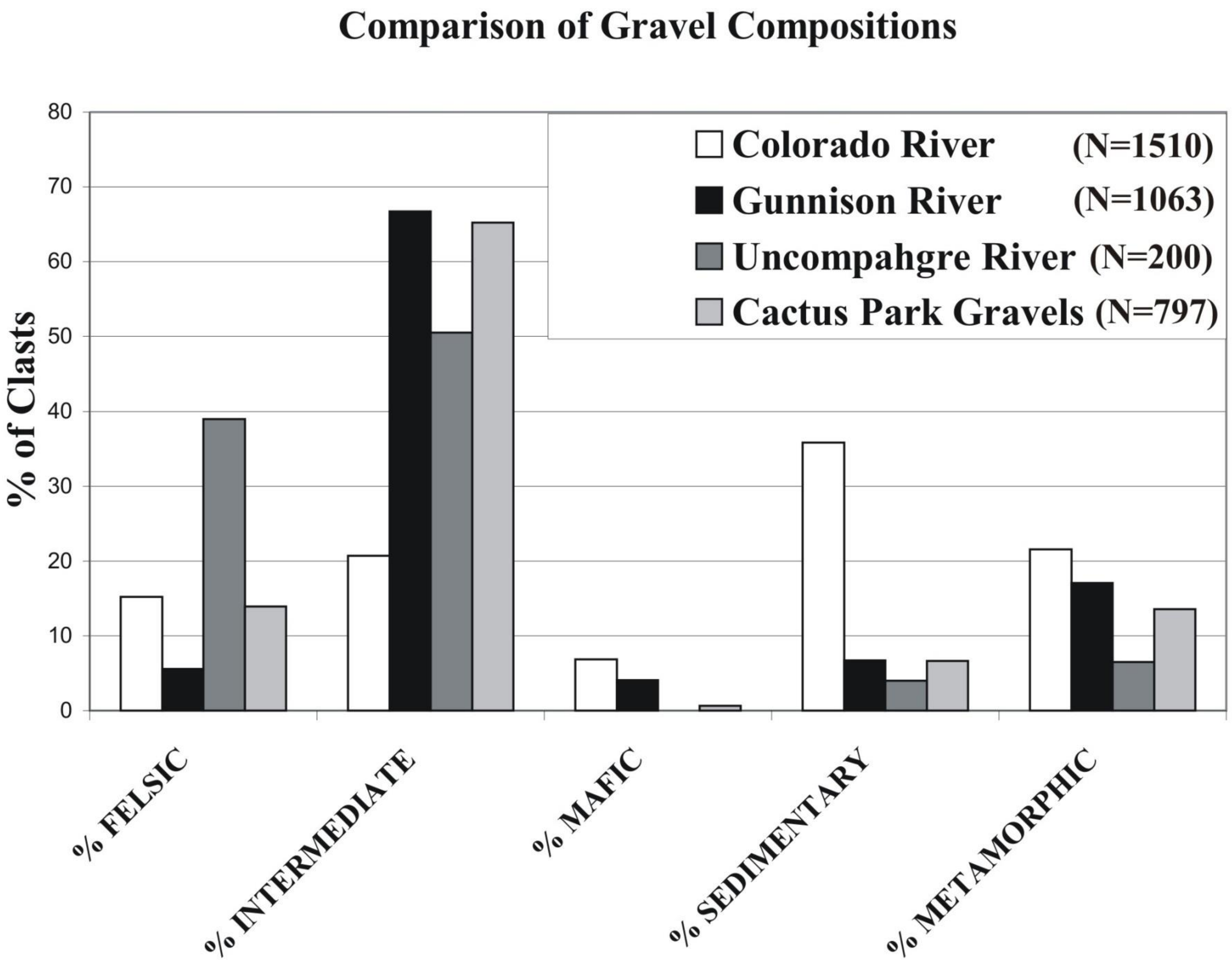


Fig. 7



Comparison of Gravel Compositions
% of Clasts
80
70
60
50
40
30
20
10
0
Colorado River (N=1510)
Gunnison River (N=1063)
Uncompahgre River (N=200)
Cactus Park Gravels (N=797)
% FELSIC
% INTERMEDIATE
% MAFIC
% SEDIMENTARY
% METAMORPHIC

Fig. 8

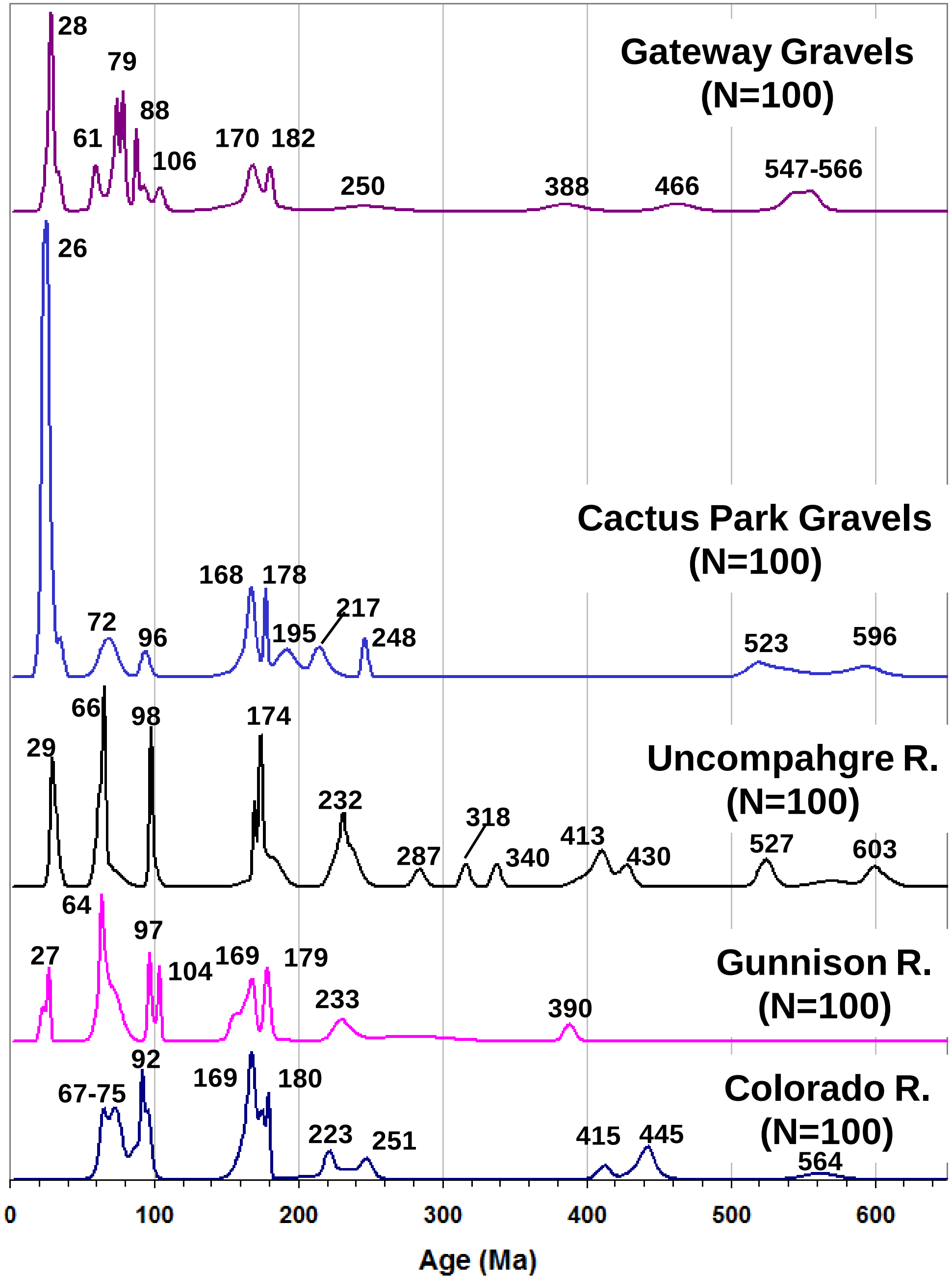

Gateway Gravels
(N=100)
28
79
88
61
106
170
182
250
388
466
547-566
26
Cactus Park Gravels
(N=100)
168
178
72
96
195
217
248
523
596
66
98
174
29
Uncompahgre R.
(N=100)
232
318
287
340
413
430
527
603
64
97
27
104
169
179
Gunnison R.
(N=100)
233
390
92
67-75
169
180
Colorado R.
(N=100)
223
251
415
445
564
0
100
200
300
400
500
600
Age (Ma)

Fig. 9

Figure 10

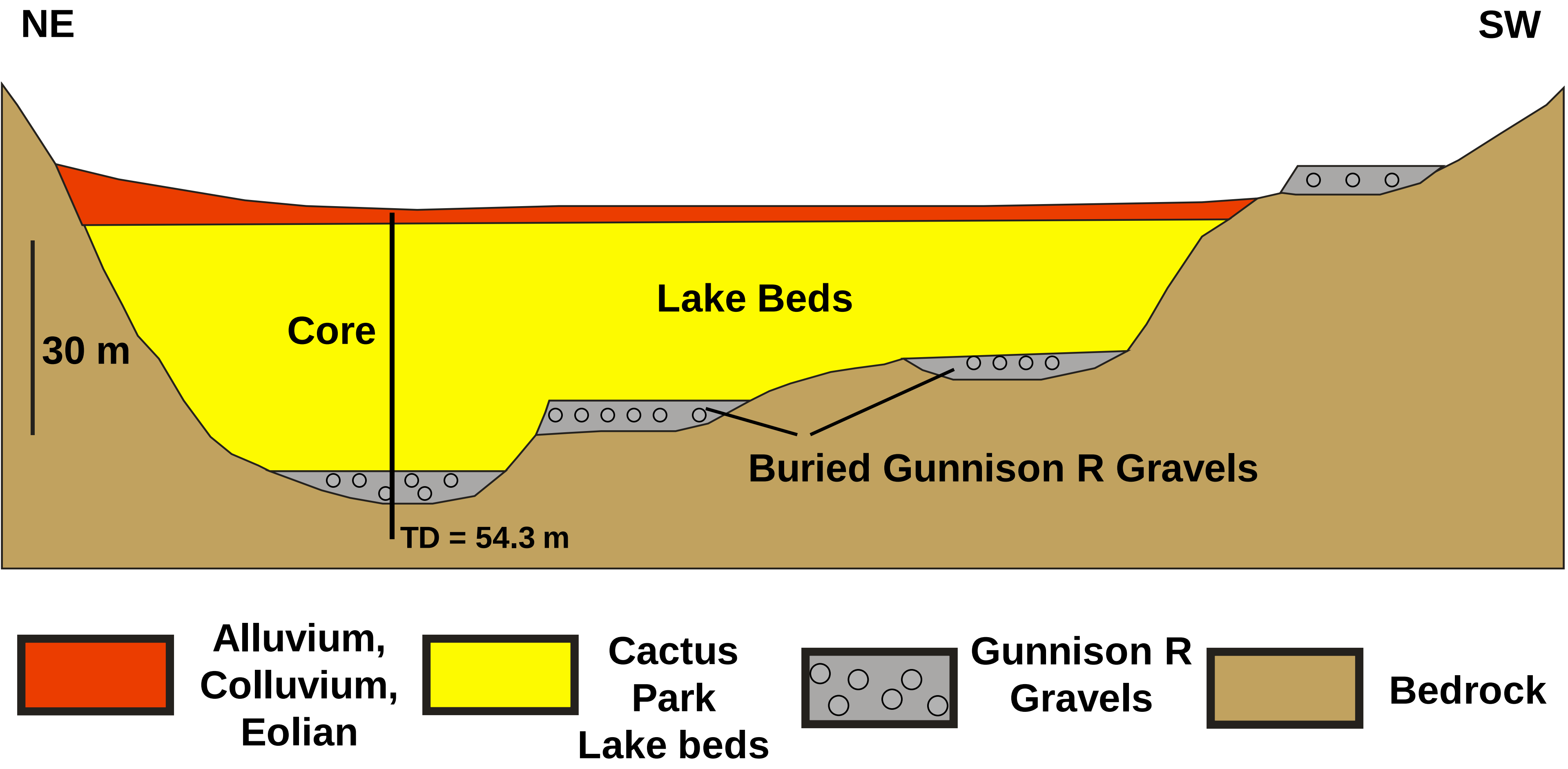

NE
SW
30 m
Core
Lake Beds
Buried Gunnison R Gravels
TD = 54.3 m
Alluvium, Colluvium, Eolian
Cactus Park Lake beds
Gunnison R Gravels
Bedrock

Fig. 11

Figure 12

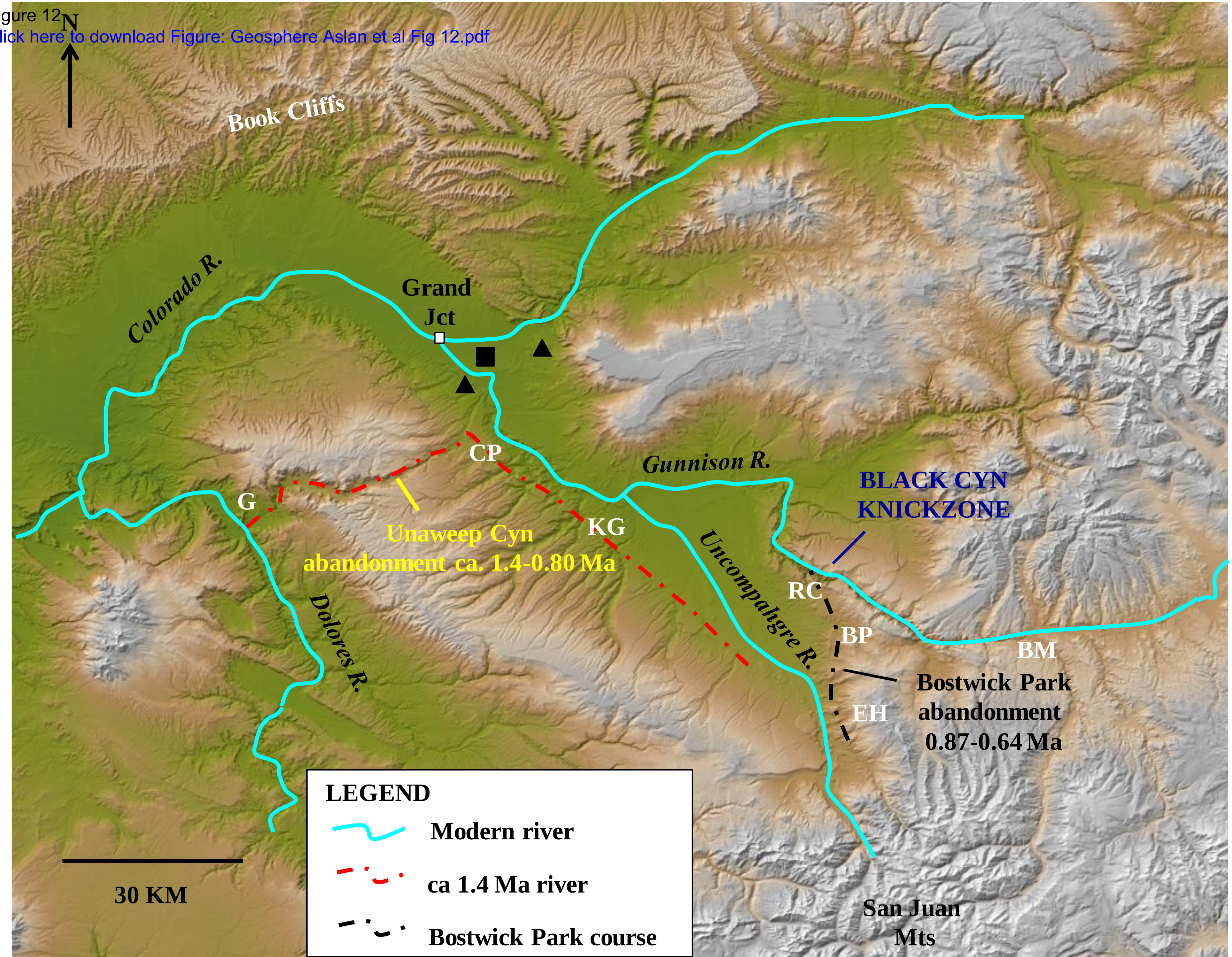

N
Book Cliffs
Colorado R.
Grand Jct
CP
G
Unaweep Cyn abandonment ca. 1.4-0.80 Ma
KG
Gunnison R.
BLACK CYN KNICKZONE
Uncompahgre R.
RC
BP
BM
Bostwick Park abandonment 0.87-0.64 Ma
EH
Dolores R.
30 KM
San Juan Mts
LEGEND
Modern river
ca 1.4 Ma river
Bostwick Park course

Figure 13

Click here to download Figure: Geosphere Aslan et al Fig 13.pdf

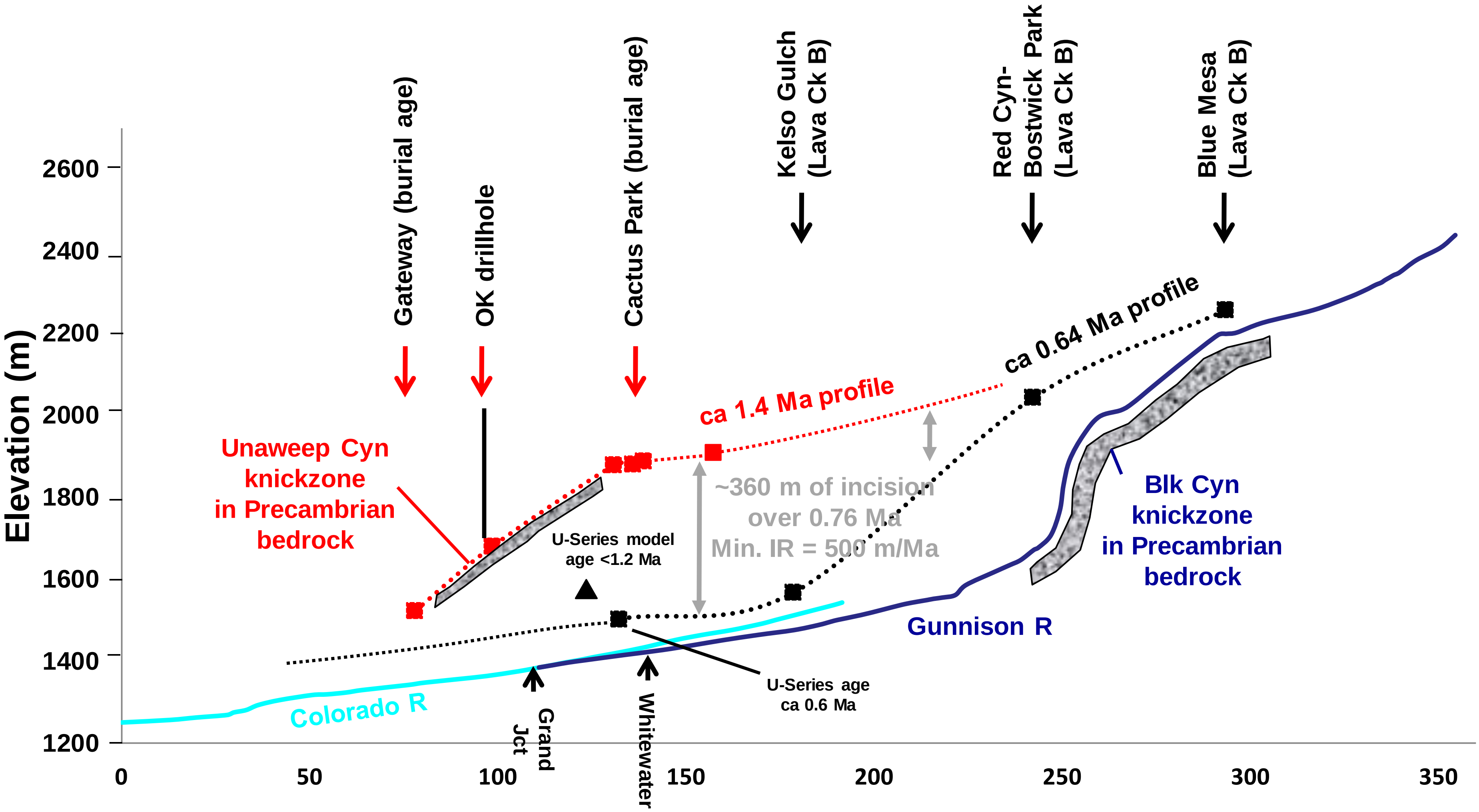


Fig. 13

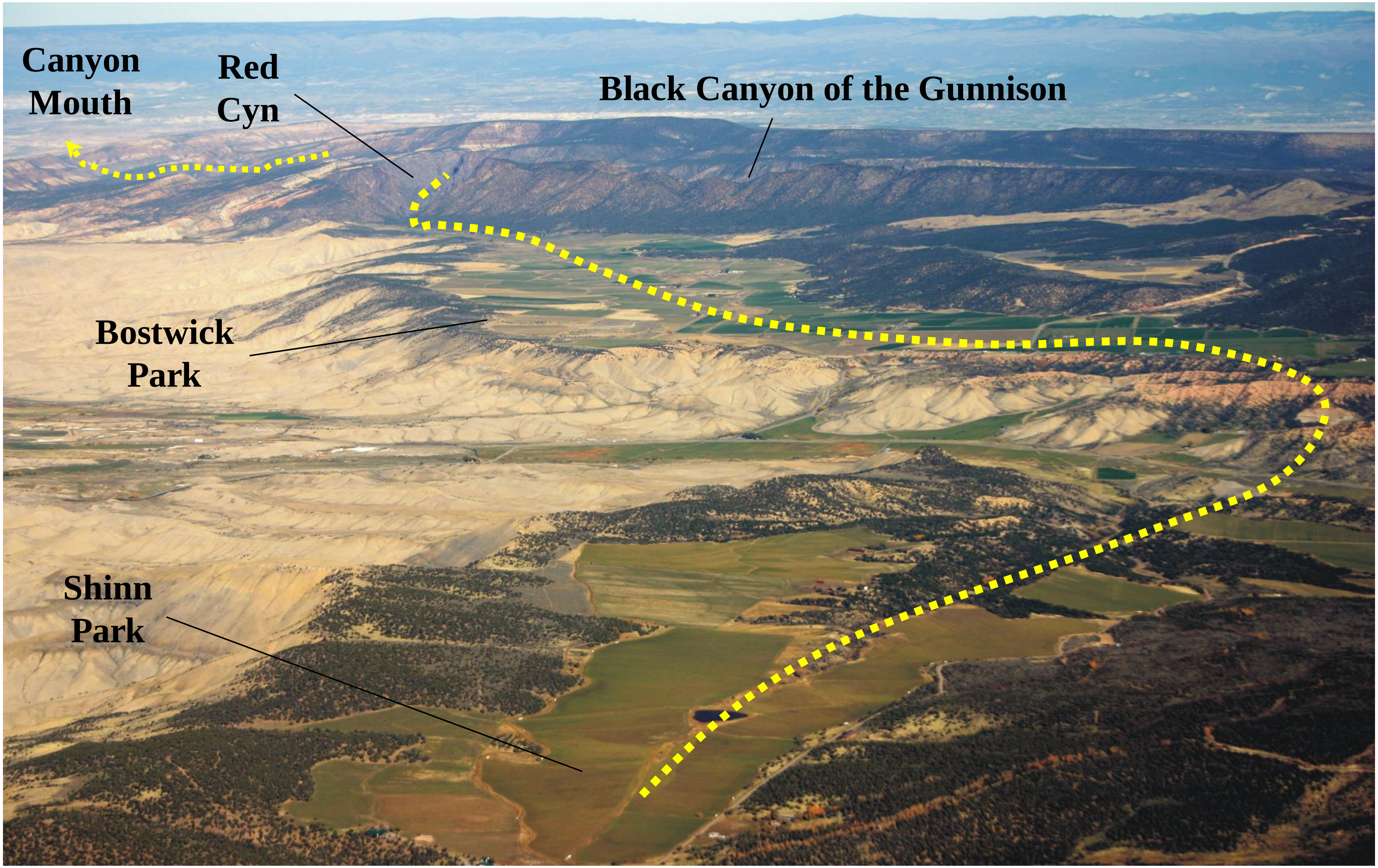

Canyon Mouth
Red Cyn
Black Canyon of the Gunnison
Bostwick Park
Shinn Park

Fig. 14

Figure 15

Fig. 15

Figure 16

Click here to download Figure: Geosphere Aslan et al Fig 16.pdf

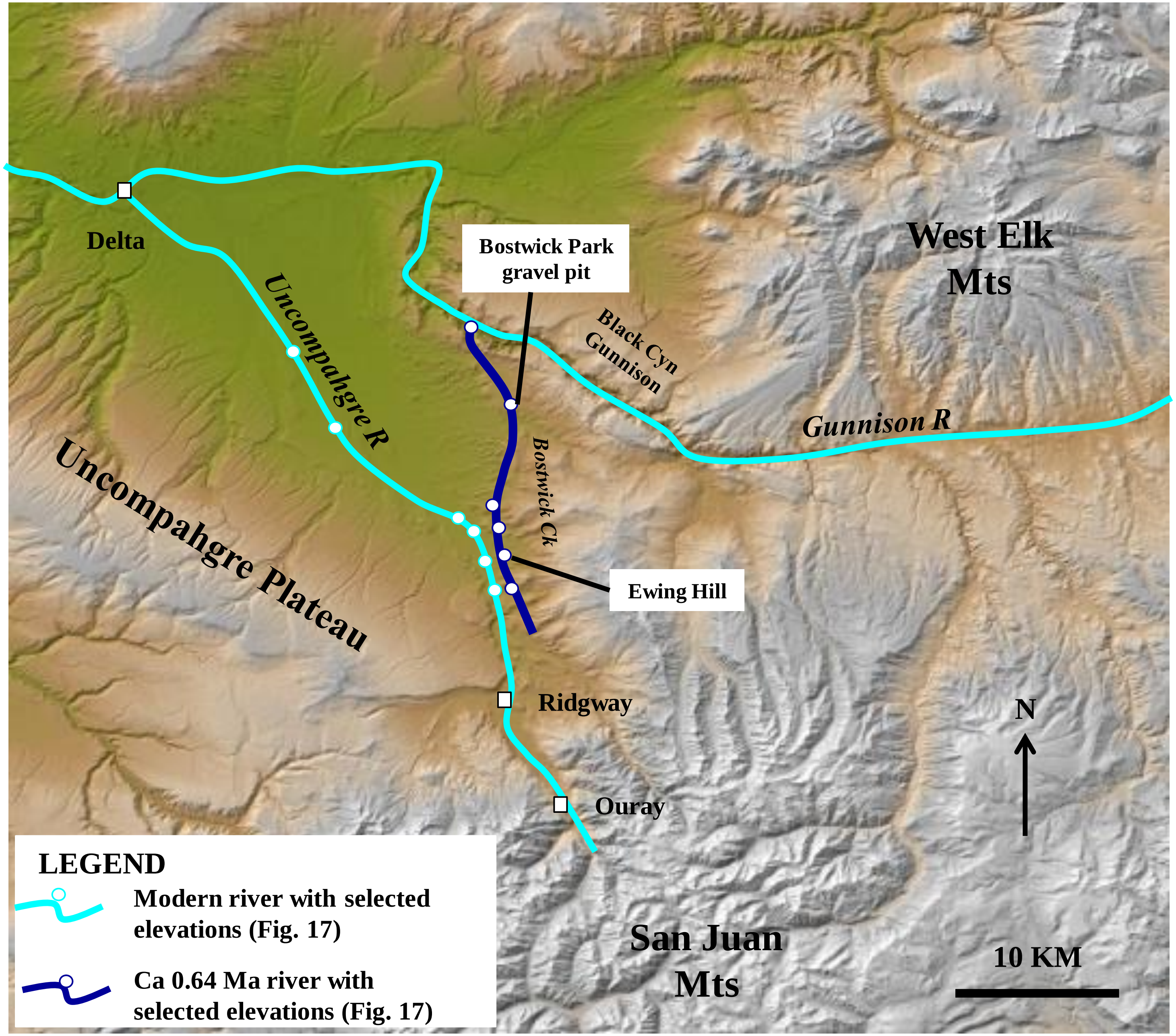


Fig. 16

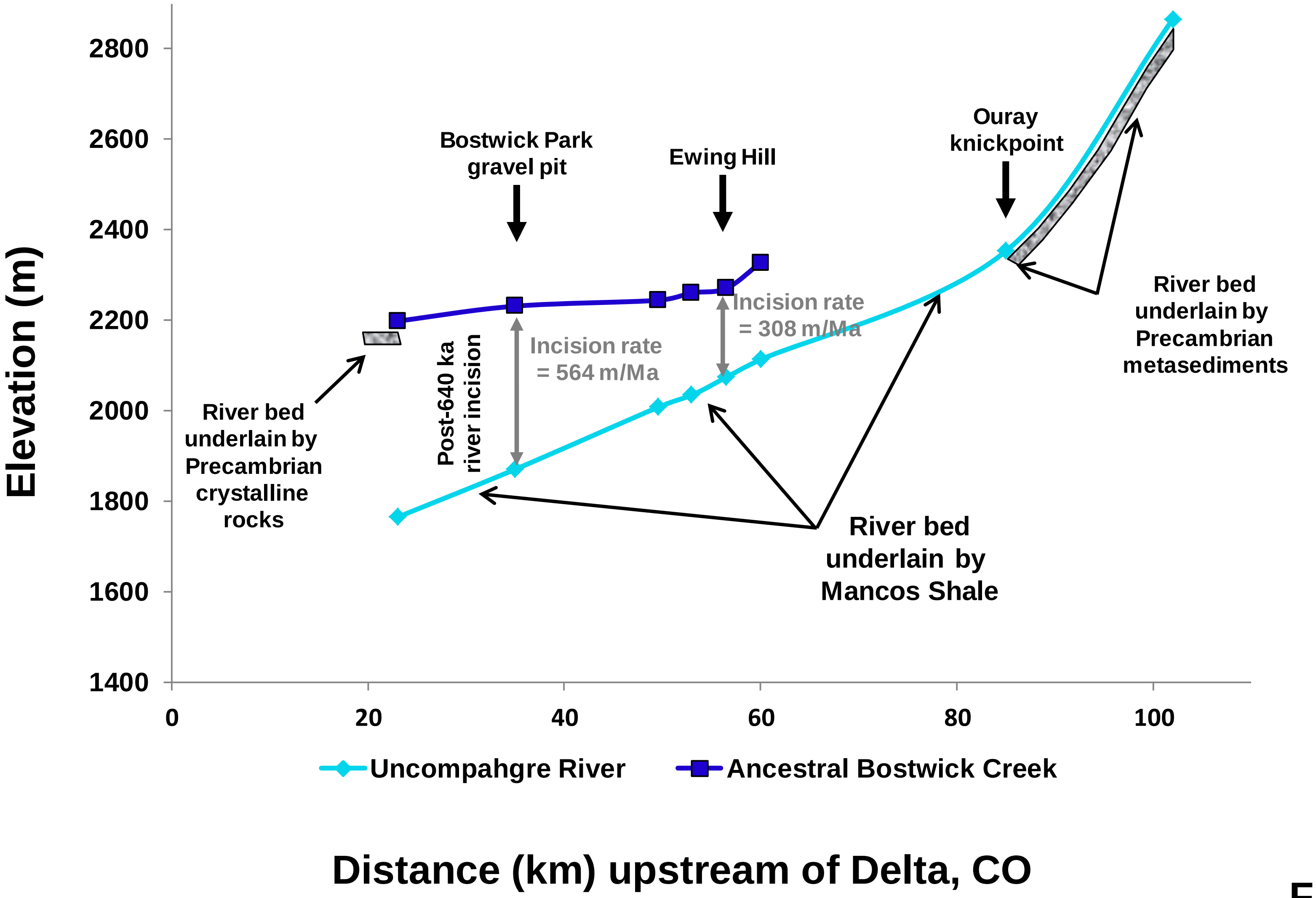

Elevation (m)
2800
2600
2400
2200
2000
1800
1600
1400
0
20
40
60
80
100
Bostwick Park gravel pit
Ewing Hill
Ouray knickpoint
Incision rate = 564 m/Ma
Incision rate = 308 m/Ma
Post-640 ka river incision
River bed underlain by Precambrian crystalline rocks
River bed underlain by Mancos Shale
River bed underlain by Precambrian metasediments
Uncompahgre River
Ancestral Bostwick Creek
Distance (km) upstream of Delta, CO

Fig. 17

Figure 18

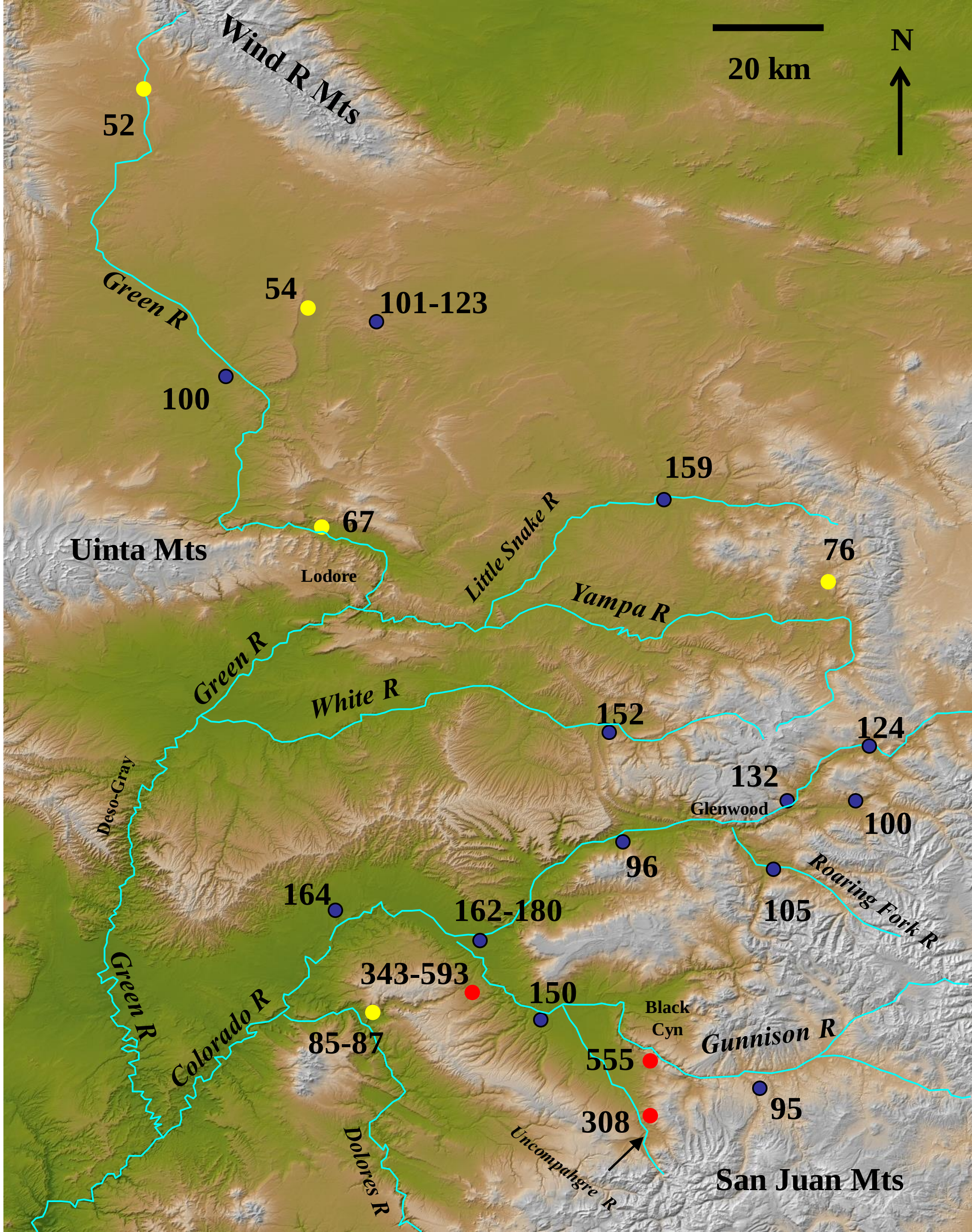


Fig. 18

Table 1. Cosmogenic nuclide data and burial ages, Cactus Park, Colorado.

Sample	Latitude	Longitude	[^{10}Be]	[^{26}Al]	Minimum burial age
			(10^3 at/g)	(10^3 at/g)	(My)
CP3	38.84235	108.45962	50 ± 3	221 ± 31	0.92 ± 0.31
CP3A	38.84235	108.45962	53 ± 8	268 ± 31	0.62 ± 0.39
average					0.80 ± 0.24

^{10}Be/^{9}Be measured at PRIME Lab; sample CP3 against NIST standards adjusted by a factor of 0.9 for consistency with Nishiizumi et al. (2007), and sample CP3A against Nishiizumi et al. (2007).

Burial ages calculated by iteration following Granger and Muzikar (2001), ignoring postburial production by muons. Age of CP3 differs from Aslan et al. (2008b) due to adoption of a new ^{10}Be standard (Nishiizumi et al., 2007) and half-life (Chmeleff et al., 2010). Source area production rates of ^{10}Be and ^{26}Al taken as 35 and 240 at/g/yr for latitude 38° elevation 3 km. Burial age is not sensitive to source area production rate.

Table 2

Table 2. U-Series ages and resulting incision rates from Colorado River terraces near Grand Junction, Colorado.

Sample Number	Latitude	Longitude	Height (m)	Corrected U/Th age (ka)	± 2σ error				Min. ^{234}U model age (ka) δ234Ui=1000	Max. ^{234}U model age (ka) δ234Ui=4000	Incision Rate (m/Ma	± 2σ error			
~~CR160-101811-3D~~	39.01411	-108.40714	~~158~~						~~679~~	~~1170~~	~~171~~	~~+~~	~~62~~	-	~~36~~
~~CR160-101811-3CA~~	39.01411	-108.40714	~~158~~						~~716~~	~~1207~~	~~164~~	~~+~~	~~56~~	-	~~33~~
CR112809-2B	39.01975	-108.41131	146						723	1213	151	+	51	-	31
CR-41012-1	39.0167	-108.44084	110	254.73	+	6.13	-	5.80			432	+	10	-	10
CR-41012-2	39.01698	-108.49997	101	581.19	+	128.51	-	67.79			174	+	23	-	31
CR100-6413-1E	39.02566	-108.44587	110	226.41	+	2.17	-	2.14			486	+	5	-	5
QT80-8812-1AA	39.06594	-108.40034	67	155.52	+	1.20	-	1.19			431	+	3	-	3
~~CRG60-71912-1~~	39.06568	-108.40045	~~64~~						~~199~~	~~690~~	~~144~~	~~+~~	~~178~~	-	~~51~~
~~CR60-6513~~	39.06557	-108.40033	~~62~~						~~182~~	~~673~~	~~145~~	~~+~~	~~195~~	-	~~53~~

Model-age-constrained incision rates were calculated using a median age between the minimum and maximum model ages.

See Data Repository Table 2 for full analytical results.

Strikethrough sample #s represent samples that exhibited open system behavior, and were not used to estimate maximum ages of terraces.

Table 3

Table 3. Apatite fission-track data for Unaweep Canyon, Colorado.

Sample Number	Rock Type	Latitude Longitude	Elevation (m)	Number of Grains Dated	r_s x 10^5 t/cm^2	r_i x 10^6 t/cm^2	r_d x 10^5 t/cm^2	Central Age (Ma) (±1 S.E.)	$P(c)^2$ **(%)**	Uranium Content (ppm)	Mean Track Length (µm) (± 1 S.E.)	Standard Deviation Track Length (µm)
07UNI01	Taylor Ranch granite	38.8376°	2130	20	1.094	2.387	1.72885	**37.7 ± 3.8**	99	17	12.9±0.7	2.2
		108.5691°			(133)	(1451)	(4600)				(39)	
07UNI02	Vernal Mesa granite	38.7246°	1550	20	2.065	7.451	1.7041	**22.5 ± 2.1**	99	53	12.7±0.6	1.9
		108.9106°			(152)	(2742)	(4600)				(35)	

r_s - spontaneous track density r_i - induced track density (reported induced track density is twice the measured density)

Number in parenthesis is the number of tracks counted for ages and fluence calibration or the number of track measured for lengths.

r_d - track density in muscovite detector covering CN-6 (1.05 ppm); Reported value determined from interpolation of values for detectors covering standards at the top and bottom of the reactor packages (fluence gradient correction)

S.E. = standard error $P(c)^2$ = Chi-squared probability

$l_f = 1.551 \text{ X } 10^{-10} yr^{-1}$, g=0.5 zeta = 4772 ± 340 for apatite

Mean track lengths not corrected for length bias

Supplemental file Table 2