New incision rates along the Colorado River system based on cosmogenic burial dating of terraces: Implications for regional controls on Quaternary incision

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ABSTRACT

New cosmogenic burial and published dates of Colorado and Green river terraces are used to infer variable incision rates along the rivers in the past 10 Ma. A knickpoint at Lees Ferry separates the lower and upper Colorado River basins. We obtained an isochron cosmogenic burial date of 1.5 ± 0.13 Ma on a 190-m-high strath terrace near Bullfrog Basin, Utah (upstream of Lees Ferry). This age yields an average incision rate of 126 +12/–10 m/Ma above the knickpoint and is three times older than a cosmogenic surface age on the same terrace, suggesting that surface dates inferred by exposure dating may be minimum ages. Incision rates below Lees Ferry are faster, ~170 m/Ma–230 m/Ma, suggesting upstream knickpoint migration over the past several million years. A terrace at Hite (above Lees Ferry) yields an isochron burial age of 0.29 ± 0.17 Ma, and a rate of ~300–900 m/Ma, corroborating incision acceleration in Glen Canyon. Within the upper basin, isochron cosmogenic burial dates of 1.48 ± 0.12 Ma on a 60 m terrace near the Green River in Desolation Canyon, Utah, and 1.2 ± 0.3 Ma on a 120 m terrace upstream of Flaming Gorge, Wyoming, give incision rates of 41± 3 m/Ma and 100 +33/–20 m/Ma, respectively. In contrast, incision rates along the upper Colorado River are 150 m/Ma over 0.64 and 10 Ma time frames. Higher incision rates, gradient, and discharge along the upper Colorado River relative to the Green River are consistent with differential rock uplift of the Colorado Rockies relative to the Colorado Plateau.

INTRODUCTION

The Colorado River system is established across complex lithology, climate, and uplift gradients. What processes have been the most significant in forming features such as Grand Canyon and the relief of the western Colorado Rockies (Fig. 1)? Focusing on the main features of this river system in its longitudinal profile (Fig. 2), we study the primary geomorphic and tectonic processes that have acted on the river system over the past five to six million years, which is the likely time for integration of Colorado Plateau drainages through Grand Canyon to the Gulf of California (e.g., Karlstrom et al., 2008; Dorsey, 2010). The upper Colorado River, on the other hand, has a history reaching back to ca. 11 Ma (Larson et al., 1975; Aslan et al., 2008, 2010). Evolution of the river system since 5–6 Ma has likely involved climatically influenced variations of discharge and sediment flux that are often presumed to drive episodic periods of downcutting and aggradation in the river (Bull, 1991). Tectonic influ-ences on the river over this time period may include regional epeirogeny (Karlstrom et al., 2008), tectonic offset on faults (Pederson et al., 2002a; Karlstrom et al., 2007), salt tectonics (Huntoon, 1988; Kirkham et al., 2002), and perhaps mantle-driven uplift via long-wavelength, whole-mantle flow (with similarities to the Arabian case, Daradich et al., 2003; Moucha et al., 2008; Liu and Gurnis, 2010), or upper mantle convection (Schmandt and Humphreys, 2010; van Wijk et al., 2010; Karlstrom et al., 2012; cf. King and Ritsema, 2000).

The modern longitudinal profile of the Colorado River is shown in Figure 2. Along this profile, knickpoints, i.e., convexities in the profile, have several hypothesized origins. In regions of nonuniform rock type, erosion-resistant substrates may affect long-profile development; studies show that channel narrowing and increased gradient correlate with harder rocks in the river substrate (Moglen and Bras, 1995; Grams and Schmidt, 1999; Stock and Montgomery, 1999; Duvall et al., 2004; Turowski et al., 2008). At short timescales, significant sediment input from debris flows in ephemeral tributaries is observed throughout the arid Colorado Plateau, and these also can create convex reaches through bed armoring and channel filling (Schmidt and Rubin, 1995; Grams and Schmidt, 1999; Hanks and Webb, 2006). Regionally, recent debate has focused on the extent to which steep reaches and the Lees Ferry

knickpoint reflect bedrock competence (Mackley and Pederson, 2004; c.f. the Desolation/Gray canyons case, Roberson and Pederson, 2001) and/or transient incision (c.f. Kirby et al., 2007; Karlstrom et al., 2008; Cook et al., 2009; Pelletier, 2010). Discussions of hypotheses regarding knickpoint formation must take into account unique features of each reach studied to discern the big-picture importance of the knickpoint to the broader river system.

This paper explores the long-term incision history of the Colorado River system in order to help evaluate the first-order controls on river evolution. This work is part of the Colorado Rockies Experiment and Seismic Transect (CREST) collaborative effort and is summarized in Karlstrom et al. (2012), in which interdisciplinary research efforts combine to increase understanding of the Colorado Rockies and the Colorado Plateau. For this paper, we first present new estimates of long-term Quaternary incision rates at six key localities along the upper Colorado River and its tributaries. We utilize a relatively new approach to dating fluvial deposits by cosmogenic burial dating isochron analysis (Balco and Rovey, 2008). This method, although costly, overcomes some of the limitations of traditional cosmogenic burial dating (e.g., Granger and Muzikar, 2001) such that it may be applied to deposits that experienced significant postburial production during either shallow burial and/or later exhumation. Our new dates and incision rates are then presented in the context of a regional synthesis of incision rates throughout the Colorado River system. Comparison of incision rates with the shape of the longitudinal profile reveals information about the convolved effects of regional uplift, climate change, and drainage reorganization that, if resolved, can help elucidate the still-controversial uplift and denudation history of the western U.S. (e.g., Pederson et al., 2002b; McMillan et al., 2006; Moucha et al., 2008; Huntington et al., 2010; Liu and Gurnis, 2010).

GEOLOGIC BACKGROUND

Tectonic Setting

The modern landscape of the Colorado Plateau and Rocky Mountains is the result of erosion and fluvial incision acting on a region with a protracted uplift history. Deformation during Laramide time (70–45 Ma) resulted in local uplifts of Precambrian basement juxtaposed with deep basins with structural relief greater than 10 km (MacLachlan et al., 1972; Dickinson et al., 1988). Paleoelevations at the end of the Laramide are not well known, and the relative

magnitudes of Laramide versus mid-Tertiary and Neogene epeirogenic uplift of the Rockies and Colorado Plateau continue to be debated. At one end member, the modern high-relief landscape developed from a Laramide plateau via later erosional processes (Gregory and Chase, 1994; McQuarrie and Chase, 2000; Huntington et al., 2010). An alternative uplift model hypothesizes Tertiary epeirogeny that may have coincided with the Tertiary ignimbrite "flare-up" due to magmatism (Roy et al., 2004; Lipman, 2007) and mantle-driven thermal topography (Eaton, 2008; Roy et al., 2009). At the other end member, evidence for post–10 Ma tilting of sediments draped along the Rocky Mountains (Leonard, 2002; McMillan et al., 2002) suggests a young component of rock uplift. Probably more realistic models involve several episodes of uplift (e.g., Karlstrom et al., 2012; Liu and Gurnis, 2010).

Regional River Systems

The Colorado River below Lees Ferry (the lower basin) and through Grand Canyon began to carry Rocky Mountain water and detritus to the Gulf of California after 6 Ma (House et al., 2008; Howard and Bohannon, 2000; Karlstrom et al., 2008; Dorsey, 2010). At this time, a paleo–Colorado River already existed in the Colorado Rockies as shown by ca. 11 Ma river gravels near Grand Mesa, Glenwood Canyon, and Gore Canyon (Fig. 1; Larson et al., 1975; Kunk et al., 2002; Czapla and Aslan, 2009; Aslan et al., 2010; Cole, 2011). Little physical evidence for where the Colorado River system flowed has been documented from the time period of ca. 11 Ma to ca. 6 Ma. However, erosion since ca. 10 Ma has been dramatic (>1.5 km in places) as the Colorado River and its tributaries began to carve deep canyons (e.g., Aslan et al., 2010).

In contrast, the Green River is a younger system. Basin filling continued within portions of the upper Green River watershed until at least 8 Ma as shown by Miocene deposits of the Browns Park Formation in Browns Park, Colorado. These deposits are mostly older than 8.25 Ma (Luft, 1985) and provide a maximum limit on the age of the Green River between Flaming Gorge and the Gates of Lodore. Neogene subsidence and graben collapse played a key role in the early development of the Green River (Izett, 1975; Hansen, 1986). Sometime after ~8 million years ago, the Green River began eroding the low-relief region north of the Uinta Mountains as a result of drainage integration events that diverted surface waters south toward and eventually across the Uinta Mountains, beyond which they join the Colorado River system (Hansen 1986; Munroe et al., 2005).

River Profiles

The longitudinal profiles of the Colorado and Green rivers are shown in Figure 2. The predominant feature of the longitudinal profile of the Colorado River is a knickpoint near Lees Ferry that separates a high gradient reach through Grand Canyon from lower gradient reaches in Glen Canyon and above (Fig. 2). The Lees Ferry knickpoint divides the upper Colorado River hydrologic basin from the lower basin and is the boundary between two distinct portions of the profile. Additional minor knickzones and convexities exist within Grand Canyon (Hanks and Webb, 2006), but these are minor perturbations at the regional scale and long time frames of interest here. There are also several other prominent knickpoints in the upper basin. There is a distinct knickzone through Cataract Canyon, a short distance downstream from the confluence of the Green and Colorado rivers. Farther upstream, the Green River has two large knickzones, one in Desolation Canyon and the other where the Green River crosses the Uinta Mountains. Upstream of the Green-Colorado confluence, the Colorado River has smaller knickpoints located in Glenwood Canyon, Gore Canyon, and Black Canyon (Gunnison River), all shown as stars in Figure 1. The profile depicts a river that is not uniformly graded. This is either a result of resistant rock locally steepening slope, or another perturbation or perturbations that the river is still adjusting to. Due to the expected high rate of transient knickpoint retreat (Whipple and Tucker, 1999; Berlin and Anderson, 2007), it is likely that any transient features are relatively young. Thus, many potential causes of the knickpoints of the Colorado River are recent perturbations (10^5–10^6 years). We attempt to test the youth of these perturbations by discussing patterns of incision rates revealed by a compilation of regional data, supplemented by new estimates that exploit cosmogenic burial dating.

METHODS

Cosmogenic Burial Dating

The objective of this project was to identify old, high terraces with thick gravel deposits suitable for cosmogenic burial dating. Such sites are scarce in the erosional landscape of the region; however, we report six new terrace dates using cosmogenic nuclide burial ages. Five of these ages from five different locations are determined using the relatively new method of isochron burial dating (Balco and Rovey, 2008), which requires only a few meters of burial. The sixth date uses simple burial dating of amalgamated clasts, which requires a much deeper burial
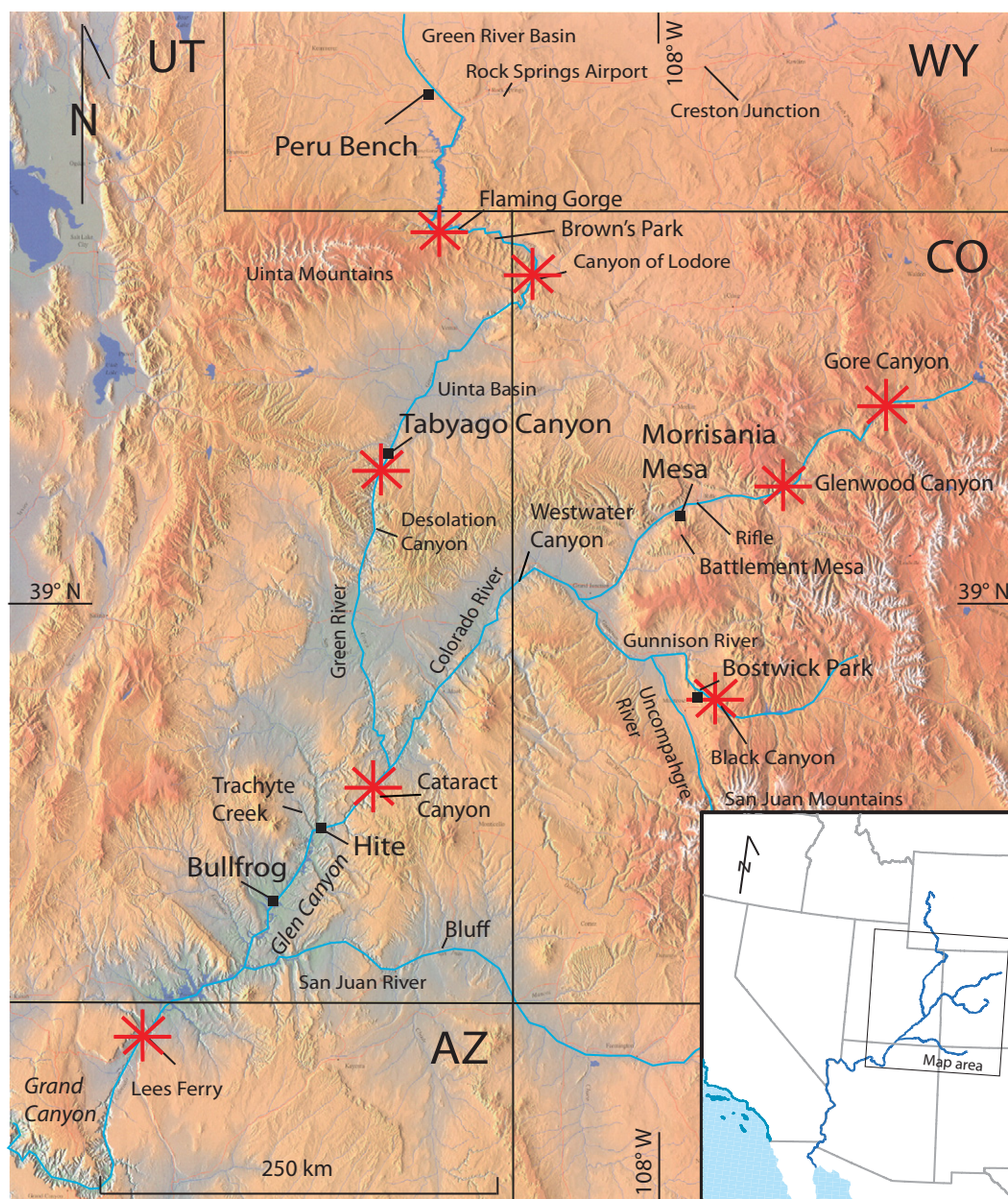
Figure 1. Map of rivers and locations throughout the Colorado Plateau, including new sample locations, marked with black squares. Stars are knickpoints in the longitudinal profile. Inset shows context of the major Colorado River tributaries. Three-second digital elevation model generated by Chalk Butte, Inc., 1995.

(>10 m). Burial dates are calculated from the differential decay of cosmogenic ^{26}Al and ^{10}Be in quartz (e.g., Granger, 2006). Cosmogenic nuclides (such as ^{10}Be and ^{26}Al) are produced when secondary cosmic ray particles interact with target nuclei in minerals. Secondary cosmic ray neutrons penetrate only a few meters beneath the ground surface, while less interactive muons continue to be important at depths to tens of meters.

Cosmogenic burial dating (Granger and Muzikar, 2001) relies on the different decay rates of ^{26}Al ($t_{1/2} = 0.717$ Ma; Granger, 2006) and ^{10}Be ($t_{1/2} = 1.387$ Ma) (Chmeleff et al., 2010; Korschinek et al., 2010). Dates as old as 4.5 Ma

(6.28 half-lives for ^{26}Al), corroborated by dated overlying basalt, have been reported on the Colorado River System (Matmon et al., 2011). Many other sites have been successfully burial dated in this range (e.g., Stock et al., 2004), and ages from 0.5 to 3 Ma are routinely reported (e.g., Granger et al., 2001; Haeuselmann et al., 2007; Craddock et al., 2010, 2011). Thus, burial dating can provide age control in a time frame from 1 to 5 Ma and in deposits otherwise devoid of datable material such as volcanic ash.

Dating deposition of river gravel by cosmogenic burial dating requires: (1) sufficient nuclide production before burial to ensure concentrations are above the detection limit of accel-

erator mass spectrometry (AMS) at the time of measurement; (2) rapid, deep (~5–10 m) sample burial for adequate shielding from postdeposition nuclide production; (3) a sample within the age range that provides measurable quantities of ^{26}Al and ^{10}Be (i.e., maximum ca. 5 Ma); (4) samples that were not previously buried within the past 10 million years or so, and (5) a stable environment to ensure continued shielding until excavation. Preferred sample sites include gravel deposited in caves (Anthony and Granger, 2007; Granger et al., 2001), quarries in alluvium (Wolkowinsky and Granger, 2004), and landslide and/or fluvially eroded scarps of very recent exposure (this study) where depth
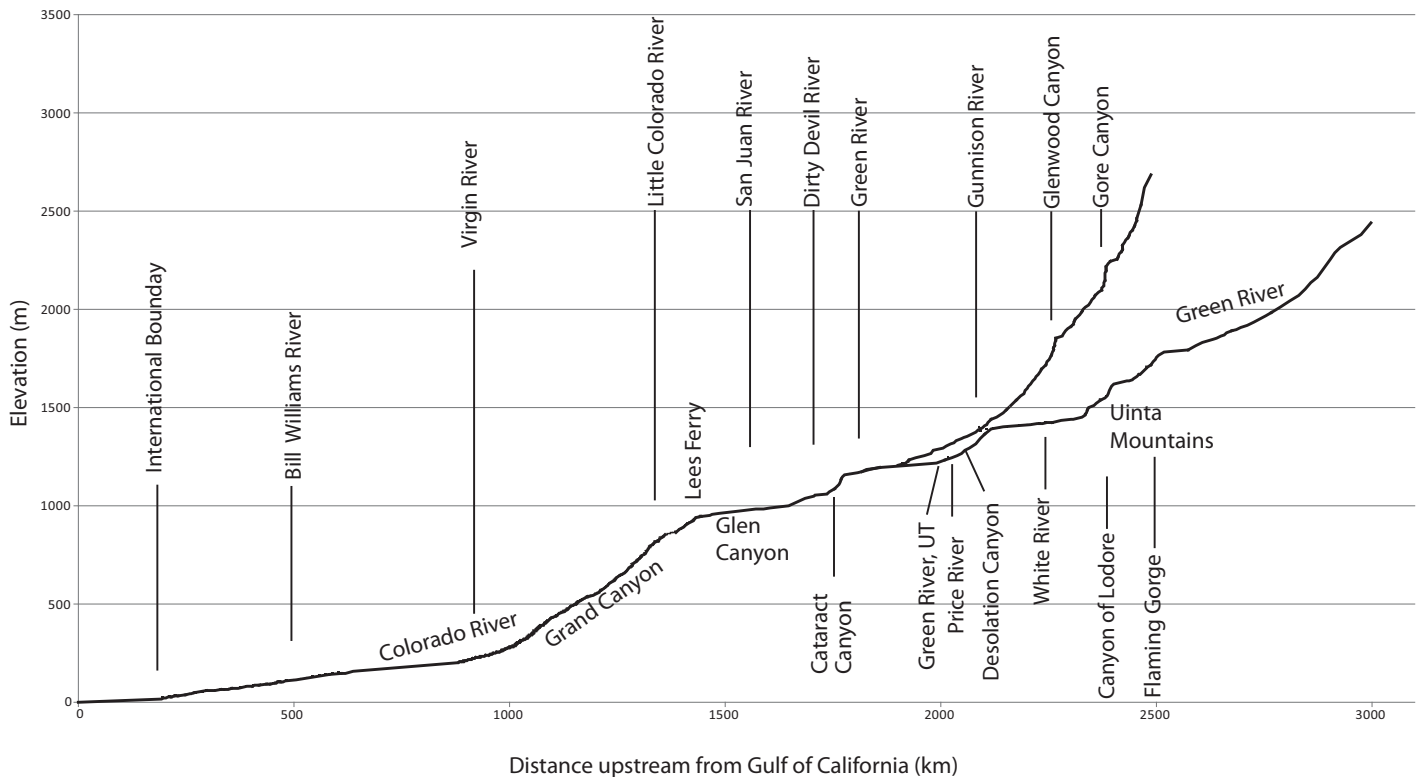
Figure 2. Longitudinal profile of the Colorado and Green rivers as determined from elevation data from U.S. Geological Survey 1:24,000 topographic maps, with distances measured along main channel.

of shielding exceeds ~4 m for isochrons (see below) and 10 m for simple burial dates. Field parameters relevant to the cosmogenic shielding for our samples are outlined in Table 1.

Two analytical techniques for determining burial ages via cosmogenic nuclide concentrations were implemented in this study. First, simple burial ages of deeply buried samples were analyzed via AMS as an amalgamation of several clasts crushed and processed together as described by Granger and Muzikar (2001). However, many of the deposits in this study consist of thin (<10 m) fluvial sand and gravel atop bedrock straths, and may have been subject to significant postdepositional production of cosmogenic ^{26}Al and ^{10}Be that complicates simple burial dating. Thus, we also used the isochron technique that involves AMS analyses of several clasts individually and sampled from a single depth. In the ideal case, decay after burial from a range of initial cosmogenic nuclide concentrations leads to systematic changes in concentration, such that one can evaluate the age of burial from an isochron plot (Balco and Rovey, 2008), similar to those used in traditional geochronology (cf. Dickin, 2004). In isochron burial dating, ^{26}Al is plotted against ^{10}Be. The burial age can be calculated from the slope of a line regressed through the data and postburial production can be estimated from

the intercept of the line. The fact that postburial production can be accounted for in the isochron technique allows for a critical advantage in many geologic settings. The dating of samples with as little as 3–4 m (Table 1) of vertical shielding is now possible, although very recent exposure is still required. However, in some ways isochron burial dating is not as simple as isochron dating in other radiometric dating methods. The initial ^{26}Al/^{10}Be ratio at the time of burial is dependent on average erosion rates in the drainage basin. Thus, a graph of ^{26}Al versus ^{10}Be is not perfectly linear, and the data must be linearized prior to regression of the slope. This is done using an iterative process. First, any postburial production is estimated from the intercept of the regression, and this value is subtracted from measured ^{10}Be concentrations. Then, an initial age estimate from the regression is used to decay-correct ^{10}Be concentrations to their pre-burial values. The initial ^{10}Be values are then used to estimate the ^{26}Al/^{10}Be ratios at the time of burial, and the ^{10}Be values are adjusted to account for lowered ^{26}Al/^{10}Be ratios that occur with slow erosion rates. The age is recalculated, and the process repeated until convergence. For details, see Balco and Rovey (2008). We use the method of York (1966) to calculate the regression of the isochrons and determine the uncertainty in the burial age, but it is

important to realize that the York (1966) method underestimates uncertainty, if the deviation of data about the regression is small. We calculate uncertainty according to measurement data, if the mean square of weighted deviates (MSWD) about the line is less than one.

Burial dating can be contrasted to cosmogenic surface exposure dating, which measures the buildup of cosmogenic nuclides in rocks that are exposed at the surface. In geologically active landscapes such as the western U.S., cosmogenic surface exposure dating tends to yield minimum exposure ages. While exposure dating can be used to date river terraces, the method assumes that there has been zero erosion, and that the terrace has never been covered by additional sediment, such as eolian sands. Surface erosion and burial both effectively reset exposure ages. Thus, exposure ages provide a minimum age for the terrace, and a maximum river incision rate, especially for terraces older than ca. 100 ka (Wolkowinsky and Granger, 2004).

Incision Rate Calculation and Compilation

The rate of erosion of the bedrock channel is the net result of a river cyclically aggrading and then incising through its alluvial cover, consequently eroding the bed and aggrading again.

TABLE 1. INCISION RATES COMPILED THROUGHOUT THE COLORADO RIVER SYSTEM ON THE COLORADO PLATEAU AND COLORADO ROCKIES

Data source	Dating method	Rating	Nearest river	Geographic location	Incision rate	Max. rate	Min. rate	Measured age (Ma)	Error (std. dev., if reported)	Burial depth (m)	Strath height (m)	Elevation	Sample material	Latitude	Longitude	Geochronology notes	Field notes
Aslan and Kirkham, 2007	$^{40}K/^{39}Ar$	2	Gunnison	Flat Top Mountain, Colorado	64	64	64	10	Not reported		640	3078	Basalt	38.683	−106.897		Basalt on river gravel: clasts derived from exposed basement rocks from the Central Rockies.
Aslan et al., 2007; Kunk et al 2002	$^{40}K/^{39}Ar$	1	Colorado	Grand Mesa, Colorado	144	148	141	10.76	0.24 (2 sigma)		1554	2935	Basalt	39.045	−108.215		
Aslan et al., 2008	Tephrochronology	1	Eagle	Eagle, Colorado	100	100	100	0.639	.002 (2 sigma)		64	2100	Ash	39.654	−106.791	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	
Aslan et al., 2008	Tephrochronology	3	Roaring Fork	Carbondale, Colorado	86	86	86	0.639	.002 (2 sigma)		55		Ash	39.395	−107.236	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	This sample is within Eagle Valley evaporite collapse region.
Aslan et al., 2008	Tephrochronology	1	White	Meeker, Colorado	141	141	140	0.639	.002 (2 sigma)		90		Ash	40.066	−108.014	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	
Aslan et al., 2008	Tephrochronology	1	Yampa	Elk Creek, Colorado	102	102	101	0.639	.002 (2 sigma)		65		Ash	40.538	−107.413	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	
Aslan et al., 2010 abstract	Cosmogenic burial	1	Colorado	Unaweep Canyon, Colorado	564	802	435	0.81	0.24 (1 sigma)		457	1884	Drill cuttings	38.858	−108.480	Mean of two burial dates, original result from one sample was reported in Aslan et al., 2007, GSA abstract.	
Berlin et al., 2008	$^{40}Ar/^{39}Ar$	2	Colorado	Battlement Mesa, Colorado	179	180	178	9.16	0.06 (2 sigma)		1640	3200	Basalt	36.386	−107.868	Not sure of source of Ar/Ar data.	Elevations reported here are near the bottom of basalt, rather than the top as reported in the abstract. No river gravel has been reported here.
Berlin et al., 2008	Burial cosmogenic	2	Colorado	Grass Mesa, Colorado	128	214	100	1.77	0.71/0.51	1	227	1860	Quartz-rich cobbles	39.509	−107.786	Single rock collected from eroding surface. Height reported is probably the tread of the alluvial fan complex.	
Brown et al., 2007	Tephrochronology	1	Colorado	Dotsero, Colorado	133	133	133	0.639	.002 (2 sigma)		85	1950	Ash	39.646	−107.058	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	Site has two locations of Lava Creek B ash; one appears to have dropped down by landsliding. Rate is for higher, nonslumped block with ash.
Brown et al., 2007; Kunk et al 2002	$^{40}K/^{39}Ar$	2	Colorado	Little Grand Mesa, Colorado	114	115	113	7.74	0.06 (2 sigma)		884	2652	Basalt	39.575	−107.154		Basalt flows, but no gravel
Brown et al., 2007; Kunk et al., 2002	$^{40}Ar/^{39}Ar$	3	Colorado	Lookout Mountain, Colorado	75	75	75	9.72	0.05 (2 sigma)		730	2500	Basalt	39.542	−107.261		Intact basalt flows and gravel, but evaporite collapsed

(continued)

TABLE 1. INCISION RATES COMPILED THROUGHOUT THE COLORADO RIVER SYSTEM ON THE COLORADO PLATEAU AND COLORADO ROCKIES (continued)

Data source	Dating method	Rating	Nearest river	Geographic location	Incision rate	Max. rate	Min. rate	Measured age (Ma)	Error (std. dev., if reported)	Burial depth (m)	Strath height (m)	Elevation	Sample material	Latitude	Longitude	Geochronology notes	Field notes
Brown et al., 2007; Kunk et al., 2002	$^{40}K/^{39}Ar$	3	Colorado	Spruce Ridge, Colorado	107	108	107	7.8	0.04 (2 sigma)		837	2605	Basalt	39.604	−107.109		Probably debris-flow basalt boulders; reported as in place with channels cut in it by Kirkham et al., 2002
Cole, 2011 USGS Open-File Report	$^{40}Ar/^{39}Ar$	1	N. Fork of Gunnison	Mount Darline, Colorado	171	171	171	10.38			1775		Basalt	39.029	−107.658		Basalt on river gravel: gravel mainly volcaniclastics from West Elk Mountains. Sparse quartzite, granite, and schist clasts likely from Central Rockies.
Cook et al., 2009	$^{26}Al/^{10}Be$ cosmogenic exposure profile	2	Trachyte	Trachyte Creek, Utah	538	1522	327	0.013	0.0084 (1 sigma)		7		Quartz-rich gravel	37.960	−110.592	Very low terrace exaggerates incision rate uncertainty.	Lat./long. location is approximate.
Cook et al., 2009	$^{26}Al/^{10}Be$ cosmogenic exposure profile	2	Trachyte	Trachyte Creek, Utah	348	414	301	0.178	.0283 (1 sigma)		62		Quartz-rich gravel	37.960	−110.592		Lat./long. location is approximate.
Cook et al., 2009	$^{26}Al/^{10}Be$ cosmogenic exposure profile	2	Trachyte	Trachyte Creek, Utah	412	448	381	0.267	.0214 (1 sigma)		110		Quartz-rich gravel	37.960	−110.592	Similar in height and age to Hite (Darling, this volume)	Lat./long. location is approximate.
Cragun, 2007	Optically stimulated luminescence (OSL)	1	Colorado	Lee's Ferry, Arizona	221	221	221	0.077	?		17	985	Sand	36.853	−111.610	Multiple chronology points reported; we chose to report those closest to the strath and report the rate to 380 m³/s water level.	Lat./long. location is approximate.
Cragun, 2007	Optically stimulated luminescence	1	Colorado	Lees Ferry	150	150	150	0.12	?		18	986	Sand	36.853	−111.610	Multiple chronology points reported; we chose to report those closest to the strath in the terrace and report the rate to 380 m³/s water level.	
Cragun, 2007	Optically stimulated luminescence	1	Colorado	Lees Ferry	289	289	289	0.142	?		41	1009	Sand	36.853	−111.610	Multiple chronology points reported; we chose to report those closest to the strath and report the rate to 380 m³/s water level.	Lat./long. location is approximate.
Darling et al., this volume	Isochron cosmogenic burial	1	Green	Tabyago Canyon, Utah	41	44	38	1.48	0.12 (1 sigma)	4	60	1475	Cobbles	39.768	−109.905	Four datapoint isochron; all clasts share a similar burial history.	Abandoned meander. Sample location is a cutbank in an ephemeral channel.
Darling et al., 2009	Tephrochronology	1	Gunnison	Sawmill Mesa, Colorado	150	151	150	0.639	.002 (2 sigma)		96	1571	Ash	38.724	−108.178	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	Weakly preserved ashfall in fine-grained sediment below locally derived gravel. This package is on top of Uncompahgre River-like gravel close to the modern Gunnison River.

(continued)

TABLE 1. INCISION RATES COMPILED THROUGHOUT THE COLORADO RIVER SYSTEM ON THE COLORADO PLATEAU AND COLORADO ROCKIES (*continued*)

Data source	Dating method	Rating	Nearest river	Geographic location	Incision rate	Max. rate	Min. rate	Measured age (Ma)	Error (std. dev., if reported)	Burial depth (m)	Strath height (m)	Elevation	Sample material	Latitude	Longitude	Geochronology notes	Field notes
Darling et al., this volume	Isochron cosmogenic burial	1	Colorado	Bullfrog, Utah	126	138	116	1.50	0.13 (1 sigma)	7	189	1207	Quartz-rich cobbles	37.520	–110.700	Mass wasted scarp yields fresh exposure for sampling. Isochron shows good linearity with six clasts. Region contains relatively vast deposits of river gravel, potentially local streams reworking Canaan Peak gravels as well.	Strath elevation a minimum estimate as strath appears to have relief, reaching ~10–15 m higher elevation. Elevation of river bottom taken from 1921 survey.
Darling et al., this volume	Burial date	3	Colorado	Morrisania Mesa, Colorado	214	671	127	0.44	0.3 (1 sigma)	110	94	1655	Drill cuttings	39.467	–107.989	Nicely shielded; however poor precision. Combining this with other bore-hole samples would be very helpful.	
Darling et al., this volume	Isochron cosmogenic burial	1	Dirty Devil	Hite, Utah	369	892	233	0.29	0.17 (1 sigma)	5	107	1167	Quartz-rich cobbles	37.917	–110.398	Isochron date with several clasts creating a slope near production rate ratio. Indicates little decay has occurred since deposition.	Terrace near the confluence of Dirty Devil and Colorado River. Sample taken from the northerly one of two road cuts.
Darling et al., this volume	Isochron cosmogenic burial	1	Green	Peru Bench, Wyoming	100	133	80	1.20	0.3 (1 sigma)		120	1865	Quartz-rich cobbles	41.587	–109.580	Four-datapoint isochron date, reasonable linearity.	One terrace in a suite of terraces. Cosmogenic samples are from the bottom of a gravel pit.
Darling et al., this volume	Isochron cosmogenic burial	1	Gunnison	Bostwick Park, Colorado	385	515	307	0.87	0.22 (1 sigma)	10+	335	2073	Quartz-rich cobbles	38.494	–107.729	Reported 1960s by Dickenson to include Mesa Falls ash (1.2 Ma). Search by Aslan ca. 2007 failed to find this ash. Cosmo date is younger than Mesa Falls by at least 200 ka at 1 sigma.	10-m-deep river gravel deposited under local gravel that includes Lava Creek B ash.
Davis et al., 2001	Cosmogenic surface	3	Colorado	Bullfrog, Utah	395	405	385	0.479	0.012 (1 sigma)		189		Quartz from surface boulder	37.542	–110.712	Cosmogenic surface date on the same terrace as our Bullfrog date; surface date is 1/3 as old. Tread reported as 204 m above river.	Location approximate; exact sample location was not reported.
Garvin et al., 2005	10Be exposure	2	Colorado	Bridge Canyon, Utah	492	632	403	0.122	0.027 (1 sigma)		60		Boulders	37.070	–110.940	Array of surface ages reported; oldest reported here. Minimum age.	
Garvin et al., 2005	10Be exposure	2	Colorado	"4103" surface, Utah	459	591	375	0.567	0.127 (1 sigma)		260	1251	Boulders	37.120	–110.960	Array of surface ages reported; oldest reported here. Minimum age.	
Garvin et al., 2005	10Be exposure	2	Colorado	Oak Island, Utah	639	825	521	0.266	0.06 (1 sigma)		170	1160	Boulders	37.120	–110.960	Array of surface ages reported; oldest reported here. Minimum age.	

(*continued*)

TABLE 1. INCISION RATES COMPILED THROUGHOUT THE COLORADO RIVER SYSTEM ON THE COLORADO PLATEAU AND COLORADO ROCKIES *(continued)*

Data source	Dating method	Rating	Nearest river	Geographic location	Incision rate	Max. rate	Min. rate	Measured age (Ma)	Error (std. dev., if reported)	Burial depth (m)	Strath height (m)	Elevation	Sample material	Latitude	Longitude	Geochronology notes	Field notes
Aslan et al., 2008	^{26}Al/^{10}Be cosmogenic exposure	2	San Juan	Navajo Mountain, Arizona	500	625	417	0.5	0.1 (1 sigma)		250	1400	Boulder surface	37.123	−110.876	The Cha surface projected toward the river, the top of the canyon walls at 4100 ft. Terrace is heavily eroded.	
Aslan et al., 2008	Tephrochronology	1	Gunnison	Lake Fork, Colorado	95	96	95	0.639	0.002 (2 sigma)		61	2354	Ash	38.448	−107.300	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	
Harden et al., 1985	Paleomagnetism	3	Green	Keg Knoll, Utah	250	571	160	1.6	0.9		400	1620	Pedogenic carbonate	38.548	−110.130	Magnetically reversed material in sediment, only allows the assumption of an age bracket.	
Hidy et al., 2010	Surface profile	1	Colorado	Lees Ferry, Arizona	203	262	173	0.0839			17	985	Quartz-rich cobbles	36.853	−111.610	Dated using Monte Carlo techniques on a shallow depth profile. Deposit is bracketed by 98 ka and 77 ka OSL dates (see Cragun, 2007).	
Izett and Wilcox, 1982	Tephrochronology	1	Green	W. of Pinedale, Wyoming	53	53	53	0.639	0.002 (2 sigma)		34	2234	Ash	42.896	1.000	#2	Elevation of strath different from publication, changed by Aslan during field check. Rate is 67 m/Ma in Izett and Wilcox, 1982.
Izett, 1975; Naeser et al., 1980	Zircon fission track	3	Green	Brown's Park, Utah	14	15	14	9.9	0.4 (?)		140	1768	Ash	40.727	−108.761	Ash in Browns Park	Little Hole Day Use Area 10 km downstream of Flaming Gorge Dam. Details in Counts, 2005, Utah State thesis.
Kunk et al., 2002	^{40}Ar/^{39}Ar	2	Colorado	Basalt Mountain, Colorado	105	106	104	10.49	0.07 (2 sigma)		1102	2870	Basalt	39.409	−106.992		Shield volcano that does not have any known relationship to river gravel.
Kunk et al., 2002	^{40}Ar/^{39}Ar	2	Colorado	Little Baldy Mountain, Colorado	115	116	114	10.38	0.12 (2 sigma)		1192	2900	Basalt	39.425	−107.467		
Kunk et al., 2002	^{40}Ar/^{39}Ar	1	Colorado	Sugar Loaf Mountain, Colorado	88	88	87	15.6	0.09 (2 sigma)		1369	3283	Basalt	39.873	−107.099		Flat Tops Wilderness Area; no river gravel. Slow rate is a function of the old age, prior to incision ~6–10 Ma.
Kunk et al., 2002	^{40}Ar/^{39}Ar	1	Colorado	Sunlight Peak, Colorado	114	117	111	10.14	0.26 (2 sigma)		1158	2926	Basalt	39.413	−107.364		Probably outside of salt collapse; no gravel.
Larson et al., 1975; Aslan et al., 2007	Tephrochronology	1	Colorado	McCoy, Colorado	124	124	123	0.639	0.002 (2 sigma)		79	2103	Ash	39.928	−106.715	Ash age given; deposits are reworked fall deposits presumed to closely postdate fall.	
Luft, 1985	Zircon fission track	3	Green	Goodman Gulch, Utah	6	7	6	8.25	0.7 (?)		52	1683	Ash	40.827	−108.906	Ash in Browns Park Formation	

(continued)

TABLE 1. INCISION RATES COMPILED THROUGHOUT THE COLORADO RIVER SYSTEM ON THE COLORADO PLATEAU AND COLORADO ROCKIES (*continued*)

Data source	Dating method	Rating	Nearest river	Geographic location	Incision rate	Max. rate	Min. rate	Measured age (Ma)	Error (std. dev. if reported)	Burial depth (m)	Strath height (m)	Elevation	Sample material	Latitude	Longitude	Geochronology notes	Field notes
Luft, 1985	Zircon fission track	3	Little Snake	East Boone Draw, Utah	27	30	25	8.6	0.8 (?)		232	1982	Ash	40.641	−108.537	Ash in Browns Park. Not a true incision rate although shows that landscape has not denuded much.	
Marchetti et al., 2005	³He cosmogenic surface exposure	2	Fremont	Ivy Canyon, Utah	258	310	221	0.6	0.1 (1 sigma)		155	2565	Boulder surface	38.555	−111.591	Detailed chronology notes in Marchetti et al., 2005.	
Munroe et al., 2005	Tephrochronology	2	Green	Browns Park, Utah	102	102	101	0.639	0.002 (2 sigma)		65	1685	Ash	40.913	−109.305	Ash age given; deposits presumed to closely postdate fall.	Preserved in large outwash gravel deposit. Lat./long. location is approximate.
Patton et al., 1991	Tephrochronology	1	Animas	Durango, Colorado	297	298	296	0.639	0.002 (2 sigma)		190		Ash	37.217	−107.847	Detailed chronology notes in Marchetti et al., 2005.	Lat./long. location is approximate.
Repka et al., 1997	²⁶Al/¹⁰Be cosmogenic exposure profile	2	Fremont	Caineville Plateau, Utah	333	392	290	0.06	0.009 (1 sigma)		20		Quartz-rich gravel	38.348	−110.985		Lat./long. location is approximate.
Repka et al., 1997	²⁶Al/¹⁰Be cosmogenic exposure profile	2	Fremont	Caineville Plateau, Utah	861	1024	743	0.151	0.024 (1 sigma)		130		Quartz-rich gravel	38.348	−110.985		
Sandoval, 2007	Tephrochronology	1	Gunnison	Redrock Canyon, Colorado	509	510	507	0.639	0.002 (2 sigma)		325	2000	Ash	38.594	−107.787		
Willis and Biek, 2001; Aslan et al., 2008	Tephrochronology	1	Colorado	Westwater Creek, Utah	164	165	164	0.639	0.002 (2 sigma)		105	1426	Ash	39.226	−109.184	Ash age given; deposits presumed to closely postdate fall.	Ash deposit is upstream in Westwater Creek, on a hill in a pediment deposit. Erosional surface is extrapolated toward the river.
Winkler, 1970; Damon, 1970	⁴⁰K/³⁹Ar	3	Green	Jesse Ewing Canyon, Wyoming	4	4	4	11.8	0.4		49	1708	Ash	40.912	−109.148	Ash in Browns Park	
Wolkowinsky and Granger, 2004	Cosmogenic burial	1	San Juan	Bluff, Utah	110	124	96	1.36	0.15/0.2 (1 sigma)		150	1450	Quartz-rich cobbles	37.293	−109.545	Gravel quarry dated with a burial profile.	

Note: We sort the data by author and then nearest river and then geographic location. The qualitative assessment of reliability ranked 1 through 3, 1 being most reliable based on analytical uncertainty and uncertainty in geologic context.

Therefore, the rates inferred from dates of bedrock strath formation proxies yield an average rate of change of the bedrock, which filters short-term climate oscillations and can be associated with rock uplift in steady-state erosion conditions (Whipple and Tucker, 1999). Bedrock incision rates can be calculated from a single dated strath, if depth to modern bedrock can be estimated (e.g., Burbank et al., 1996; Pederson et al., 2002a; Karlstrom et al., 2007). If multiple datable strath terraces are present, a preferred method is to calculate variation in incision rates through time using strath-to-strath comparisons (Pederson et al., 2006; Karlstrom et al., 2007). Because of the difficulty in obtaining age control on preserved deposits that doesn't violate any critical assumptions, most published incision rates rely on a single dated deposit. In addition, because average river depth and (especially) depth to bedrock are rarely known, strath heights are commonly reported relative to the modern river (usually the water level shown on U.S. Geological Survey [USGS] maps). The Bureau of Reclamation has used mid-channel drilling to assess dam-site feasibility. The depth to bedrock provided by these data is valuable for incision rate calculations where available; however, drilling data are very limited on the Colorado and tributaries, precluding reach-to-reach comparisons of bedrock depth. Drilling data combined with sonar sounding studies (which measures only water depth) suggest that bedrock is commonly on the order of ~10 m below the river surface, but can be 30 m or more (e.g., Miser, 1924; Woolley, 1930; Hanks and Webb, 2006; Karlstrom et al., 2007). For the purposes of this paper, however, and comparison with published incision rate data, Table 1 reports terrace height as calculated from the difference in elevation between a strath and the water surface of the nearest river. Hence, reported incision rates are underestimates of bedrock incision rates, but at the long timescales of most of our ages (1–3 Ma), this is only a small (~10%) underestimate.

The compilation in Table 1 reports incision rates as a range based on the maximum and minimum date reported for each date where available. Geologic uncertainty such as the amount of time between strath development and deposition of overlying datable sediment is often unknown. To address this source of error, we apply a relative quality rating ("1"–"3") for incision rate data, where "1" is most reliable. The quality rating is based on the following criteria: methods that date material directly associated with the fluvial system (e.g., analytically precise burial dates, interfingered lava flows, and fluvial gravel) are reported as reliable ("1").

Certain rates are analytically or geologically uncertain and rated "2" or "3" depending on degree of perceived or quantified uncertainty. Chronology points from the literature (such as basalt dates) that do not have direct field relationships to river gravel are less reliable and are not necessarily reported in this compilation. We report some rates as "apparent incision rates" in central Colorado because of numerous locations where basalt flows and gravel deposits are offset by normal faults activated by salt dissolution and/or deformation (Kirkham et al., 2002). Locally faulted incision rates are considered low ("3") quality rates for the purpose of understanding regional bedrock incision patterns (the focus of this study); however, the dated deposits can yield fault-slip rates calculated from apparent incision rates (Pederson et al., 2002a; Karlstrom et al., 2007).

RESULTS

Incision rate estimates presented here are organized within regional context. Incision data reported and compiled in this paper are plotted for both short-term (<1 Ma) and long-term (>1 Ma) time frames (Figs. 3 and 4, respectively). Rates determined from dates that are less than ca. 200 ka may reveal complex patterns due to glacial oscillations that alter incision rate (Hancock and Anderson, 2002; Pan et al., 2003); hence, we concentrate on longer-term bedrock incision.

Uncertainties and Empirical Evaluation of the Isochron Method

One of the disadvantages of cosmogenic burial dates is their large analytical uncertainties. In addition, there are also uncertainties about the geologic history of the gravels. Many of the isochrons presented below are strongly leveraged by a single point that happened to have relatively high ^{10}Be and ^{26}Al concentrations. There is nothing inherently suspect about these points, but for all of the clasts, there is a small but significant possibility that they have been reworked from a paleoterrace and hence have compound histories involving multiple phases of production and burial (e.g., Hu et al., 2011). If this is the case, then one would expect that the reworked clast would lie below the isochron defined by the other samples. It is thus helpful to have as many single clasts analyzed as possible. On the other hand, cosmogenic nuclide analyses are expensive and time consuming, placing a practical limit on the number of samples in any given isochron. We chose to analyze four to seven individual clasts from each terrace. Additional samples would likely improve the dating, and can be done in future work. At present, we interpret the results as the best available ages on the terraces and attempt to place the new ages in the context of incision rates obtained by other methods.

As an empirical test of this method, one of our samples was taken from Bostwick Park, Colorado, where fluvial gravels contain a deposit of Lava Creek B ash (Figs. 2 and 5). More detailed discussion of the geology at Bostwick Park is in Sandoval (2007) and Sandoval et al. (2011) with an overview in Aslan et al. (2008). At this site, ~10 m of channel gravel was deposited by a paleotributary to the Gunnison River within a confined valley. The paleotributary was captured and the channel abandoned such that the river gravel is overlain by tens of meters of locally derived gravel and sand that, near their base, contain layers of reworked Lava Creek B ash (639 ± 2 ka; Lanphere et al., 2002). Approximately 10 m stratigraphically below Lava Creek B ash (exposed in a gravel pit, Fig. 5), several quartzite clasts were collected and analyzed using the cosmogenic isochron method for burial dating. The isochron estimated age for deposition of the gravel is 870 ± 220 ka. The slope of the line for this isochron is controlled by the ^{26}Al/^{10}Be concentrations from one clast, while the other data are clustered (Fig. 6). Geologic relationships suggest the basal gravels must predate 0.64 Ma by an unknown duration such that the 870 ± 220 ka burial age is a reasonable, albeit imprecise, estimate for the basal Bostwick gravel and hence a positive empirical test for the isochron technique.

Glen Canyon Burial Dates

Two samples were taken from upstream of Lees Ferry at Bullfrog Bay and Hite Crossing, ~50 km apart, in Glen Canyon (Fig. 1). These sites were analyzed with the isochron technique due to relatively shallow burial (7 m and 5 m, respectively; Table 1). At Bullfrog, we sampled a large gravel deposit ~4 km north of the modern river with a somewhat complex and debated geologic history. As visible in Figure 7A, the deposit is interbedded gravel and fine-grained sediment. Much of this fine material is probably from local streams (e.g., paleo–Bullfrog Creek). We interpret the extensive gravel deposit to indicate a temporarily aggrading condition in the Colorado River that caused the river and tributaries to backfill a few tens of meters at most. There are two possible sources for far-traveled quartzite (much of the coarse fraction): the Colorado River and/or clasts eroding out of the Cretaceous–Paleocene Canaan Peak Formation (T.C. Hanks, 2011, personal commun.) to the north and brought down along the paleo–Bullfrog Creek. The river and streams in this area shared a common base level, meaning that if the main stem changed incision rate, the tributaries would respond directly. Therefore, data from the clasts yield information on Colorado River incision regardless of clast source area. The nuclide inventories in the gravel are dependent on the duration of burial of the clasts and the paleoerosion rate, both of which can be solved for using the ^{26}Al/^{10}Be nuclide pairs, if the nuclides are detectable. Thus, dating the deposit at Bullfrog provides a constraint on the history and timing of incision along the main-stem Colorado River.

The Bullfrog terrace has a strath ~190 m above the pre–Glen Canyon Dam river elevation (Birdseye et al., 1922) and a tread ~204 m above the river. Gravel exposed at the base of one landslide scarp (suggesting very recent exposure) was sampled (depth of ~7 m; Fig. 7) for burial dating and analyzed using the isochron technique. Six cobbles of quartzite were collected, and each cobble was analyzed separately. The sampling locality was estimated to be within a few meters (<3 m) of the bedrock strath, which was not exposed. Five points yielded ^{26}Al/^{10}Be ratios with errors less than 10% and produced an isochron cosmogenic burial date of 1.5 ± 0.13 Ma (Fig. 6). The sixth sample did not yield ^{26}Al data and was therefore not included in the analysis. All five samples lie within error of the regressed line and therefore have a shared burial history. There is a small but statistically significant amount of postburial production, indicated by the intercept. The resulting incision rate is 126 +12/–10 m/Ma (Table 1). The terrace tread (204 m above the river) was previously dated with a cosmogenic surface date of 479 ± 12 ka (Davis et al., 2001; Table 1), yielding apparent incision rates higher by a factor of three. The surface data may differ because of two possibilities. Either the deposit represents ~1 Ma of stability or aggradation on the Colorado and its graded tributaries, or the surface date is biased by erosion and resetting of the exposure age.

The Hite Crossing terrace exposure is a roadcut along Highway 95 (Fig. 1). The current exposure is vertically shielded ~5 m (Fig. 7B). The sample at Hite consists of seven analyzed clasts. Six clasts lie on a clearly defined isochron, with the seventh well below the line and inferred to be reworked (Fig. 6). The isochron yields a very young burial age of 0.29 ± 0.17 Ma. In this case, we limit the isochron to have a positive intercept, and there is no evidence for significant postburial production.
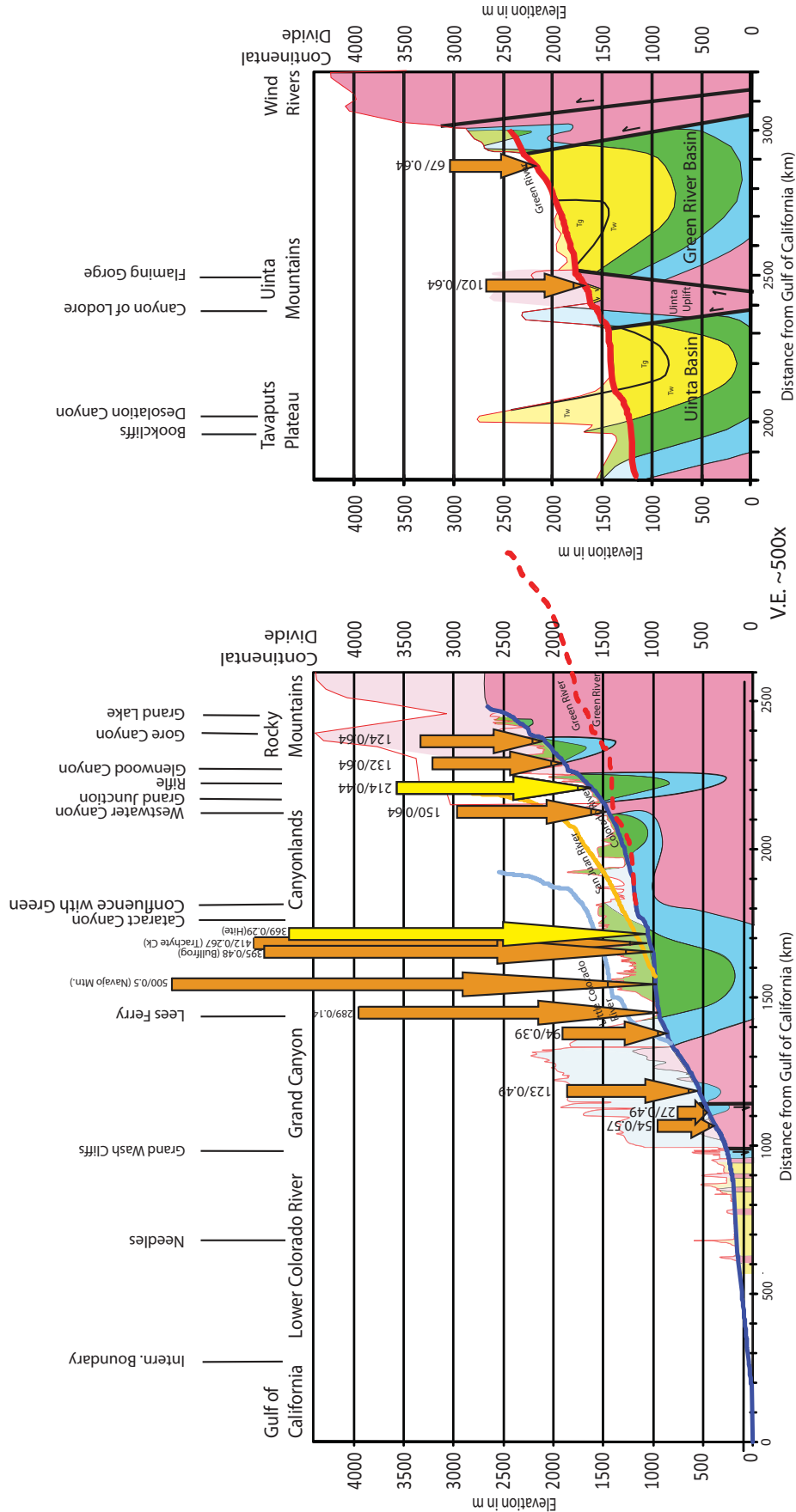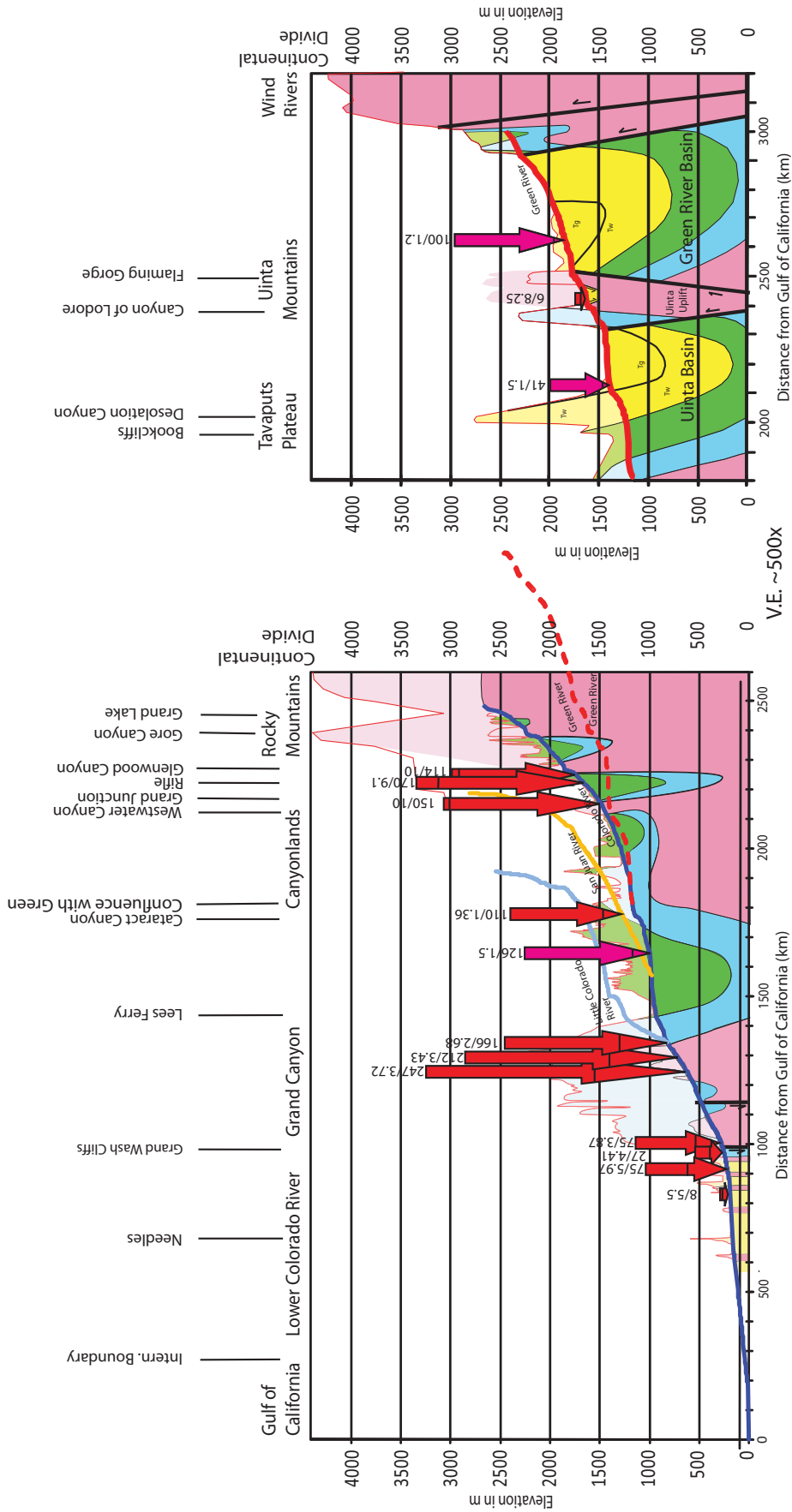
Figure 3. Short-term rates on longitudinal profiles of the Colorado (left panel) and Green (right panel) rivers with schematic bedrock geology and canyon names. Vertical exaggeration (V.E.) 500x. Yellow—Tertiary sedimentary rocks; green—Mesozoic sedimentary rocks; blue—Paleozoic sedimentary rocks; pink—Precambrian igneous and metamorphic rocks. Compiled short-term (less than 1 Ma) incision rates (including new data points); orange arrows—previous publication; yellow arrows—this publication. Arrows are proportional to rate magnitude; horizontal bars within arrows represent strath elevation of dated terraces. Numbers indicate rate and date of the deposit (i.e., rate/date = 369/0.29 for the new Hite date). Vector length: 1 km; elevation change = 100 m/Ma.

Figure 4. Long-term rates on longitudinal profiles of the Colorado (left panel) and Green (right panel) rivers with schematic bedrock geology and canyon names. Vertical exaggeration (V.E.) ~500x. Yellow—Tertiary sedimentary rocks; green—Mesozoic sedimentary rocks; blue—Paleozoic sedimentary rocks; pink—Precambrian igneous and metamorphic rocks. Compiled long-term (greater than 1 Ma) incision rates (including new data points); red arrows—previously published; purple arrows—this publication. Arrows are proportional to rate magnitude; horizontal bars within arrows represent strath elevation of dated terraces. Numbers indicate mean rate and date of the deposit (i.e., rate/date = 126/1.5 for the new Hite date). Vector length: 1 km; elevation change = 100 m/Ma.

Figure 5. Photograph of Bostwick Park, near Black Canyon of the Gunnison, western Colorado (photo by L. Crossey). Strath is the base of the gravel pit. Approximately 10 m of fluvial gravel rest below the white band of Lava Creek B ash (Sandoval, 2007).
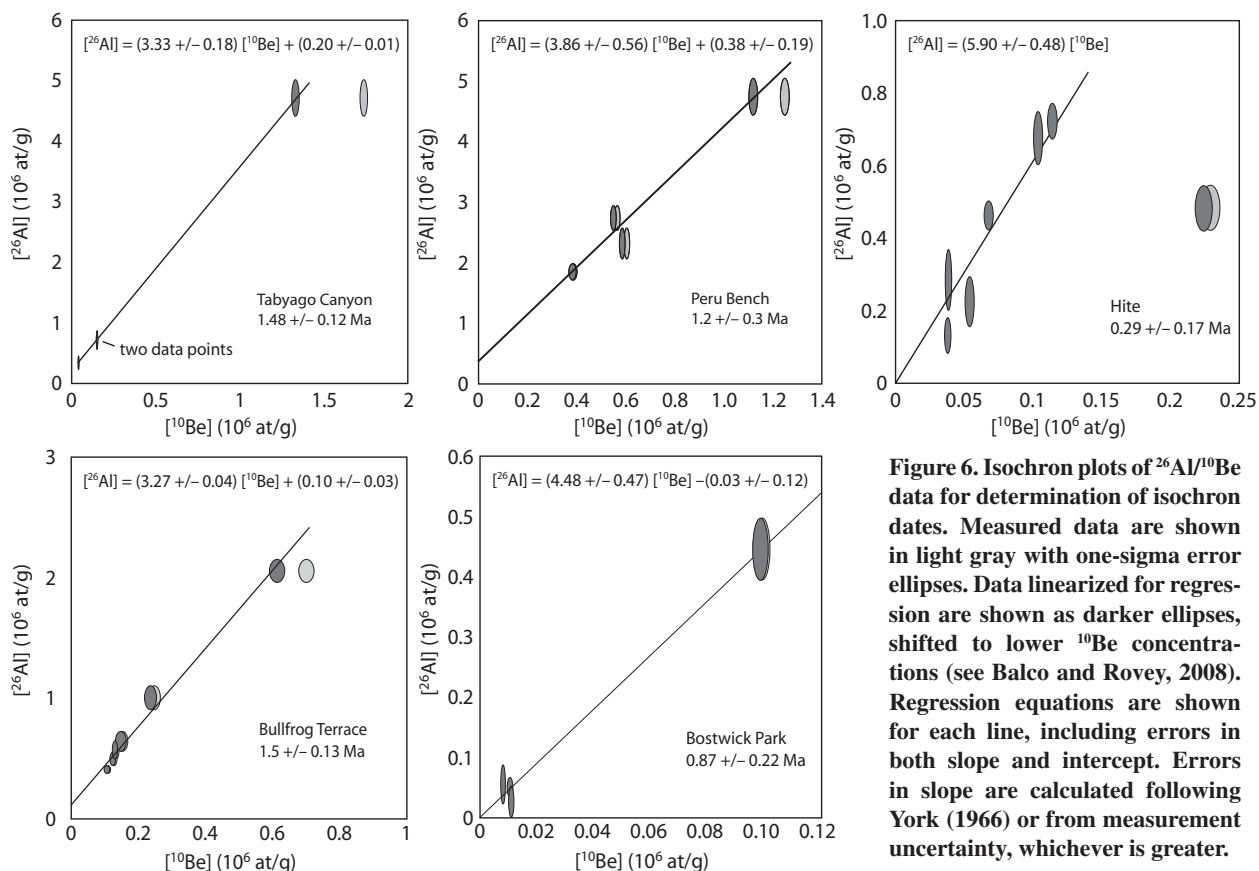
Figure 6. Isochron plots of ^{26}Al/^{10}Be data for determination of isochron dates. Measured data are shown in light gray with one-sigma error ellipses. Data linearized for regression are shown as darker ellipses, shifted to lower ^{10}Be concentrations (see Balco and Rovey, 2008). Regression equations are shown for each line, including errors in both slope and intercept. Errors in slope are calculated following York (1966) or from measurement uncertainty, whichever is greater.

Figure 7. (A) Photograph of Bullfrog sampling site (photo by L. Crossey). View is to the south-southwest. Navajo Mountain is in the background. Interbedded gravel and fine-grained material are exposed below a protective calcrete soil horizon. (B) Photo taken near Hite Crossing in a roadcut above the Dirty Devil River. Gravel is composed mostly of Mesozoic sedimentary rocks, moderately imbricated to the right in photo (photo by S. Blessing).
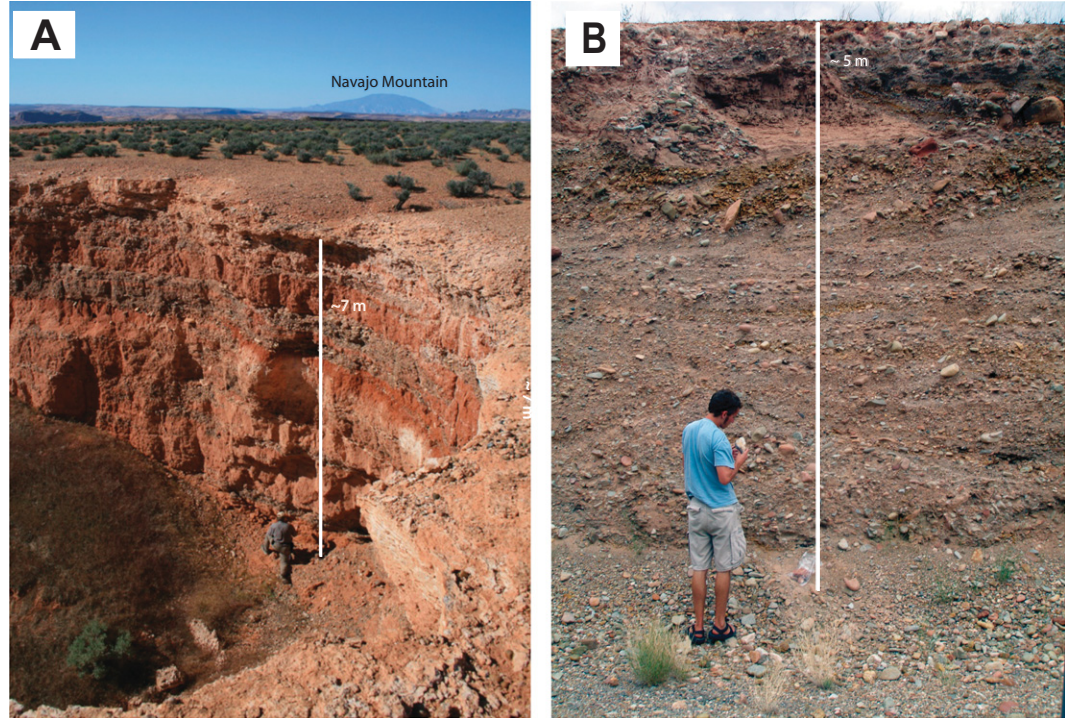
No postburial production may seem surprising for a shallow deposit. However, short burial time reduces the likelihood of measureable postburial nuclides. Since this terrace rests 107 m above the confluence of the Dirty Devil and the Colorado River, the imprecise date implies a relatively high rate of incision of 300–900 m/Ma (Table 1).

Comparing the Upper Colorado and Green Rivers

The upper Colorado River has been a fluvial system for at least 11 million years (e.g., Aslan et al., 2010), but the evidence for the early Green River is less well known (see Geologic Background section). For instance, have the rivers evolved with similar or different controlling parameters? Incision of the Colorado and Green rivers is marked by extensive erosion, leaving a sparse record to explore these parameters. In the following sections, we compare what is known of the Green and upper Colorado rivers to resolve the first-order controls on the development of these systems.

Figure 8. Plot of age versus height above the river for samples near Rifle, Colorado, for four incision rate markers and the modern river. All locations except Grand Mesa are along a 50 km stretch in which the river drops ~130 m. Grand Mesa is an important regional reference ~50 km downstream from westernmost Morrisania Mesa. Heights of terrace straths that are currently undated are shown as red lines. The data for this plot are listed in Table 1 for samples from Battlement, Grand, Grass, and Morrisania mesas. Current data show apparent semi-steady long-term average rates of incision in this region but need improved chronology.
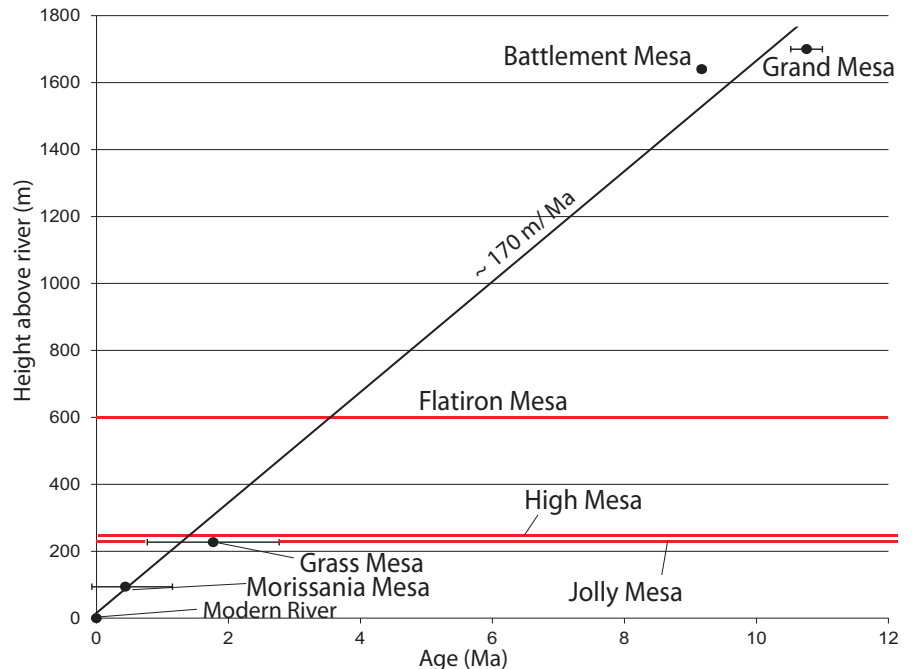
Burial Dating Results—Morrisania Mesa

Existing incision rate data from western Colorado show rates of ~150 m/Ma from both 640 ka and 10 Ma time markers (Darling et al., 2009; Aslan et al., 2008, 2010). To fill in the gap in these timescales, we collected a cosmogenic burial sample from near Rifle, Colorado (Fig. 1). At Rifle, an extensive series of alluvial fan remnants are preserved along the northern flank of Battlement Mesa (Fig. 1). These deposits represent ancient alluvial fan and/or pediment complexes that are comprised of locally sourced, coarse colluvium and debris-flow deposits that locally bury Colorado River gravel deposits (Stover, 1993). Substantial oil and gas drilling activity has led to numerous drill holes that pierce these high abandoned terraces and alluvial fans. Morrisania Mesa is one alluvial fan complex on the north flank of Battlement Mesa. This site provided ideal shielding for a simple burial date from an amalgamation of quartz-rich drill-hole cuttings 94 m above the river. Our sample contained fragments of Colorado River gravel from a well-shielded depth of 110 m.

Despite the ideal sample setting, this sample yielded an imprecise burial age of 440 ka ± 300 ka (Table 1) due to a low $^{26}Al/^{27}Al$ ratio.

Thus, the incision rate at Morrisania Mesa is poorly constrained; the average incision rate is 214 m/Ma, but the uncertainty of incision rate ranges from 127 to 671 m/Ma (Table 1). A future research goal beyond this paper in this and other reaches is to establish variability of incision rates through time in this and other reaches of the Colorado River system. All available incision rate data in this area (Fig. 8) show a semi-linear array suggesting a steady incision rate of 170 m/Ma from the 10 Ma basalt flows on Grand Mesa to the younger cosmogenically dated Colorado River deposits. Although the data are indistinguishable from constant steady state, the data are sparse enough that diverse incision histories would also be consistent with the data. Several other terraces buried by alluvial fans exist in this region. Berlin et al. (2008) dated sediments beneath Grass Mesa at a height of 227 m above the Colorado River and reported a date of 1.77 +0.71/–0.51 Ma, which also yields an incision rate between 92 and 180 m/Ma. More chronology may reveal incision rate changes after 10 Ma; however, the simplest scenario, weighted with other rates from western Colorado, is semi-steady incision along this stretch of the Colorado River at ~150 m/Ma (Willis and Biek, 2001; Aslan et al., 2008; Darling et al., 2009; Aslan et al., 2010; Table 1).

Green River Burial Dates

Desolation Canyon represents a knickzone on the Green River (Figs. 1 and 2) as it cuts through the Tavaputs Plateau, which separates the Uinta Basin from the Canyonlands region. Near the upstream end of Desolation Canyon is Tabyago Canyon, which contains a large entrenched Green River meander with a thin but laterally continuous gravel deposit (Fig. 9) that is overlain by locally derived colluvial material. The strath surface is cut into the shale and thin fine-sandstone beds of the Green River Formation ~60 m above the present day level of the Green River. Recent erosion in an ephemeral tributary cut bank exposed an outcrop of river gravel (Fig. 10). Further excavation by hand allowed us to sample clasts just above the strath surface. Burial depth of the sample was only ~4 m below the surface, and the upper 0.5 m of this terrace consisted of reworked locally derived slope wash and colluvial material. The colluvial wedge of the deposits is deeper nearby and suggests the sample site was deeper in the past. Approximately 3.5 m of gravel with primary sedimentary structures is preserved in the deposit, and thus the majority of the gravel is not reworked. AMS results for four clasts (Fig. 6) yielded an isochron burial date of 1.48 ± 0.12 Ma for this terrace. Concentrations for one
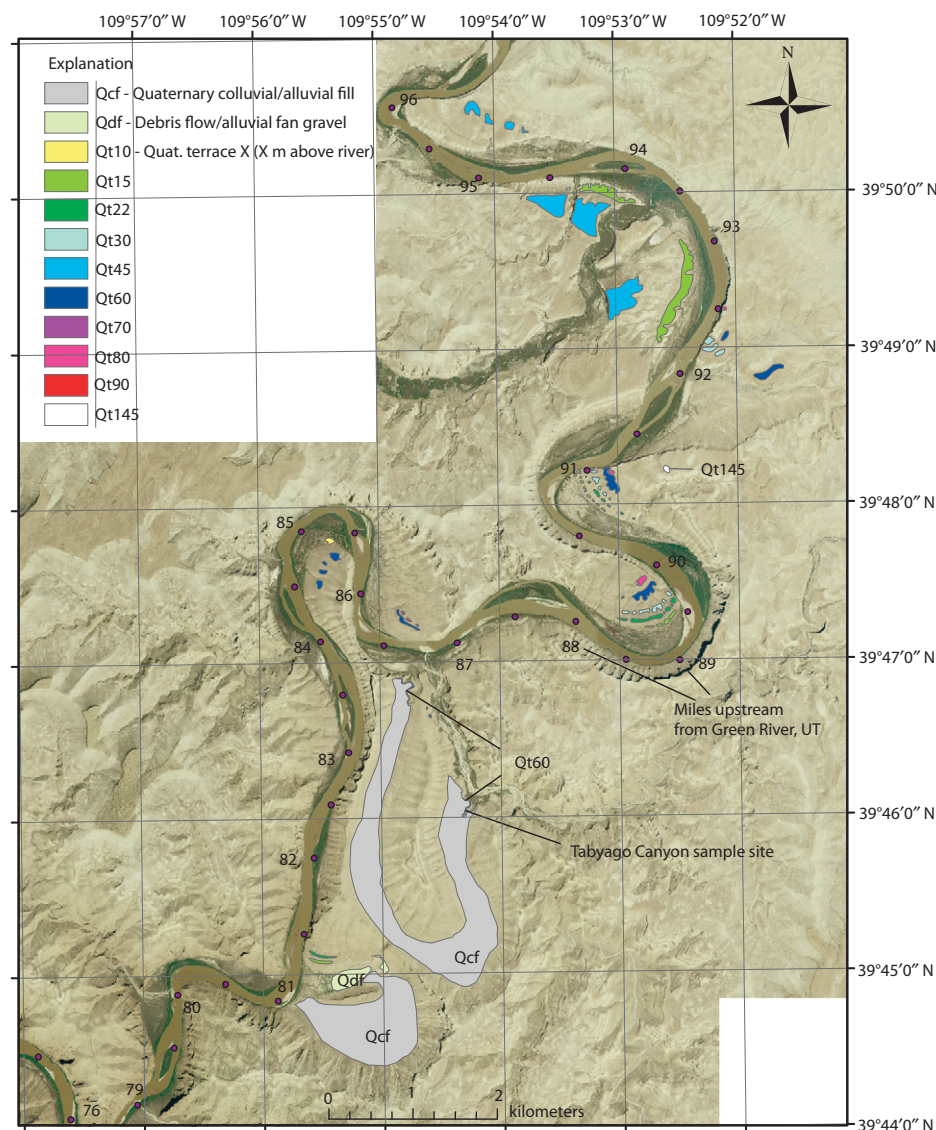

Figure 9. Map of Pliocene–Pleistocene terraces throughout Desolation Canyon. Sample location for new burial date for Tabyago Canyon is shown. Heights to terraces were measured with a laser range finder. Abandoned meanders and point bar deposition have punctuated canyon incision.

sample are very high, indicating slow erosion prior to burial. The intercept indicates some postburial production, as expected. From these data, we estimate an average incision rate of 41 ± 3 m/Ma (Fig. 4).

Peru Bench, located in the Green River Basin near Green River, Wyoming, represents a flight of Green River terraces that are up to 180 m above the river (Figs. 1 and 11; Hansen, 1986). These gravels are deposited on siltstone deposits of the Green River Formation. The sampled terrace on Peru Bench is 120 m above the river and was sampled in a gravel pit (Fig. 12). The pit exposed ~3 m of imbricated sandy pebble- to cobble-sized gravel overlain by a ~1 m thick calcic soil with stage III carbonate development. Clast types include quartzite from the Proterozoic Uinta Mountain Group, granite from the Wind River Mountains, and sparse black chert typical of far-traveled Green River gravels. The sample depth was 4 m. The $^{26}Al/^{10}Be$ ratios from four clasts lie on an isochron with no outliers, indicating a common burial history for all of the clasts (Fig. 6). Uncertainty in ^{26}Al concentrations leads to a higher uncertainty in this isochron fit than for the Tabyago Canyon sample. Postburial production at Peru Bench was significant, due to the very shallow burial depth. The isochron analysis indicates a date of 1.2 ± 0.3 Ma (Peru Bench; Table 1 and Fig. 1). This terrace date yields an average incision rate of 100 +33/–20 m/Ma (Fig. 4). This rate is compatible with an incision rate of 90–115 m/Ma from a Lava Creek B ash site on a Green River terrace in western Browns Park (Munroe et al., 2005; Counts, 2005), but it is faster than a terrace in the Green River Basin, Wyoming, that is 52–67 m/Ma over the past 640 ka based on Lava Creek B ash reported by Izett and Wilcox (1982). The Lava Creek B sites of Izett and Wilcox (1982) are not affected by faulting that may have been active in Browns Park, and the relationships between ash, straths, and river are more obvious; thus it is a more robust measure of incision. Therefore, our data and that of Izett and Wilcox (1982) show the incision rate of the upper third of the Green River to range from 50 to 100 m/Ma.
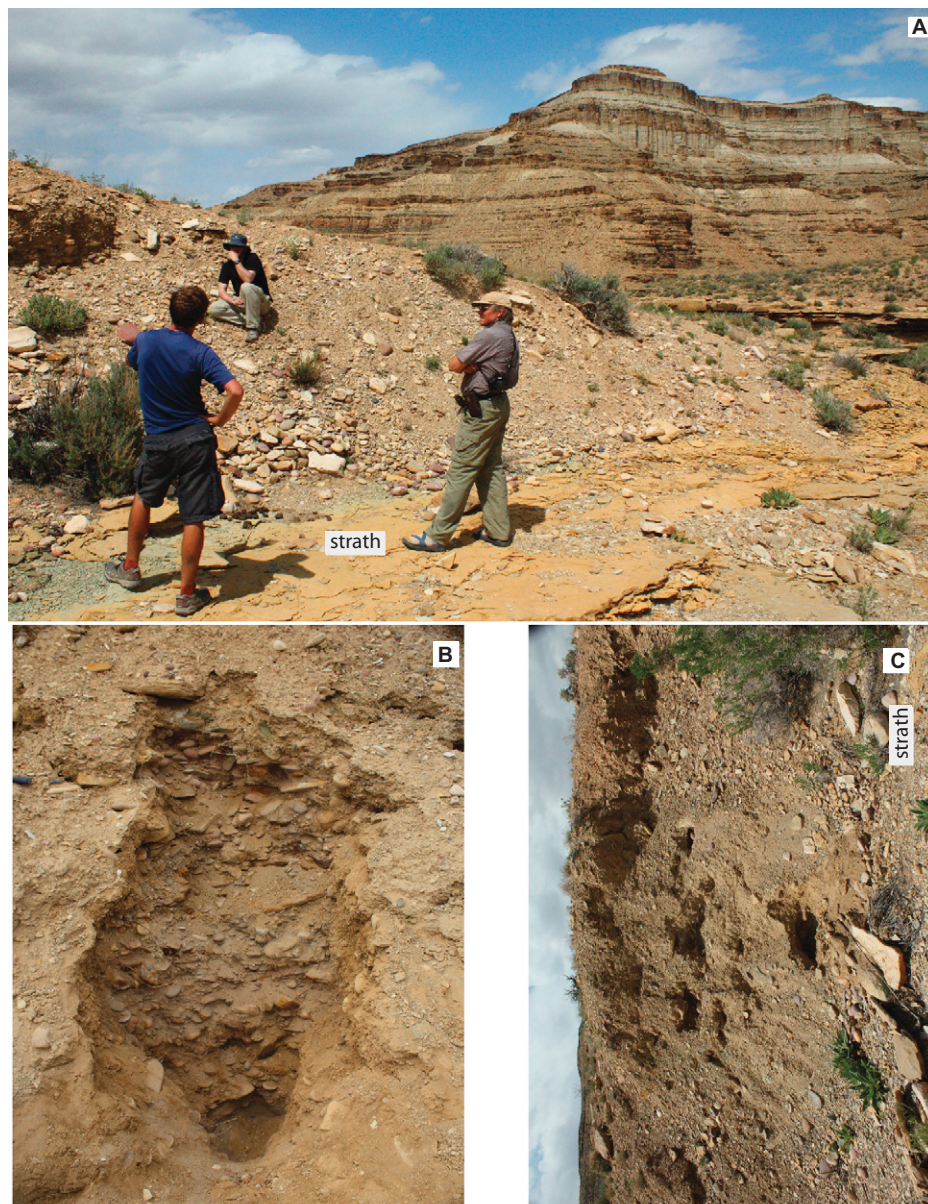

Figure 10. Collage of photos from Tabyago Canyon sample from Desolation Canyon. (A) Deposits in a meander bend in ephemeral stream that was excavated. (B) Pit excavated for burial samples; dated cobbles were taken from the bottom of the hole, ~4 m below the surface of the terrace. (C) Photo of the cut bank; excavation of the pit is started in lower center (photos by Ryan Crow).

DISCUSSION AND IMPLICATIONS

Grand and Glen Canyon Compilation Results

Long-Term Incision Patterns

The long-term incision rates of the Colorado River appear to exhibit spatial differences in incision rates across the Lees Ferry knickpoint. Incision rates in eastern Grand Canyon are on the order of ~170–230 m/Ma (Fig. 4; Pederson et al., 2002a; Polyak et al., 2008; Karlstrom et al., 2008), whereas rates upstream of Lees Ferry appear to be ~110–130 m/Ma (Fig. 4; Wolkowinsky and Granger, 2004; this paper). Although some of these data from eastern Grand Canyon are measured over timescales of 10^5 ka (e.g., Pederson et al., 2002a), and may be subject to short-term variations in incision and/or aggradation driven by climate cycles, other data are averaged over 2–3 Ma (e.g., Polyak et al., 2008). Karlstrom et al. (2008) showed that both Quaternary rates and post–3–4 Ma rates are similar and suggest semi-steady incision over the past 3–4 Ma. Because these data average similar timescales as our new estimates of incision rate above Lees Ferry (Fig. 4), we suggest the data reveal a robust pattern of higher average incision rates below the knickpoint.

Global climate change in the Pleistocene (since ca. 2 Ma) is marked by an increase in climatic variability as recorded in the magnitude and frequency of polar ice variation recorded

in δ¹⁸O (e.g., Lisiecki and Raymo, 2005). How and whether these cycles are expressed in the efficiency of fluvial systems on the Colorado Plateau is not clear. Globally, the onset of Plio-Pleistocene climates has been suggested to have increased erosional efficiency due to increased climate variability since ca. 2–4 Ma (e.g., Zhang et al., 2001), although this conclusion has been strongly challenged recently (Willenbring and von Blanckenburg, 2010). Chapin (2008) suggests that the onset of monsoonal variability in late Miocene time beginning ca. 6 Ma (see fig. 3, Chapin, 2008) could have contributed to an increase in exhumation rates. Sediment derived from the Colorado River delta in the Salton Trough has an average accumulation rate of 2–3 mm/a from Pleistocene–Holocene data and an average of 1.9–2.3 mm/a throughout 5.3 Ma of deposition (Dorsey, 2010 and references therein). These data do not show a bulk difference in deposition rate in the delta (but may still average across short-term variations in rate). From these studies, it is probable that the effect of climate on erosion rate was either an increase or negligible change in erosion rate on the Colorado Plateau in the past 2–6 Ma.

Here, we consider whether a climate change can result in a false positive test for transient incision. If we consider the influence of changing erosional efficiency through time, it is possible that differences in the timescale over which the data average incision rate can affect the pattern of incision rates. The time frame of our data at Bullfrog (~1.5 Ma) and that from Polyak et al. (2008), ~3 Ma, bracket the beginning of the Pleistocene. If the onset of Pleistocene climate was associated with more efficient erosion, then average measures of incision that span this transition would be artificially lower than those measured within the Quaternary. This would only enhance the spatial difference between rates measured across the Lees Ferry knickpoint. In fact, only for a decrease in erosional efficiency, and a corresponding reduction in incision rates, would climatic modulation of erosion rate lead to a spurious, false-positive result. Thus, although we cannot at present rule out the possibility that the observed differences in erosion rate across the Lees Ferry knickpoint are an artifact of climate change, we find this to be unlikely. The simpler interpretation is that high rates of incision downstream of the knickpoint reflect sustained, upstream migration of this feature (cf. Cook et al., 2009).

Short-Term Incision Patterns

Previous studies of incision in the Glen Canyon region have suggested incision rates as high as 500 m/Ma based on surface exposure dating of clasts on terrace treads and optically stimu-
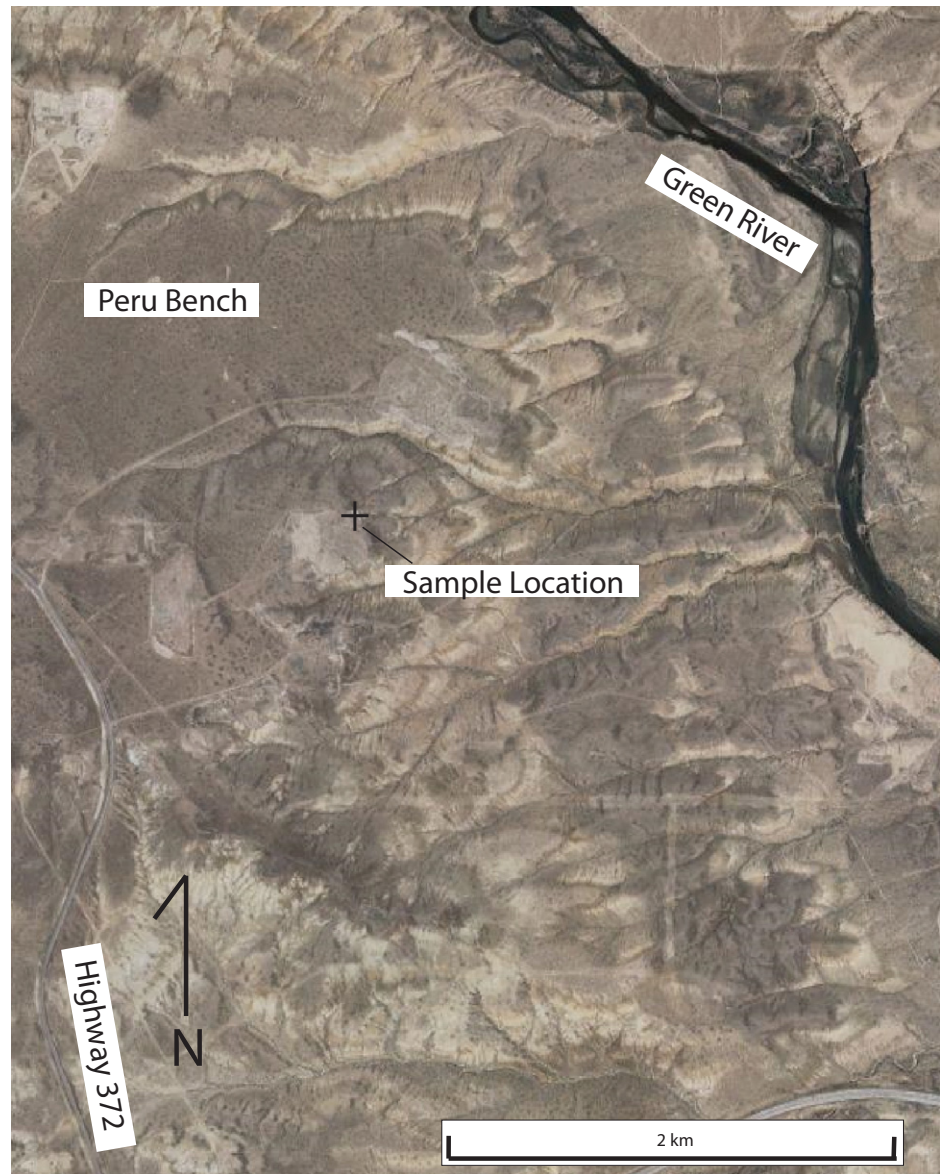

Figure 11. Location map of sample taken on Green River terrace on Peru Bench along the Green River, north of the town of Green River, Wyoming.

lated luminescence (OSL) dating of terrace fill (Table 1; Fig. 13A; Davis et al., 2001; Hanks et al., 2001; Garvin et al., 2005; Cragun, 2007; Cook et al., 2009; Hanks et al., 2011). The surface exposure dates may be subject to bias that arises from the history of erosion and deposition on the surface, including transient eolian cover and/or denudation of the surface. To reconcile the contradictory dates for the Bullfrog terrace, we infer that the previously published exposure date of the deposit underestimates the depositional age of the Bullfrog gravels and the age of the bedrock strath. Further, the Bullfrog burial date reported here is consistent with the data from Bluff in Wolkowinsky and Granger (2004).

The surface exposure dates in the literature (e.g., Garvin et al., 2005) inherently date final deposition (if zero erosion) and not the bedrock strath. If future data can show roughly continual, slow deposition from 1.5 to 0.5 Ma in the Bullfrog terrace, then the surface dates on high elevation terraces may be accurate. However, bedrock incision rate estimates would not be affected.

The incision rates of Glen Canyon are plotted as age versus height above the river in Figure 13B. The bedrock incision rate is estimated to be within the gray bar defined by the older burial dates and the younger exposure and burial dates from terraces at most ~100 m above the river. The data in Figure 13B include terraces

Figure 12. Photograph of Peru Bench sample location in a gravel pit. Strath is exposed along the bottom of the photo. Gravel is 3.8 m deep (photo by A. Aslan).

within Glen Canyon (Davis et al., 2001; Hanks et al., 2001; Garvin et al., 2005), at Lees Ferry (Cragun, 2007; Hidy et al., 2010) and along Trachyte Creek (Fig. 1; Cook et al., 2009). Four high elevation dates are outside of the gray bar. These dates are the surface exposure dates of Bullfrog (Davis et al., 2001) and other high surfaces in Garvin et al. (2005) and Hanks et al. (2001). Readers will note the roughly linear trend the surface exposure dates have produced in past work, and that the oldest of these produce a maximum age that does not vary with elevation ("4103," Navajo and Bullfrog surface dates). Previous paragraphs discuss possible explanations for divergence of burial dates and surface dates, and the more likely implication in our estimation is that surface dates are minimum age estimates in older terraces. The maximum ages achieved in the three highest terraces imply a limit in the exposure ages, leaving the data uninterpretable, and that a general positive trend in high terraces matching lower ones is coincidental. The data sets in Fig 13B are summarized in the long profile of Figure 13A, except the small Trachyte Creek for simplification. Cragun (2007) used OSL dating of terraces at Lees Ferry with straths at most 41 m above the river, and obtained incision rates that varied ~300 m/Ma (summarized in Table 1). Trachyte Creek terraces are cosmogenic surface dates from Cook et al. (2009) with the highest terrace

110 m above the river. These dates imply consistent high incision rates within Glen Canyon from three independent techniques (cosmogenic surface and burial; OSL), and they bracket the rate change in time and space.

We note that the recent numerical study of Cook et al. (2009) suggests that the knickpoint at Lees Ferry reflects the interaction of a transient knickpoint and a dipping contrast in lithologic strength between the Kaibab Limestone and the softer Mesozoic rocks above the knickpoint. This hypothesis is compatible with the incision rate acceleration in Figure 13B through Glen Canyon (Hanks et al., 2001; Garvin et al., 2005), which may be affecting the Fremont River (Marchetti et al., 2005; Repka et al., 1997) and Trachyte Creek (Cook et al., 2009), since it predicts a recent (~250–500 ka) acceleration of incision throughout the Glen Canyon as shown in Figure 13B. Since burial, surface and OSL dating seem to more or less agree in young, low-lying deposits (<~100 m above the river), and the transition in rate between Bullfrog and Hite (and numerous other young dates) provides an average of slow incision (~60 m/Ma) for most of the past 1.5 Ma, with an acceleration of incision rate (to ~400 m/Ma) within the past ~250–500 ka. These data and analysis represent this acceleration in time, and especially space, much more effectively than previous estimates.

Overall, the data are compatible with integration of the Colorado River through the Grand Canyon region ca. 5–6 Ma (e.g., Karlstrom et al., 2008), where topographic relief developed locally in response to a significant drop in local base level between the elevated Plateau and extending Basin and Range. Incision likely proceeded upstream as a transient wave of incision, increasing relief in the region. When this incisional wave reached the Paleozoic–Mesozoic contact near but downstream of Lees Ferry, it engendered a quick local drop in base level above Lees Ferry and resulted in rapid incision upstream over the past few hundred thousand years in Glen Canyon (Cook et al., 2009; cf. Garvin et al., 2005). It is unclear if this wave of incision has reached the area of Bluff, Utah, where Wolkowinsky and Granger (2004) find slightly lower long-term average rates of incision than Bullfrog (~110 m/Ma at Bluff).

Insight on Early Development of the Green River

Our new incision rates derived from burial dating of fluvial deposits along the Green River provide new insight into the history of the Green River. Integration of the Green River across the Canyon of Lodore must have taken place between the end of Browns Park deposition <8.25 Ma and prior to terrace gravel deposition on Peru Bench at (1.2 ± 0.3 Ma) and Tabyago Canyon (1.5 ± 0.13 Ma). Higher and older undated terraces along many portions of the Green River system suggest that our terrace date places a minimum constraint on the time of postulated drainage integration and development of a south-flowing Green River across the Uinta Mountains to >1.5 Ma. Thus, we differ from the interpretation of Hansen (1986) that the Green River flowed east away from the location of the town of Green River as recently as 640 ka.

Comparison of the Colorado and Green River Systems

The most prominent feature of the profile of the upper Colorado River system (Fig. 2) is that the Colorado River maintains a steeper gradient than the Green River above their confluence. In many rivers, channel steepness is inversely proportional to discharge (Osterkamp, 1978) and, thus, canonical explanations for a "graded" profile (e.g., Mackin, 1948) attribute downstream decreases in gradient as adjustments to downstream increases in discharge. To assess whether the steeper gradient of the upper Colorado relative to the Green River may reflect differences in discharge, we compare USGS records for historic discharges (U.S. Geological

Figure 13. (A) Incision constraints from eastern Grand Canyon and Glen Canyon from Karlstrom et al. (2008), Hanks et al. (2001), Garvin et al. (2005), Cragun (2007), and this volume on the long profile of the Colorado River near Lees Ferry. Long-term rates are red (previous publication) or purple (this paper). Short-term rates are orange (previous publication) or yellow (this paper). Previous incision rates that underestimated terrace age are transparent (i.e., orange arrows with a gray outline at Bullfrog and Navajo Mountain ["Cha surface" of Hanks et al., 2001]). (B) Plot of age versus height above the river for data between Lees Ferry, Arizona, and Bluff, Utah, through Glen Canyon. All data are in Table 1 under Cook et al. (2009), Cragun (2007), Garvin et al. (2005), Hanks (2001), Hidy et al. (2010), Wolkowinsky and Granger (2004), and Davis et al. (2001). Burial dates are larger text. Note that the Trachyte Creek samples of Cook et al. (2009) are not on the long profile figure because they repeat already apparent age patterns and overcomplicate the figure. Error bars are one standard deviation about the mean for published analytical uncertainty. The four highest elevation surface dates of Garvin et al. (2005) and Hanks et al. (2001) are excluded from the gray bar of likely bedrock incision rates through time. Gray shaded area is a best guess of progression of the incising river through time. Approximate fast and slow incision rates are from linear regressions of either all the data younger and lower than Hite in the plot, or from the trio of burial dates at Bluff, Bullfrog, and Hite, respectively.
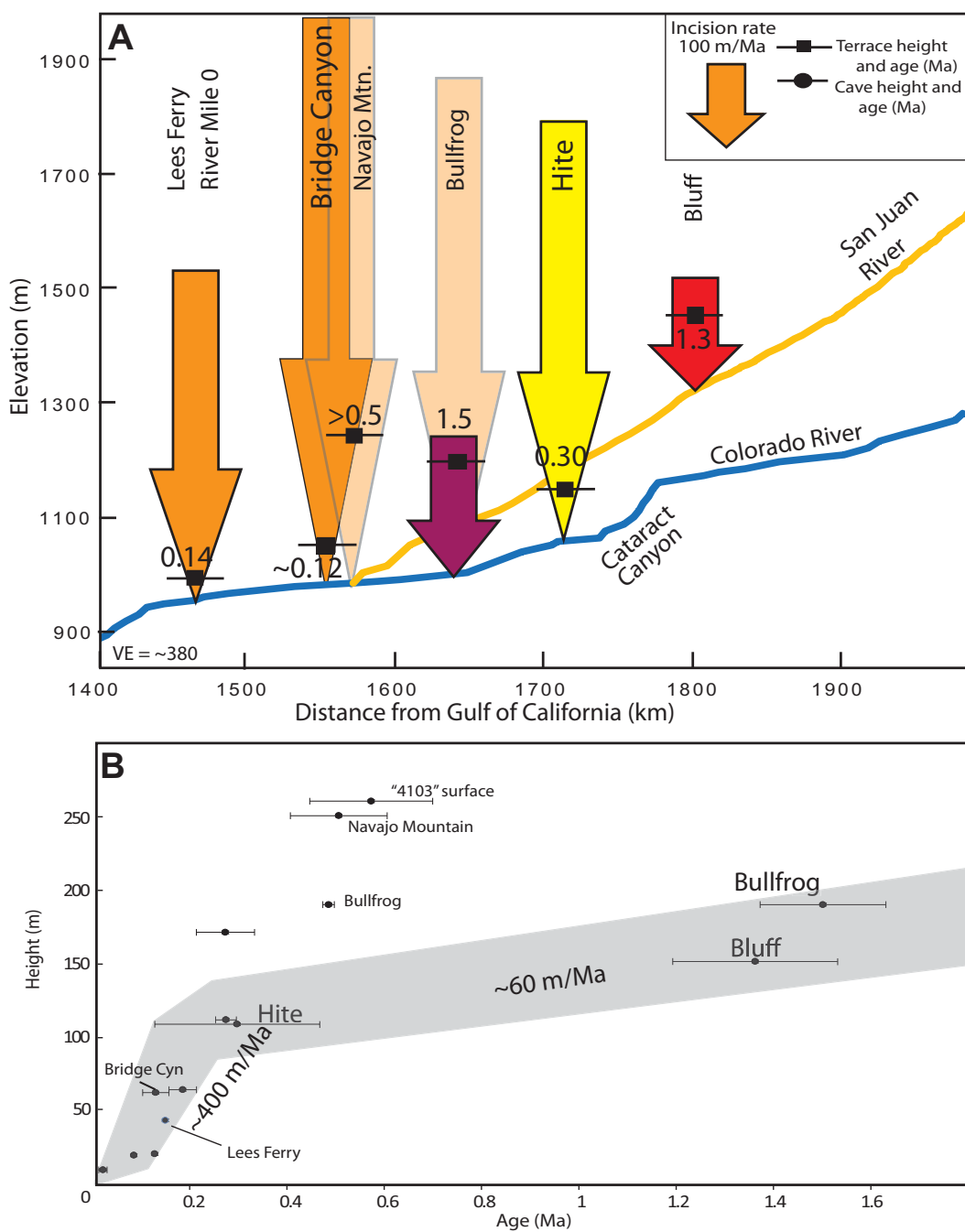
Survey, 2001) along both rivers. Data were averaged over several years from the same years of record for both systems whenever possible to avoid annual variation in storm tracks and hydrograph shape. We concentrated on predam data (Table 2) in order to avoid substantial removal of flow via dams and irrigation systems. Since records are not complete and minor anthropogenic surface water alteration began before the earliest records, specific values of

discharge are minimum estimates of natural flow patterns. These discharge records nevertheless show that the upper Colorado River consistently carries greater discharge than the Green River per unit drainage basin area (Fig. 14). Thus, if the relative pattern in discharge data is relevant over millennial and million-year timescales, a steeper upper Colorado River gradient relative to the Green River would be inconsistent with generally accepted connec-

tions between discharge and slope (Mackin, 1948; Osterkamp, 1978).

Three possible explanations for why the Colorado River is steeper than the Green River are (1) uplift of the Colorado River segment, (2) more resistant underlying bedrock along the Colorado, or (3) a substantial topographic step along the western Rockies at the onset of incision. If rock strength is the primary control on fluvial evolution in this system, then

TABLE 2. COMPILATION OF U.S. GEOLOGICAL SURVEY DISCHARGE DATA USED TO DERIVE THE DISCHARGE COMPARISON
GRAPH TO COMPARE RELATIVE PATTERNS OF DISCHARGE BETWEEN THE GREEN AND COLORADO RIVERS

Location	Peak Q (cfs)	Area (mi²)	Peak Q (m³/s)	Area (km²)	Peak log (Q)	Log (area)	Record
Green River discharge data							
Warren Bridge, Wyoming	2665	468	76	1212	1.88	3.08	1932–1935
Daniel, Wyoming	4050	932	115	2414	2.06	3.38	1914–1917
La Barge, Wyoming	7830	3910	222	10,127	2.35	4.01	1947–1950
Green River, Wyoming	14,838	7670	420	19,865	2.62	4.30	1915–1918
Flaming Gorge, Wyoming	11,798	14,900	334	38,591	2.52	4.59	1924–1927
Linwood, Wyoming	10,904	18,300	309	47,397	2.49	4.68	1929–1932
Greendale, Utah	14,125	19,350	400	50,116	2.60	4.70	1951–1954
Jensen, Utah	31,300	29,660	887	76,819	2.95	4.89	1904–1906
Ouray, Utah	30,600	35,500	867	91,945	2.94	4.96	1948–1951
Green River, Utah	42,250	44,850	1197	116,161	3.08	5.07	1914–1917
Colorado River discharge data							
Baker Gulch, Colorado	511	63.9	14	166	1.16	2.22	1953–1957
Grand Lake, Colorado	1138	102	32	264	1.51	2.42	1914–1917
Granby, Colorado	2675	323	76	837	1.88	2.92	1908–1911
Hot Sulphur Springs, Colorado	5640	825	160	2137	2.20	3.33	1914–1917
Kremmling, Colorado	12,028	2382	341	6169	2.53	3.79	1914–1917
Glenwood Springs, Colorado	21,425	4558	607	11,805	2.78	4.07	1914–1917
Palisade, Colorado	35,500	8738	1006	22,631	3.00	4.35	1914–1917
Fruita, Colorado	47,700	17,100	1352	44,289	3.13	4.65	1914–1917
Cisco, Utah	56,550	24,100	1603	62,419	3.20	4.80	1914–1917

the generally weaker rocks of the Green River would allow more rapid incision than the Colorado. However, measured incision rates on the Colorado River are higher than on the Green River (Figs. 3 and 4). Thus, rock type may not be the sole control on the long profile. The topography that existed at the onset of integration of the upper Colorado around 11 million years ago is available from limited data sets, but these paleo-topographic reconstructions support relatively horizontal-planar topography across the western Rockies and Colorado Plateau (Pederson et al., 2002b; Karlstrom et al., 2012). Thus, we infer that the Colorado River channel is likely being steepened relative to the Green River by recent or ongoing epeirogeny in the Colorado Rockies that is further supported by numerous data sets in Karlstrom et al. (2012) and subsequent papers from those authors.

CONCLUSIONS

Our new burial ages from fluvial deposits along the Colorado and Green rivers, in conjunction with existing constraints on incision rates during the late Cenozoic, lead us to the following conclusions.

(1) The combined data sets of incision rates around Grand and Glen Canyons support a transient incision model for the Lees Ferry knickpoint. The data imply that the shallow-dipping lithologic contrast at the top of the Kaibab Formation may have split the migrating knickpoint, leaving the Lees Ferry knickpoint behind and separately excavating Glen Canyon. This split may have led to the sudden incision rate increase in the latter half of the Pleistocene through Glen Canyon. Our comparison of cosmogenic surface, cosmogenic burial, and
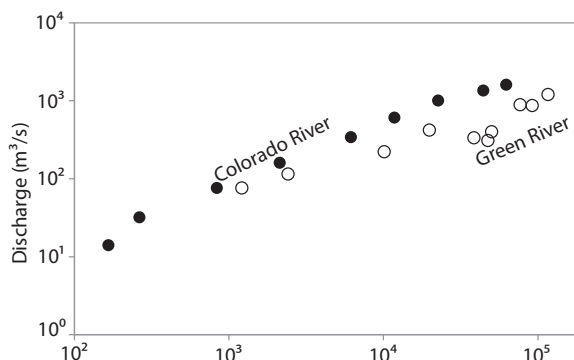
Figure 14. Historical discharge of the Green and Colorado rivers compiled from U.S. Geological Survey records. The Green River has systematically less discharge per drainage area than the Colorado River in these records, and we suggest the relative discharge distances could have been similar throughout Pleistocene climates. Dates of record are tabulated in Table 2.

OSL dates of terraces leads to measurement of rapid incision rates corroborated by all three techniques, which followed long-term slower incision rates.

(2) The observations that the Colorado River is steeper, has higher discharge, and higher incision rates than the Green River may be well explained by uplift of the Colorado Rockies relative to the Colorado Plateau in the past 10 Ma.

(3) The new Green River data brackets integration across the Uinta Mountains between 8.5 and >1.5 Ma, and further research is needed to elucidate integration timing.

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