

8-31-2011

New incision rates on the Colorado River system based on cosmogenic burial dating of terraces : implications for a transient knickpoint at Lees Ferry and differential uplift of the Rocky Mountains

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**NEW INCISION RATES ON THE COLORADO RIVER SYSTEM
BASED ON COSMOGENIC BURIAL DATING OF TERRACES:
IMPLICATIONS FOR A TRANSIENT KNICKPOINT AT LEES FERRY
AND DIFFERENTIAL UPLIFT OF THE ROCKY MOUNTAINS**

BY

ANDREW LEE DARLING

**B.S., ENVIRONMENTAL GEOLOGY
MESA STATE COLLEGE, 2008**

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

Earth and Planetary Sciences

The University of New Mexico
Albuquerque, New Mexico

August, 2010

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ACKNOWLEDGMENTS

I would like to acknowledge funding, which amounted to a substantial sum, for this project which came from the NSF Continental Dynamics program grant (EAR-0607808) to Karl Karlstrom and a grant from PRIME Lab, Purdue University.

We would like to extend thanks to many extraordinary ladies and gentlemen who helped in the field including Ryan Crow, Fran Lazear, Bruce Coriell, Richard Elliott, Tyler Doane, Robert Jacobsen, Alexander Kerney, Anna Kutkiewicz, Kira Olsen and Anna Phelps. Collecting samples in the field is tough work and requires incredible fortitude, but our arduous journey through Desolation Canyon provided a challenge I'm sure we all immensely enjoyed. Laboratory assistance from Tom Clifton and Greg Chmiel at PRIME is also greatly appreciated.

Undying support from family (thanks Mom and Dad!) and educators for my entire life have led to this degree. I can derive a piece of my motivation to accomplish this journey from nearly every educator I've worked with. Substantial thanks goes to my Advisor Karl Karlstrom, and Laura Crossey, who encouraged me to go to graduate school a full three years before I finished college, and have been helpful at every step of the way. I continue to work with my undergraduate mentors and am grateful for the support of Andres Aslan and Rex Cole, who taught me the basics. I'd also like to thank my Master's thesis committee who I have not yet mentioned, Dr. Coblenz and Dr. Kirby, for their efforts in helping me through this process.

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ABSTRACT

The Green and Colorado Rivers comprise the drainage system of the western slope of the Colorado Rockies and Colorado Plateau. Comparison of river profiles and rates of incision between these rivers provides a natural laboratory for resolving controls on river evolution. Disequilibrium profiles in both rivers are evident by numerous knickpoints and convexities. By compiling existing age constraints and applying cosmogenic burial dating techniques to previously undated bedrock strath terraces, we determine spatial and temporal patterns of incision and profile evolution over the last 10 Ma. In several cases, incision rates are faster below knickpoints than above, suggesting that knickpoints are dynamically evolving and likely migrating upstream. Reconstruction of paleo-profiles from the 640 ka Lava Creek B terrace suggests rates of knickpoint migration of >150 m/ka in soft rock. Hard bedrock often coincides with knickzones and

appears to slow knickpoint migration (<50 m/ka). Semi-steady average incision rates of 150 m/Ma over the last ten million years on the upper Colorado has resulted in 1.6 km of incision.

The Lees Ferry knickpoint (ca. 950 m elevation) is interpreted to be an upstream-migrating knickpoint initiated by integration of the system through Grand Canyon at about 6 Ma. A burial date of 1.5 ± 0.13 Ma, on a 190-m-high strath terrace 169 km above the knickpoint indicates a rate of 126 m/Ma and is three times older than a cosmogenic surface age of the same terrace. Thus high terraces dated by surface techniques are misleading. This plus a compilation of available incision rates across Lee's Ferry knickpoint show moderate rates of 150- 175 m/Ma below Lees Ferry, ca. 100- 130 m/Ma above the knickpoint in long term rates and 230-300 m/Ma above the knickpoint in very low and young terraces with lower rates farther upstream (e.g. 100 m/Ma on the San Juan and 150 m/Ma near Grand Mesa). Previous authors noted convex features in tributaries above the knickpoint are at elevations between 1200 and 1400 m suggesting they are all responding to a change in incision rate on the Colorado River. Thus longitudinal profiles and incision rates are consistent with diffuse knickpoint propagation extending perhaps 300 km above Lees Ferry on very short time scales. Very high short term rates of 300-500 m/Ma over ~ 500 ka at Lee's Ferry, and upstream of the knickpoint (e.g. Navajo Mountain, Fremont River and Trachyte Creek) partly result from minimum estimates of age but still may suggest incision rates had increased ca. 500 ka due to knickpoint propagation following slower average incision in the last 1-2 Ma.

A new cosmogenic burial isochron date of 1.48 ± 0.12 Ma on an abandoned meander 60 m above the river in upper Desolation Canyon gives an incision rate of 40

m/Ma. Thus, the Green River below Canyon of Lodore displays much slower incision rates relative to a similar distance upstream on the Colorado River. The combination of higher gradient, higher discharge, and higher incision rates over the last several million years, for the upper Colorado River relative to the Green, is interpreted to be due to differential rock uplift of the Colorado Rockies relative to the Canyonlands and Uinta Basin regions. This may be driven by mantle bouyancy associated with the Aspen Anomaly of central Colorado.

The overall conclusions of this paper are that: 1) differential incision across the Lees Ferry and Desolation knickpoints records upstream-propagating incision transients in a disequilibrium river system; 2) the upper Colorado River system is incising faster than the Green River over the last several million years due to rock uplift of the Colorado Rockies relative to the central Colorado Plateau.

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PREFACE

This thesis will be submitted for publication to the Geological Society of America's peer-reviewed journal, *Geosphere*, in Fall, 2010. The following thesis is a modified version of the manuscript to be submitted of the same title. As the first author, I, Andrew L. Darling, performed the majority of the research and work on the paper. The manuscript is multi-authored by: Andrew L. Darling and Karl E. Karlstrom (Department of Earth and Planetary Sciences, University of New Mexico); Darryl Granger (Department of Earth and Atmospheric Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 4790, USA); Andres Aslan (Mesa State College, Department of Physical and Environmental Sciences, 1100 North Ave., Grand Junction, CO 81501, USA); Eric Kirby (The Pennsylvania State University, Department of Geosciences, 503 Deike Building, University Park, PA 16802, USA); Will Ouimet (Amherst College, Department of Geology, 11 Barrett Hill Road, Amherst, MA 01002, USA); Greg Lazear (20508 Brimstone Rd., Cedaredge, CO 81413, USA); David Coblenz (Geodynamics Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA)

As required by the Department of Earth and Planetary Sciences, this introduction outlines the roles of the different coauthors. As first author, my role included planning and organizing a major field expedition to Desolation Canyon in Utah. In addition, I handled field sampling and mapping, crushing samples and performing mechanical, gravitational, magnetic and heavy liquid separations, and then dissolving quartz grains in hydrofluoric acid, then chemical separation of ions. I then re-oxidized ion separates and pounded sample material into metal cylinders for measurement on the Accelerator Mass Spectrometer at PRIME Lab, Purdue University. After data reduction for determination of burial dates I compiled dates in the literature and compared our results to these to

evaluate ours and existing hypotheses. I drafted appropriate figures and wrote and revised the manuscript and revised figures. I am listed as corresponding author for the Geosphere submission.

My advisor Karl Karlstrom helped formulate the research based on past work throughout the Colorado Plateau and Rocky Mountains, provided funding of the work mainly through the CREST (Colorado Rockies and Seismic Experiments) research grant, enabled research river trips, provided edits of various drafts, and helped with data interpretation. Darryl Granger provided access to the preparatory labs at Purdue University and to PRIME Lab for ion measurements, handled data reduction and provided useful insights on the validity of our data, and provided edits and input to the manuscript. Andres Aslan helped with literature compilation, collected a sample in Wyoming, and helped with manuscript revisions. Eric Kirby provided helpful insights from a much broader understanding of the research, suggested regions to focus our efforts, and provided revisions to the manuscript in addition to serving on the committee. Will Ouimet helped collect samples in Desolation Canyon and provided feedback at meetings and to the manuscript. Greg Lazear helped collect samples in Desolation Canyon and provided insights on rock uplift to the manuscript. David Coblentz provided digital elevation model data for one figure, served on the committee and provided helpful comments for the manuscript.

INTRODUCTION

The Colorado River system, as the main river draining the Colorado Rocky Mountains, is an excellent natural laboratory for studying regional landscape development and is ripe for a modern compilation of bedrock incision rates combined with addition of new incision rates in undated reaches. We focus on the Colorado River above Grand Canyon (the upper Colorado River system) and especially on a comparison of the Green and Colorado rivers above their confluence (Fig. 1). Many of the main features of the modern profile have developed in the last 5-6 Ma due to integration of Colorado Plateau drainages through Grand Canyon to the Gulf of California (Karlstrom et al., 2008), however, the upper Colorado River reaches may be older and extend back to ca. 10 Ma (Larson, 1975; Aslan et al., 2008). Tectonic influences interact with climatic oscillation of discharge and sediment flux to determine the gradient of rivers. Tectonic influences discussed in the literature include regional epeirogeny (Karlstrom et al., 2008), offset on faults, (Pederson et al., 2002a; Karlstrom et al., 2007), salt tectonics (Huntoon, 1988; Kirkham et al., 2002), and perhaps tilting that reflect buoyancy in the mantle, either via long wavelength whole mantle flow (Moucha et al., 2008), or upper mantle convection (van Wijk et al., 2010).

In regions of non-uniform rock type, erosion-resistant substrate also effects long-profile development and studies show that channel narrowing and increased gradient correlate with harder rocks in the river substrate (Grams and Schmidt, 1999; Duvall et al., 2004; Mackley and Pederson, 2004). At shorter 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).

The regional debate has recently focused on whether steep reaches reflect bedrock competence (Pederson et al., 2010) or transient incision (Karlstrom et al., in prep; Cook et al., 2009) or both. The answer to this question carries implications for the regional patterns of surface deformation inferred from incision history.

Two data-sets are explored in this paper with the goal of understanding first order controls on the development of the Colorado River system: 1) analysis of river profiles, and 2) incision history through time in various reaches determined by dated strath terraces. These data contain information about the combined effects of regional uplift, climate change, and drainage re-organization that, if resolved, can help elucidate the still-controversial uplift and denudation history of the western U.S. (Pederson et al., 2002b; McMillan et al., 2006).

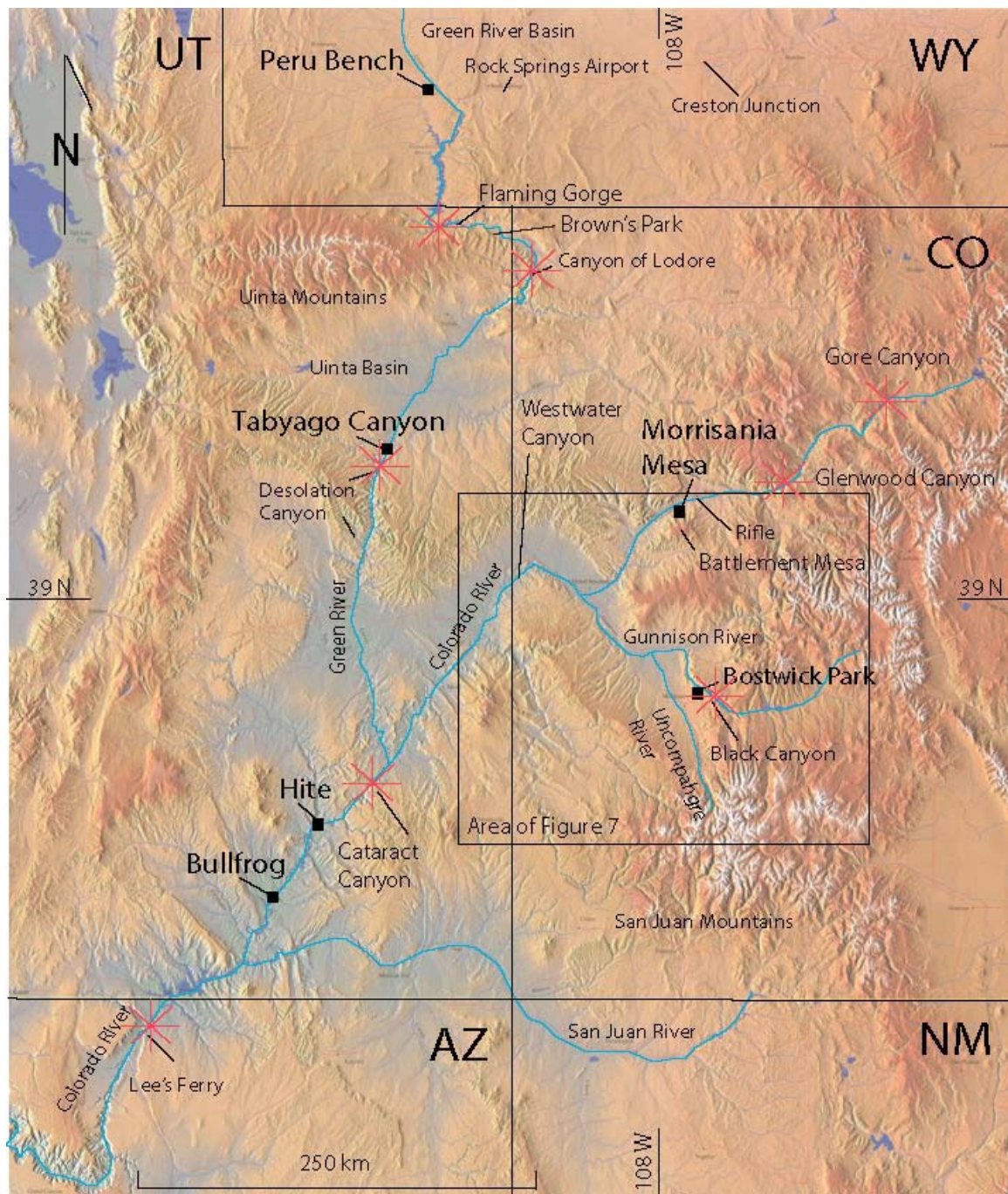


Figure 1. Map of rivers and locations mentioned throughout the Colorado Plateau, including sample locations, marked with black squares. Stars are knickpoints in the longitudinal profile. Three second DEM generated by Chalk Butte Inc., 1995.

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 history of both orogeny and epeirogeny. It seems certain that deformation during Laramide time resulted in local highlands and basins (Dickinson et al., 1988). Laramide structural features consist of basement-cored uplifts and major reverse faults with Tertiary and younger basins and structural relief from uplifts to basins exceeded 10 km in some places (MacLachlan et al., 1972). However, paleo elevations 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, most of the modern high elevations were established during the Laramide, for example by crustal thickening via mid-crustal injection of lithosphere into the Colorado Plateau during the Sevier Orogeny (Gregory and Chase, 1994; McQuarrie and Chase, 2000). In this model, the modern high relief landscape developed from some early plateau via erosional and geomorphic processes. 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, mounting evidence for post-10 Ma increases in elevation in the Rocky Mountains (Leonard, 2002; McMillan et al., 2002; Sahagian, 2002) suggests a young component of rock uplift. More realistic models involve several episodes of uplift (e.g. Liu and Gurnis, 2010). This paper evaluates the importance of the late-Neogene uplift component as recorded by the fluvial system and elucidated in incision rate patterns.

Regional River System

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 (Karlstrom et al., 2008). However a paleo-Colorado River already existed in the Colorado Rockies as shown by gravels beneath 25-10 Ma basalts of the Flattops (25-10 Ma) and Grand Mesa region (Fig. 1; Kirkham et al., 2002; Czapla and Aslan, 2009). These basalt remnants flowed into the low parts of the topography at the time and, because they are resistant to erosion, they are now the highest topography. There is very little difference in elevation between flows of 25 to 10 Ma basalts and hence this time is thought to have been a period of low-relief and little erosion in central Colorado (Yeend, 1969; Larson et al., 1975; Kirkham et al., 2002). Erosion since 10 Ma has been dramatic (>1500 m in places) as the Colorado River and its tributaries carve deep canyons (Aslan et al., 2008).

In contrast the Green River appears to be a somewhat younger system. Infilling of the Green River Basin (Fig. 1) took place throughout the Tertiary, until 7-8 Ma. Miocene deposits of the Brown's Park Formation are somewhat younger than the youngest dated ash (<8.25 Ma, Luft 1985), which is an older limit on the age of Green River near its present course. Neogene subsidence and graben collapse played a key role in the early development of the Green River (Hansen, 1986). The Green River began eroding the low-relief region north of the Uinta Mountains as a result of drainage integration events which brought water across the Uinta Mountains and flowed south into the Colorado River system (Hansen 1986; Munroe et al., 2005).

River Profiles

Several datasets exist for the longitudinal profile of the Colorado River system (Fig. 2). Early U.S. Geological Survey (USGS) reports (La Rue, 1916) are shown in Fig 2A; these provide precise elevation control for selected points but river distance between points was not calculated to represent meanders well, and thus underestimates channel distance. These locations are hence plotted with the same distance upstream as topographic map derived distances. More modern USGS 1:24,000-scale topographic maps provide reasonable precision for both river channel length and elevation control and profiles from these (Fig. 2B) are preferred as they are the most accurate available. Digital elevation models (DEMs) provide a more readily accessed dataset (Fig. 2C), however 90 m and 30 m resolution DEM's may sometimes have artifacts in the extracted long profile in narrow canyons and reservoirs force interpolation.

The main features for all three versions of the longitudinal profile are similar (Fig. 2). The predominant feature of the profile is a knickpoint near Lee's Ferry that separates a high gradient reach through Grand Canyon from a very low gradient reach in Glen Canyon. For clarity, we use the following terminology: 1) a "knickpoint" is an abrupt convex change in slope of a river's longitudinal profile; 2) a "knickzone" is the relatively steep reach below a knickpoint; 3) a "convexity" is a more gradual convex bulge in a river profile, i.e. more broad than a knickpoint. The Lee's Ferry knickpoint divides the Upper Colorado River hydrologic basin from the Lower Basin and has been described as the boundary between two separate concave portions of the profile (Karlstrom et al, 2007). Additional minor knickzones and convexities exist within Grand Canyon (Hanks and Webb, 2006) but these are less obvious in the long profile and reported to strongly

correlate with recent debris flow frequency and distribution and are thus attributed here to shorter time scale features. There are several prominent knickpoints in the upper basin. 1) 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 knickpoints located in Glenwood Canyon, Gore Canyon and Black Canyon (Gunnison River) shown as stars in Figure 1.

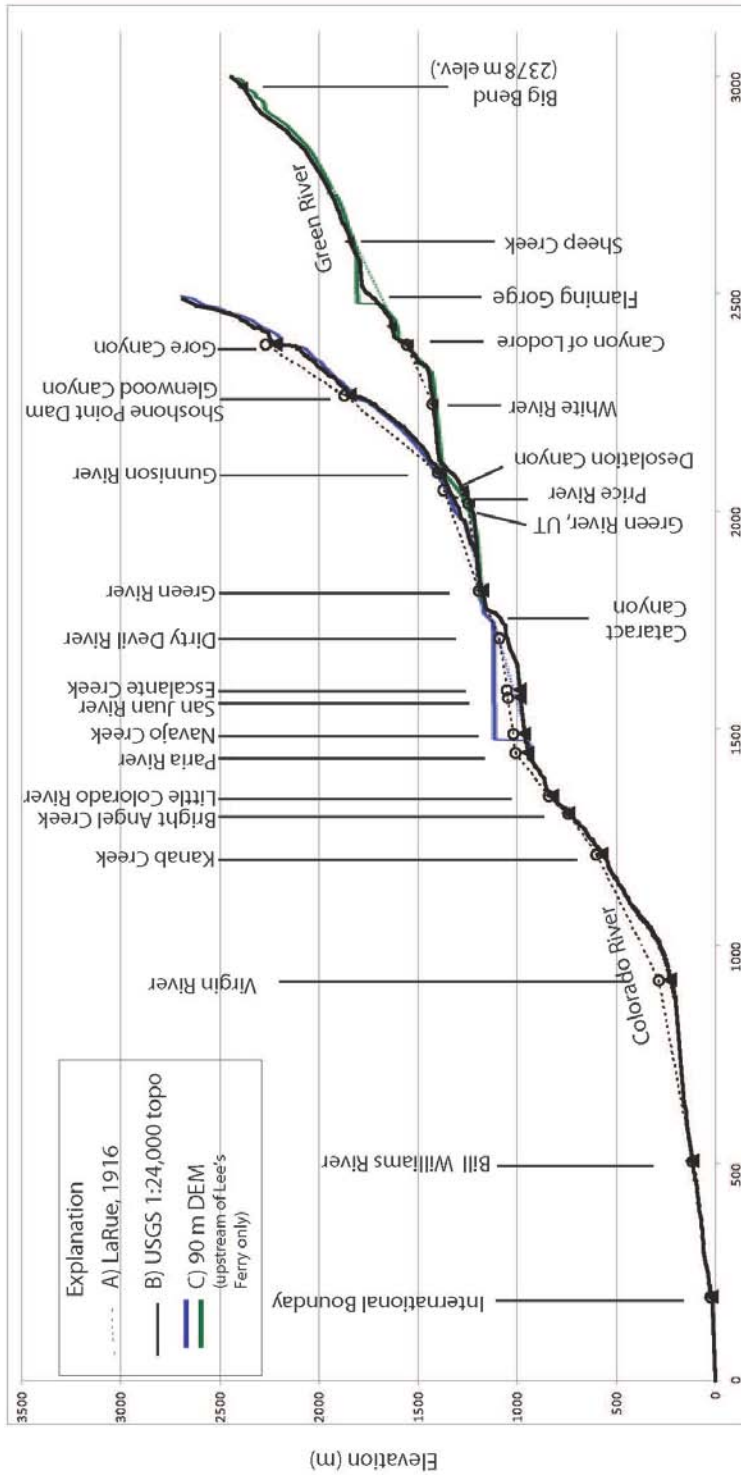


Figure 2. Longitudinal profiles of the Colorado and Green Rivers as determined from: A) Elevations from LaRue, 1916 Survey, surveyed elevation at known points (same distances as topographic map B) Elevations from USGS 1:24,000 Topographic maps, with distances measured along main channel, and C) Profile generated from Digital Elevation Models (90 m); river labels represent the confluence of the tributary river with the Colorado River.

Discharge and Slope Comparison

Another prominent feature of the profile is that the Colorado River has a steeper gradient than the Green River above their confluence. In many rivers slope is inversely proportional with discharge (Osterkamp, 1978) and may be the explanation for this slope difference. To compare discharge magnitude between the Colorado and Green rivers, we used USGS records for historic discharges (U.S. Geological Survey, 2001). 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 pre-dam data (Table 1) in order to avoid substantial removal of flow via dams and irrigation systems. Since records are not complete and minor surface water flow alteration began before the earliest records, specific values of discharge are minimum estimates.

Discharge records at several stream gauges show that the upper Colorado consistently produces greater discharge than the Green per unit drainage basin area (Fig. 3). From models of stream power, river gradient decreases as discharge increases either along a river or as juxtaposed between rivers (Howard, 1994). Comparison of longitudinal profile of the rivers shows the Colorado to be much steeper than the Green (see profile figures). This is verified by Ouimet et al., (in prep.; Karlstrom et al., 2010) using K_s analysis via methods outlined in Kirby et al., (2007) that normalize gradient for drainage area and reveal reaches that are obviously steeper than normal (e.g. immediately below knickpoints). This analysis also confirms a visual inspection that shows that the entire upper Colorado River is systematically steeper than the Green River per unit drainage area. The gradient observed from the long profiles (see profile figures) and

stream power model derived estimates of gradient yield a steep upper Colorado River that is inconsistent with the fact that the Colorado produces greater discharge and implies different longitudinal profile controls are acting on the system.

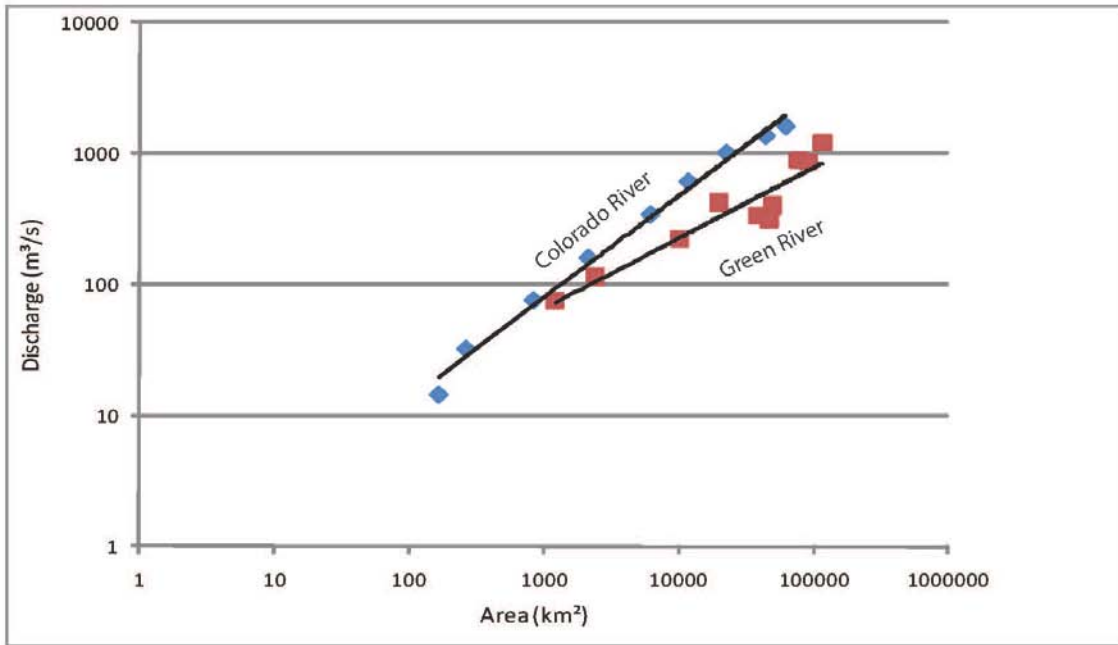


Figure 3. Historical discharge of the Green and Colorado Rivers compiled from USGS records. The Green River has systematically less discharge per drainage area than the Colorado. Dates of record are tabulated in Table 1.

Green River Discharge Data

Location	Peak		Peak		Peak Log (Q)	Log (A)	Record
	Q	Area	Q	Area			
	cfs	mi ²	m ³ /s	km ²			
Warren Bridge, WY	2665	468	76	1212	1.88	3.08	1932-1935
Daniel, WY	4050	932	115	2414	2.06	3.38	1914-1917
La Barge, WY	7830	3910	222	10127	2.35	4.01	1947-1950
Green River, WY	14838	7670	420	19865	2.62	4.30	1915-1918
Flaming Gorge	11798	14900	334	38591	2.52	4.59	1924-1927
Linwood, WY	10904	18300	309	47397	2.49	4.68	1929-1932
Greendale, UT	14125	19350	400	50116	2.60	4.70	1951-1954
Jensen, UT	31300	29660	887	76819	2.95	4.89	1904-1906
Ouray, UT	30600	35500	867	91945	2.94	4.96	1948-1951
Green River, UT	42250	44850	1197	116161	3.08	5.07	1914-1917

Colorado River Discharge Data

Location	Peak		Peak		Peak Log (Q)	Log (Area)	Record
	Q	Area	Q	Area			
	cfs	mi ²	m ³ /s	km ²			
Baker Gulch	511	63.9	14	166	1.16	2.22	1953-1957
Grand Lake	1138	102	32	264	1.51	2.42	1914-1917
Granby Hot Sulphur	2675	323	76	837	1.88	2.92	1908-1911
	5640	825	160	2137	2.20	3.33	1914-1917
Kremmling	12028	2382	341	6169	2.53	3.79	1914-1917
Glenwood	21425	4558	607	11805	2.78	4.07	1914-1917
Palisade	35500	8738	1006	22631	3.00	4.35	1914-1917
Fruita	47700	17100	1352	44289	3.13	4.65	1914-1917
Cisco	56550	24100	1603	62419	3.20	4.80	1914-1917

Table 1. Data used to derive discharge comparison graph (U.S. Geological Survey, 2001).

Connections between Uplift, Denudation and Incision

We follow terminology of England and Molnar (1990) in distinguishing different types of “uplift” for discussion of evolving landscapes in tectonically active and erosional settings like the western U.S. In these types of active regions one needs to consider river incision rates, the related landscape denudation rates, isostatic rebound that accompanies denudation, and any tectonic uplift or subsidence.

A major goal of this paper is to compile and analyse bedrock incision rates as calculated from dates on strath terraces near the trunk river channels to understand patterns of downcutting through time. When available, multiple datable terraces in a given reach provides data on changes in incision rate through time, and comparison of differential incision rates reach-to-reach provides information on tectonic forcings (Karlstrom et al., 2008) and/or incision transients. This paper compiles available high quality incision rate data as a step towards those goals. Older and higher terraces are preferred as these tend to average out the climatically driven cycles of aggradation and incision that are superimposed on overall rock uplift patterns (Hancock and Anderson, 2002). Only where paleo-profiles are referenced to sea level (Karlstrom et al., 2007) can differential incision become interpreted in terms of surface uplift as well as rock uplift.

Differential incision rate data can be used to evaluate possible transient knickpoints. To outline our thinking, we use an example from the Gunnison River that has a relatively well understood incision history due to numerous terraces that are datable with Lava Creek B ash (640 ka; Fig. 4). Downstream of the Black Canyon of the Gunnison to Westwater Canyon (a distance of 185 km) incision rates are ~150 m/Ma since 640 ka (Aslan et al., 2008; Darling et al., 2009). Near the Black Canyon knickpoint,

Lava Creek B dated terraces from a paleo-tributary to the Gunnison indicate rates of ~500 m/Ma within the knickzone (Sandoval, 2007; Aslan et al., 2008). Upstream of the Black Canyon another Lava Creek B locality yields an incision rate of 95 m/Ma (Hansen, 1965). This example suggests that differential incision rates, with moderate rates below, highest within, and lowest rates above the knickpoint, can be used to identify transient knickpoints. Downstream incision rates are adjusted to relative base-level fall for the system, the upper incision rate is not yet affected by the new relative base level, and the highest rate (largest arrow on the figure) is where the profile is most rapidly adjusting to a new baselevel. This differential incision pattern suggests that the knickpoint itself will migrate upstream as an incision wave.

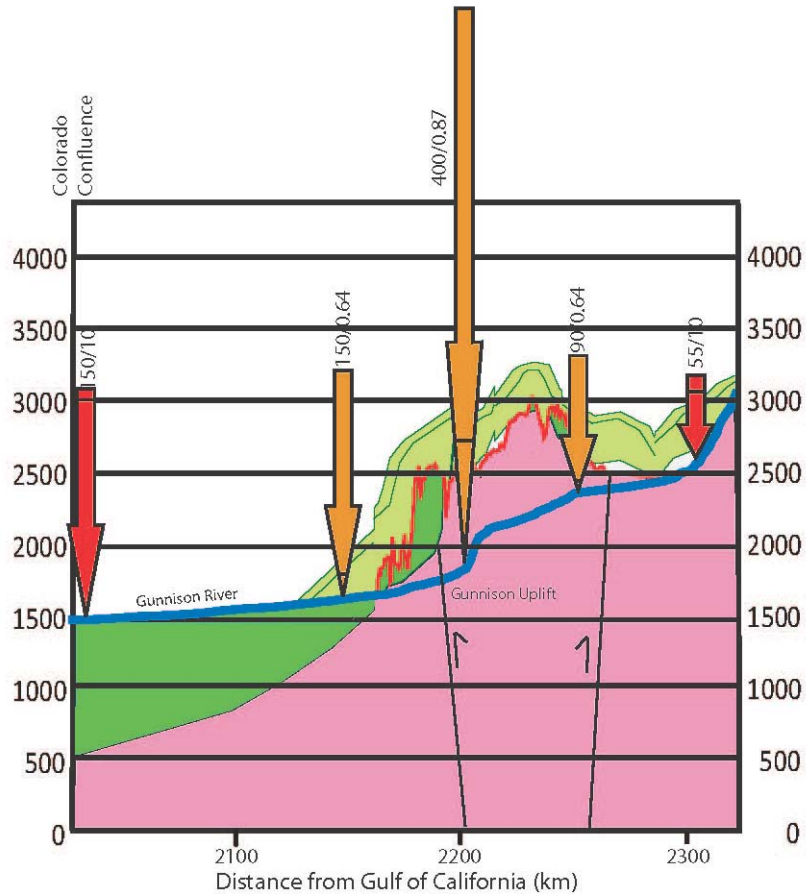


Figure 4. Gunnison River profile and rates: an example of an upstream-propagating transient knickpoint. Orange arrows are short term (<1 Ma rates) and red arrows are long term rates. Green = Mesozoic sedimentary rocks. Pink = Precambrian igneous and metamorphic rocks. Arrows are proportional to rate magnitude, horizontal bars within arrows represent strath elevation of dated terraces.

Knickpoint Propagation Rates

From compiled incision rates on the Gunnison River, we estimate how quickly knickpoints migrate laterally (Fig. 5). Recent work indicates a rapid incision wave in the Gunnison River sometime after ~1 Ma, possibly triggered by drainage reorganization following abandonment of Unaweep Canyon (Fig. 5; Aslan et al., in prep). The knickpoint would have traveled mainly in soft Mancos Shale, passed Sawmill Mesa (~40 km upstream) before 640 ka as inferred from the moderate incision rate of 150 m/Ma (Darling et al., 2009). Sawmill Mesa is both an ancient confluence and site of Lava Creek B ash. At this confluence the incision wave probably split, heading up the Uncompahgre and Gunnison rivers. The Uncompahgre River drains the San Juan Mountains (~100 km south from Sawmill Mesa) and quickly rises up a box canyon in hard rock, providing a minimum recession rate of 160 m/ka from Sawmill Mesa over 640 ka. Near the modern confluence of the Gunnison and North Fork of the Gunnison, moderate incision rates have been determined on a ~700 ka terrace (Sandoval et al., in prep.), and the paleo knickpoint was then located an additional 40 km (80 km total) upstream partly through basement rocks. This provides an approximate minimum retreat rate of 200 m/ka (~400 ka; from 1 Ma to 640ka) through soft rock from Unaweep Canyon to the North Fork confluence. Just upstream of the confluence, the Gunnison encounters basement, and some 20 km upstream of the confluence is the mouth of the paleo-Bostwick Creek, terraces of which are closely associated with Lava Creek Ash. Ten kilometers above that is the modern knickpoint. Bostwick Park contains a Lava Creek B ash preserved stratigraphically above 10 m of river gravel with primary sedimentary structures, resulting in an incision rate of 400-500 m/Ma (Aslan et al., 2008 and

references therein). Thus, transient incision passed the Gunnison-North Fork confluence before 640 ka and passed Bostwick Park sometime after 640 ka. This provides a maximum (30 km/640 ka) and a minimum retreat rate (10 km/640 ka) through mostly crystalline basement rocks of ~50 -15 m/ka, respectively. This suite of estimates results in a minimum propagation rate on the order of 15 m/ka and an average rate of >150 m/ka since inception (since most of the rock the rivers were flowing through are Cretaceous shale). These rates are 100 to 1000 times greater than vertical incision rates over the same time period.

The resulting range of >150m/ka (softer rock) to >15 m/ka (harder rock) for knickpoint propagation rates are comparable in magnitude to the modeling results from Pelletier (2010) for Grand Canyon related knickpoint propagation. While the fluvial geometry and discharge of and bedrock underlying these rivers is very different, it may be expected that knickpoints in large rivers on the Colorado Plateau can migrate within an order of magnitude of these rates or higher. Much smaller drainages, such as Parachute Creek, have resulted in propagation rate estimates of 7 – 12 m/ka in soft rock (Berlin and Anderson, 2007) and are near the minimum Gunnison rates. This comparison illustrates how propagation rate can scale with drainage area. The important conclusion for regional profile studies is that transient major knickpoints in the large tributaries of the Colorado River system migrate at high rates and are unlikely to persist in the system beyond a few million years. This reinforces the interpretation that certain knickpoints that are shown to be transient are temporarily slowed by harder bedrock (where propagation rates are slower) rather than being entirely caused by harder rock.

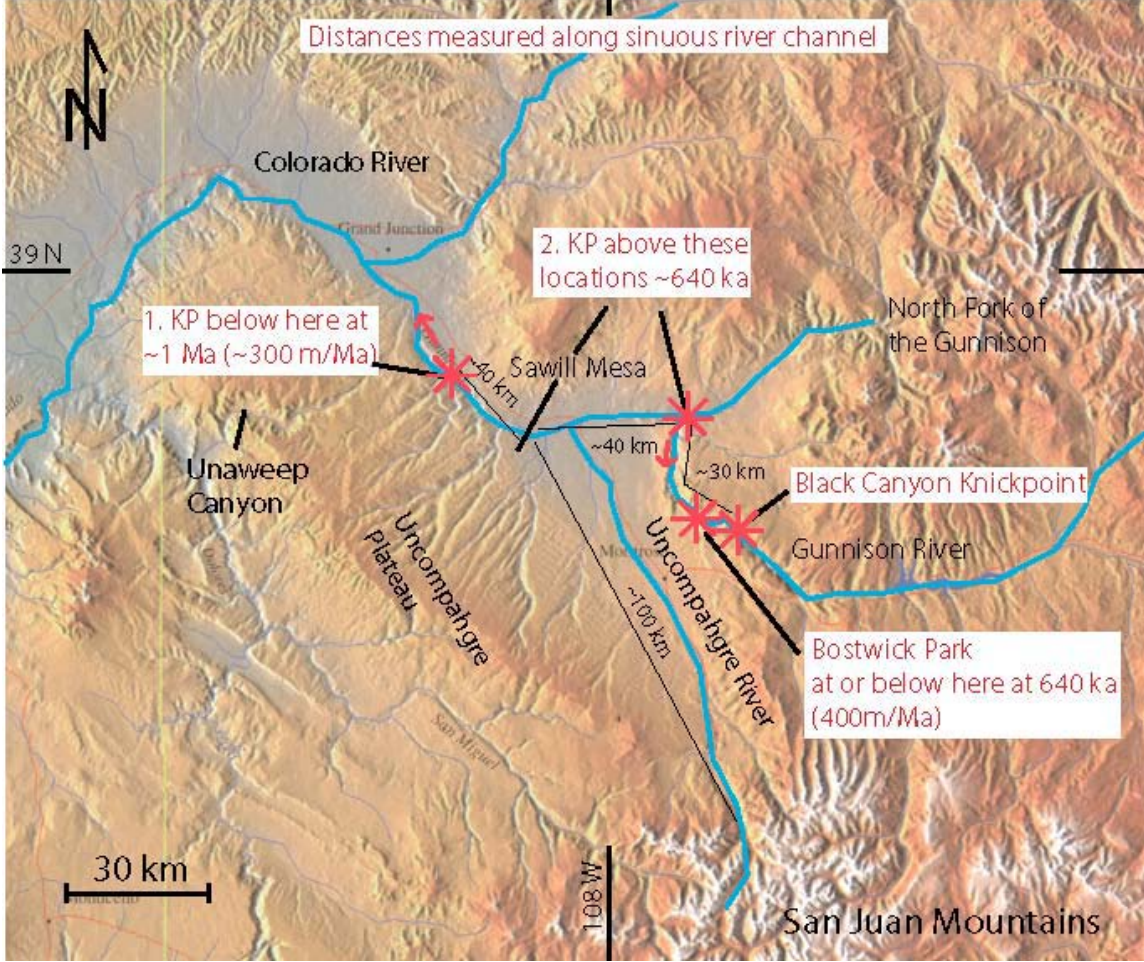


Figure 5. DEM (3 second elevation data, Chalk Butte Inc., 1995) of the Gunnison River valley. Sample locations are labeled with the chronology and incision rate for given sites. Approximate distances of knickpoint migration along the river channel are given for reaches and timeframes mentioned in the text. Time spans used to calculate rates are 1 Ma to 640 ka and 640 ka to Recent.

METHODS

Incision Rate Compilation

Bedrock incision rates can be calculated from a single dated terrace if depth to modern bedrock can be estimated (e.g. Burbank et al., 1996; Pederson et al., 2002; Karlstrom et al., 2007). If multiple datable terrace flights are present, a preferred method is to calculate variation in incision rates through time using strath-to-strath comparisons, i.e. using the elevation difference between two bedrock straths divided by their age difference (Pederson et al., 2005; Karlstrom et al., 2008). Because of the difficulty in obtaining good age control, most published incision rates rely on single dated straths. In addition, because water depth and depth to bedrock are rarely known, strath heights are commonly reported relative to the modern river (usually the water level shown on USGS maps). The limited mid-channel drilling data that is available preclude reach-to-reach comparisons, but suggest that bedrock is commonly on the order of ~10 m below the river level (e.g. Miser, 1924; Woolley, 1930; Hanks and Webb, 2006; Karlstrom et al., 2007), but can be as much as 30 m or more (Woolley, 1930; Karlstrom et al., 2007). For the purposes of this paper, however, and comparison with published incision rate data, Table 2 uses strath elevation above river-level projected to the nearest river.

Cosmogenic Burial Dating

Multiple dating methods have been used to estimate the strath terrace ages compiled in Table 2. This study contributes new dates using the cosmogenic burial technique. Cosmogenic nuclides (^{10}Be and ^{26}Al) are produced when cosmic ray particles (mostly very high energy protons) impact atoms and molecules in the Earth's atmosphere creating a cascade of nuclear reactions, mostly spallation reactions. Eventually less high-energy subatomic particles reach quartz crystals at the surface and produce ^{10}Be and ^{26}Al in quartz. Cosmogenic *surface* dating relies on production of various nuclides (technique depending) at rates which vary with latitude and altitude. Surface dates are subject to degradation of the surface of both sampled material and deposits, such that surface accumulation rates are minimum dates and hence yield maximum incision rates.

Cosmogenic *burial* dating (Granger and Muzikar, 2001) relies on the different decay rates of ^{26}Al ($t_{1/2}=0.72$ Ma; Muzikar et al., 2003) and ^{10}Be ($t_{1/2}=1.5$ Ma) (Nishiizumi et al., 2007). Dates as old as 4.5 Ma (6.25 half-lives for ^{26}Al), corroborated by dated overlying basalt, have been reported (Matmon et al., 2010), and ages from 0.5-3 Ma are routinely reported (e.g. Granger et al., 2001; Haeuselmann et al., 2007). Thus, this geochronometer is important to fill the critical few million year time frame of river incision in non-volcanic regions.

Dating deposition of river gravel by cosmogenic burial dating techniques applied to quartz require: 1) sufficient nuclide production before burial to ensure concentrations are above the detection limit of Accelerator Mass Spectrometry (AMS) at the time of measurement; 2) rapid, deep (10 m) sample burial for adequate shielding from post-deposition 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); and 4) a stable environment to ensure continued shielding until excavation. Preferred sites include gravel deposited in caves, quarries in alluvium or a landslide scarp of very recent exposure, where depth of shielding exceeds about 10 m. Field parameters relevant to the cosmogenic shielding for our samples are outlined in Table 2.

Two unknown quantities exist in determining a burial age. First, we wish to determine the age, i.e. how long the gravel has been buried. Second, it is unknown how long the gravel clasts were exposed to cosmogenic nuclide production prior to burial in the terrace. This “inheritance” sets the initial concentration of ^{26}Al and ^{10}Be for clasts that were exposed thoroughly before burial. These two variables (age and inheritance) necessitate two independent radioactive decay patterns (^{26}Al and ^{10}Be) for age estimates (Granger and Muzikar, 2001).

Two techniques for determining burial dates were implemented in this study. 1) Burial date estimates 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). 2) The isochron date method (Balco and Rovey, 2008) involves separate AMS analyses of several clasts that ideally produce a linear fit for ^{26}Al vs ^{10}Be for each set of clasts. In this method, post-burial production is given by the y-intercept of the linear fit of ^{26}Al and ^{10}Be data points for multiple clasts and burial age is inversely proportional to the slope of line (Fig. 6). Uncertainty for isochron cosmogenic dates is calculated by choosing maximum and minimum line slopes through the data. Reported dates are calculated from the best fit slope and uncertainty values are calculated from the differences in estimated maximum and minimum range of slopes. The fact that post-

burial production can be accounted for in the isochron technique appears to allow dating of samples with as little as 3-4 meters (Table 2) of vertical shielding, although very recent exposure is still required.

Shielding at several sites is less than 10 m which resulted in the use of the isochron method for analysis of the depositional age since post-burial production was expected. Each sample was collected from the strath with individual clasts collected from the same level as per suggestion by Granger (noted in Balco and Rovey, (2008)). Samples collected for burial dating were crushed and separated physically and chemically at PRIME Lab, Purdue University by Darling and data reduction for dates was done by Granger. Sample processing procedures are discussed in Granger and Muzikar, (2001).

Uncertainty in interpretation of the accuracy of cosmogenic burial dates often depends on uncertainties about the geologic history of the gravels and/or the terrace they have ended up within. Many of the isochrons presented below are strongly leveraged by a single point that happened to have high ^{10}Be and ^{26}Al concentrations. There is nothing inherently suspect about these points, but for all of the clasts, there is a significant possibility that clasts get reworked from a paleo-terrace and hence have compound histories involving multiple phases of production and burial. Recent cosmogenic data from rivers in South Africa suggest that approximately 20% of clasts in terraces are reworked from terraces into younger deposits, and thus have compound burial histories (Granger). Thus, future additional samples should be added to the isochrons, and/or the addition of a cosmogenic profiling approach might improve the geologic models to help interpret results. But pending additional work, the results presented below tend to form 4-6 point isochrons with reasonable precisions and hence 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.

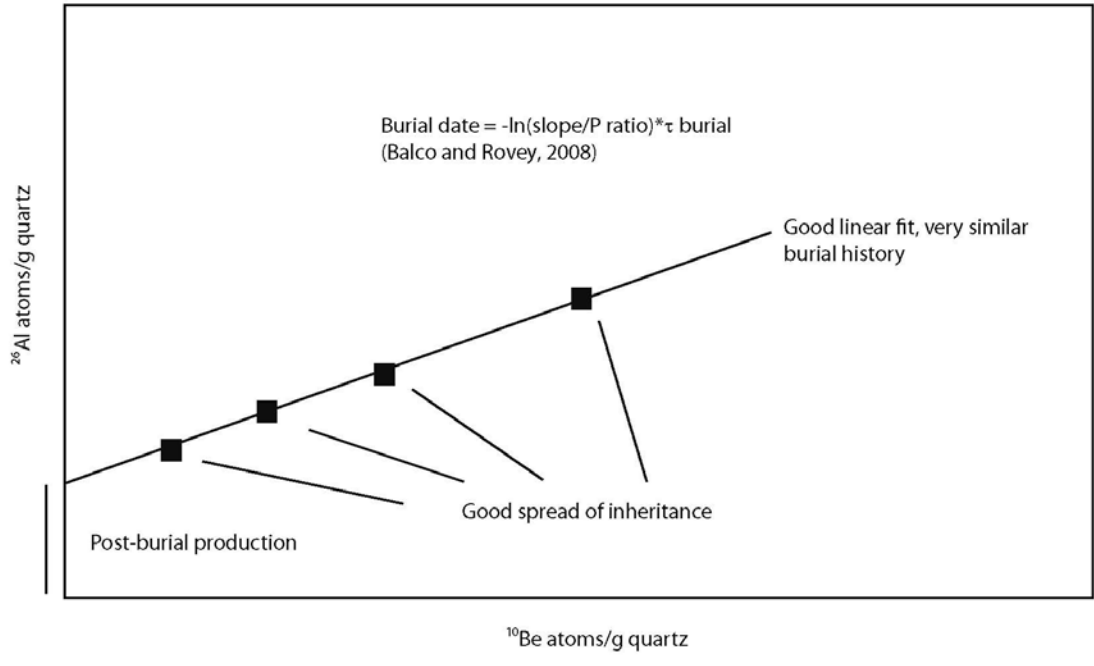


Figure 6. Example of a generalized isochron cosmogenic burial date sample result.

INCISION RATE COMPILATION

All compiled incision rate data for the Upper Colorado and Green rivers are tabulated in Table 2. A range of incision rates is reported based on the maximum and minimum error reported for each date where available. In the text, median incision rates are usually used to simplify discussion. Analysis of maximum and minimum analytical date does not speak to geologic uncertainty, such as unknown time from deposition to reworking of ash-fall tuff, or biased chronology methods. We determined a relative quality rating (1-3) for incision rate data, where “1” is most reliable, based on the following criteria: Chronology points from the literature (such as basalt) that do not have known field relationships to river gravel are less reliable and generally are not reported in this compilation. We report some rates as “apparent incision rates” in central Colorado because of numerous locations where rates have been dampened by tectonism such as normal faulting (Pederson et al., 2002) and salt-tectonism related collapse (Kirkham et al., 2002). Locally dampened incision rates are considered low (“3”) quality rates for the purpose of understanding regional incision as these rates are too low. However they do offer insight into tectonic fault slip and collapse rates and magnitudes that interact with incision. Cosmogenic surface dating is a minimum estimate of age and we assign a quality estimate of “2” to these samples when ages are > 200,000 ka. $^{40}\text{K}/^{39}\text{Ar}$ dates of basalts are generally considered maximum dates and are less reliable, either reported as a “2” or “3” depending on geologic constraints at each site.

Incision data are plotted for both short-term (<1 Ma) and long term (>1 Ma) time frames (Fig. 7 and 8, respectively). Rates determined from dates that are less than ca. 200 ka are not favored for long term patterns due to complexities of increased apparent

incision rates as glacial oscillations alter incision rate (Hancock and Anderson, 2002; Pan et al., 2003), hence we concentrate on longer term bedrock incision.

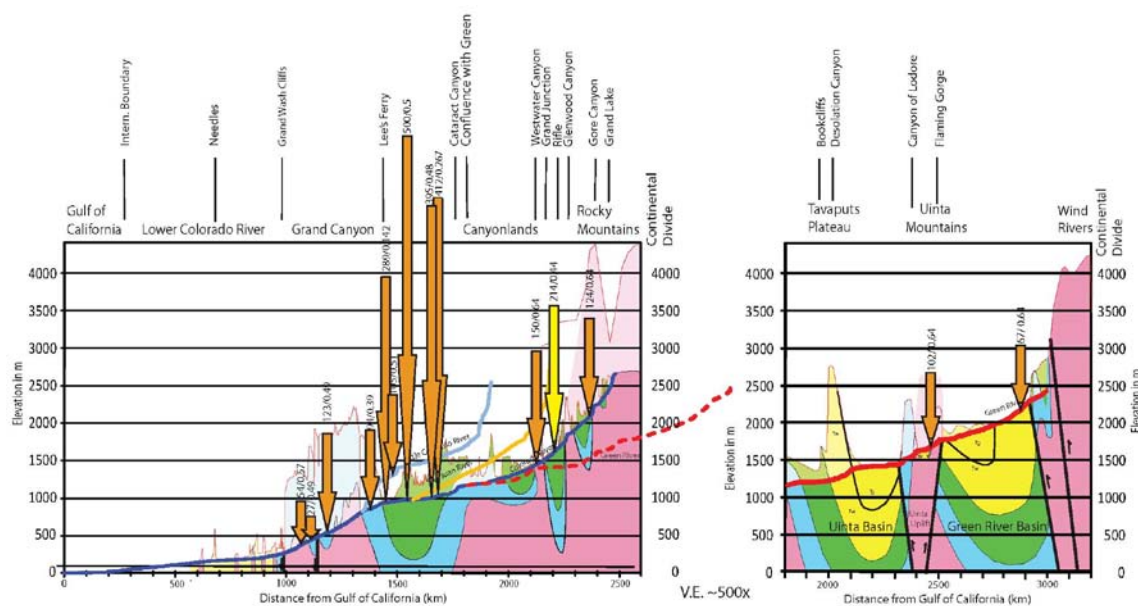


Figure 7. Longitudinal profiles with schematic bedrock geology and canyon names. V.E. 500x. Yellow = Tertiary sedimentary rocks, Green = Mesozoic sedimentary rocks, Blue = Paleozoic sedimentary rocks, Pink = Precambrian igneous and metamorphic rocks. Compiled short term (less than 1 Ma) incision rates (including new data points); arrows are proportional to rate magnitude, horizontal bars within arrows represent strath elevation of dated terraces. These constraints show highly variable incision rates through time and space. 1 km elevation change = 100 m/Ma rate vector length.

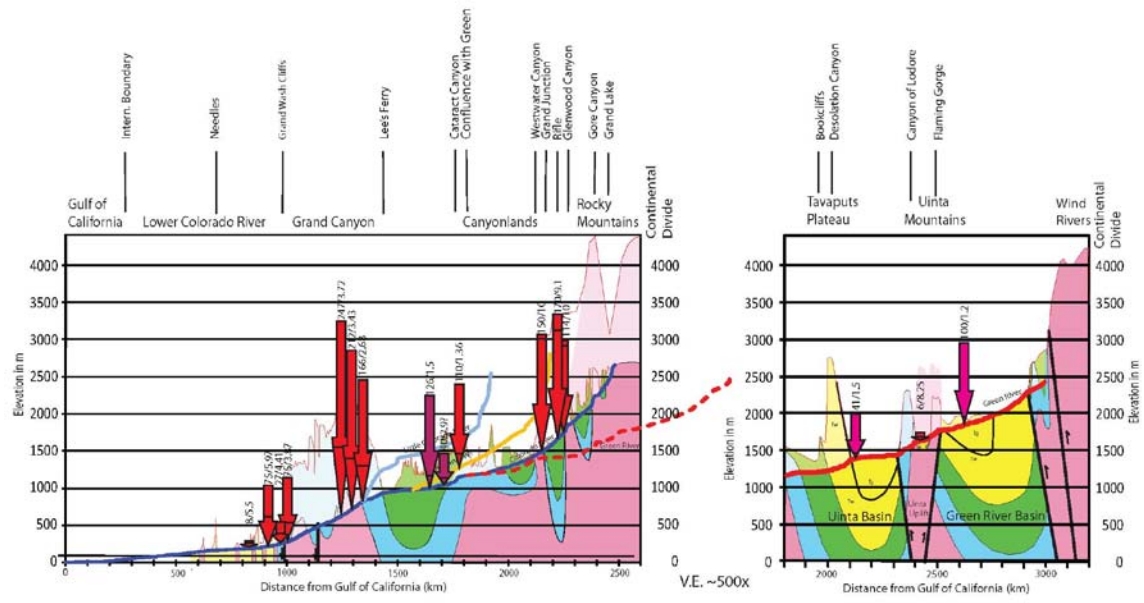


Figure 8. Longitudinal profiles with schematic bedrock geology and canyon names. V.E. ~500x. Yellow = Tertiary sedimentary rocks, Green = Mesozoic sedimentary rocks, Blue = Paleozoic sedimentary rocks, Pink = Precambrian igneous and metamorphic rocks. Compiled long term (greater than 1 Ma) incision rates (including new data points); arrows are proportional to rate magnitude, horizontal bars within arrows represent strath elevation of dated terraces. 1 km elevation change = 100 m/Ma rate vector length.

COMPARING AN ISOCHRON DATE TO KNOWN CHRONOLOGY

Available chronology for Bostwick Park provides an empirical “calibration” for the isochron cosmogenic technique. A detailed discussion of the geology at Bostwick Park is in Sandoval et al., (2007) and Aslan et al., (2008). At this site, about 10 m of gravel was deposited in a paleo-tributary to the Gunnison River. Then the tributary was abandoned leaving a hanging canyon with an underfit ephemeral stream leading into Black Canyon. Locally derived gravel and sand mixed with reworked ash (640 ka Lava Creek B) deposited soon after gravel deposition. Approximately 10 meters stratigraphically below Lava Creek B ash (in a quarry) several quartzite clasts were collected and analyzed using the isochron method for burial dating (Fig. 9). The isochron date for deposition of the gravel is 870 +/-220 ka. The slope of the line for this isochron is controlled by the $^{26}\text{Al}/^{10}\text{Be}$ concentrations from one clast, while the other data is clustered (Fig. 10). Thus, we interpret the age of this deposit to be 640- 870 ka and note that, while relatively imprecise, the burial date agrees with the tephrochronology and field relationships that show the gravel to be older but close in age to the Lava Creek B ash.



Figure 9. Photo of stratigraphy at Bostwick Park showing LCB Ash, gravel and the strath at the bottom of the quarry, (Photo L. Crossey).

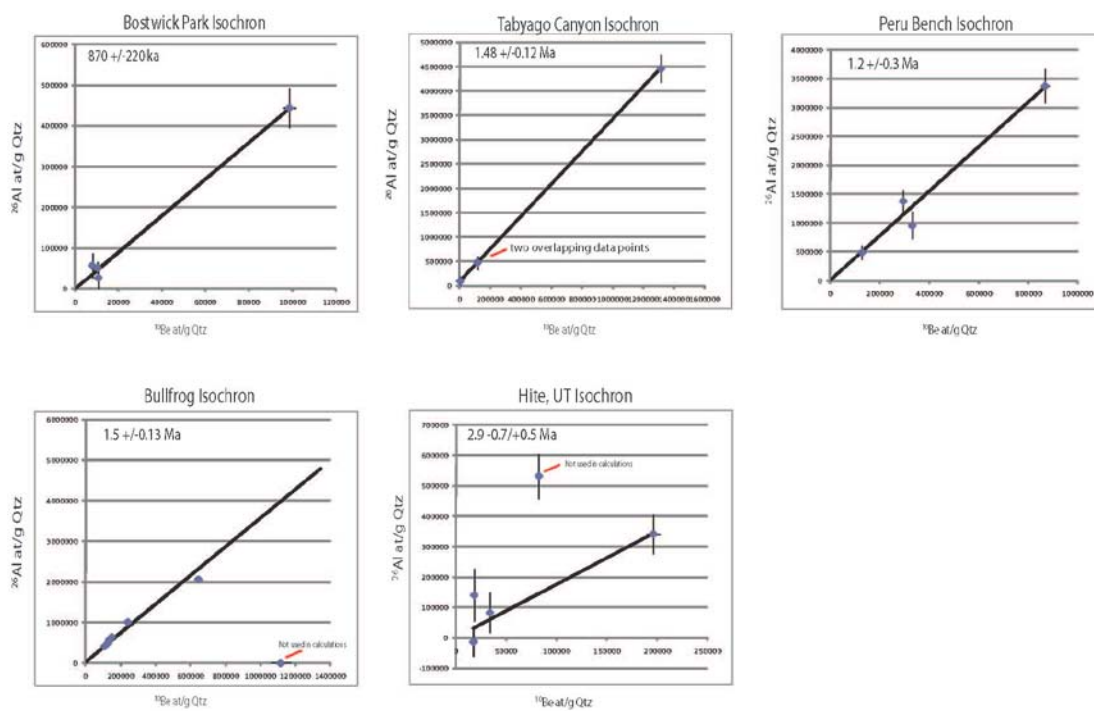


Figure 10. Isochron plots of $^{26}\text{Al}/^{10}\text{Be}$ data for determination of isochron dates. Certain data points on the plots are omitted from calculation because they do not fall on the line. Reworked clasts (possibly 20% of samples) may cause inaccurate date calculations, thus multiple samples on the same line provide more robust data.

GRAND AND GLEN CANYONS

Compilation Results

Published incision rate constraints near the knickpoint at Lee's Ferry and along Glen Canyon yield incision rates up to 500 m/Ma (Hanks et al., 2001; Garvin et al., 2005; Cook et al., 2009; Pederson et al., 2010). These high rates are from dates of 500 ka or less and include multiple cosmogenic surface exposure dating techniques and optically stimulated luminescence (OSL) dating. We focus on rates reported for the main stem from the river. For each area under discussion, we first report new rate data (from cosmogenic burial dating), then summarize the new results in the context of our incision rate compilation.

Burial Dating Results

Two samples were taken from different parts of the region upstream of Lee's Ferry at Bullfrog Marina and near Hite in Glen Canyon. Both were analyzed with the isochron technique due to relatively shallow burial. We sampled a high terrace which has a strath 190 m above the pre-Glen Canyon Dam river elevation (Birdseye, 1922) and a tread 205 m above the river. Gravel exposed at the base of one landslide scarp was sampled (depth of ~7 m, (Fig. 11) for burial dating and analyzed using the isochron technique. Six cobbles of far-traveled quartzite were collected, and each ground separately. By collecting large clasts, we obtained enough quartz from a single clast to assure uniform inheritance for the clast. This spot is estimated to be within a few meters of the bedrock strath, which was not exposed. Five points yielded good $^{26}\text{Al}/^{10}\text{Be}$ ratio, with errors less than 10 % and produced an isochron cosmogenic burial date of 1.5 +/- 0.13 Ma (Fig. 10). The resulting incision rate is 126 m/Ma (Table 2). The terrace tread (204 m above the river) was previously dated with a cosmogenic surface date of 480 ka

(Davis et al., 2001; Table 2), a factor of three different. We conclude that the surface date underestimates the terrace age due to degradation of the surface and/or movement of boulders on the terrace surface.

A second sample came from a terrace near Hite, Utah, about 240 km above the knickpoint and 50 km upstream of Bullfrog. The sample consisted of 5 clasts of sandstone collected from a ~5 m deep road cut through the terrace of the Dirty Devil River, ca. 4 km from the Colorado River (Fig. 11). This terrace has a strath 107 m above the Dirty Devil River and a tread 112 m above the river. This sample yielded an isochron age of $2.9 \pm 0.7 / -0.5$ Ma giving an incision rate of 37 m/Ma (Table 2).

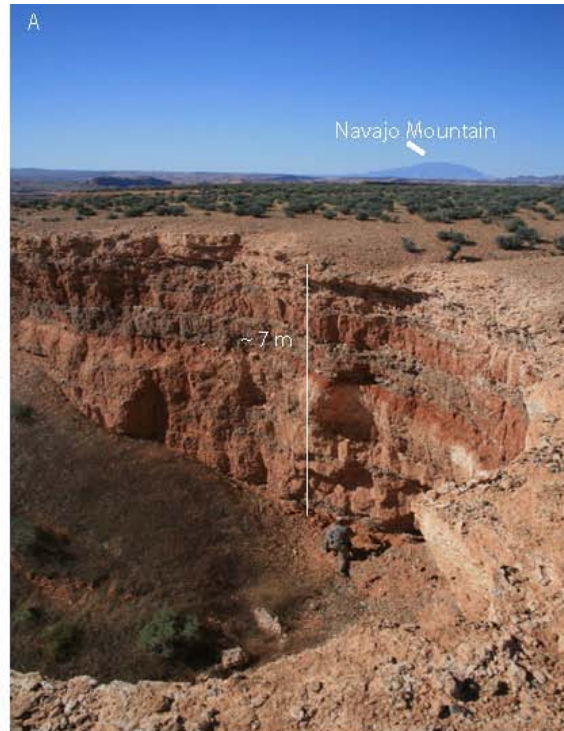


Figure 11. A. Photo taken while collecting the Bullfrog isochron samples (photo L. Crossey). B. Photo of the road cut sampled at Hite for a burial date. (Photo A. Darling).

Discussion of Rates

These two ages need to be understood in the context of regional published rates of 150-175 m/Ma over the last 2-3 million years in Grand Canyon, below the knickpoint (Pederson et al., 2002; Polyak et al., 2008; Karlstrom et al., 2008) and a rate on the San Juan River of 100 m/Ma over 1.3 Ma (Wolkowinsky and Granger, 2004). Locally our rates disagree with rates of up to 500 m/Ma just upstream of the knickpoint derived from cosmogenic surface dates ca. 500 ka and younger (Hanks et al., 2001, Garvin et al., 2005; Cook et al., 2009) as discussed above. To explain the apparently contradictory incision rates for the Bullfrog terrace, we infer that the rates based on the cosmogenic surface ages are too young, and/or average incision rates have increased in the last few hundred thousand years. We note that our rate of 126m/Ma is consistent with the burial date at Bluff, UT on the San Juan River (Wolkowinsky and Granger, 2004) in suggesting that, over 1-2 Ma timeframes, incision has been slower above, than below, the Lees Ferry knickpoint.

The difference in incision rate between Bullfrog and Hite is difficult to interpret and could be explained by at least three possible scenarios. 1) One or both dates could be inaccurate. Of the two, the Hite date is most in need of testing (presently underway). 2) The difference in incision rate, 126 m/Ma (Bullfrog) and 37 m/Ma (Hite), could be explained in terms of an incision transient that has reached Bullfrog but not Hite. 3) Perhaps a more serious problem arises because the upstream 2.9 Ma terrace at Hite (50 km upstream) is at a lower elevation than the downstream 1.5 Ma terrace at Bullfrog (a difference of 35 m) seeming to require tectonic tilting.

Figure 12 shows hypothetical terrace heights above the present river for 400 ka and 1.5 and 3 Ma timeframes interpolated from all available incision rate data that is near the Colorado River. We use our own rates for Bullfrog rather than Davis et al., 2001 as discussed above. This leads to a model to explain the data that includes aspects of both 2 and 3 above. The recent model of Cook et al., (2009) suggests that the knickpoint at Lees Ferry reflects both a hard bedrock ledge of the Kaibab Limestone at the knickpoint itself and a zone of “diffuse” transient knickpoint incision through softer rocks above the knickpoint. The latter results from modeling by Cook et al., whom point out that the model seems to be compatible with high incision rates from young terraces near Navajo Mountain (Hanks et al., 2001), the Fremont River (Marchetti et al., 2005), and Trachyte Creek (Cook et al., 2009). This model is also supported by knickpoints in tributaries above and below the mainstem knickpoint which are at similar elevations and may be a result of an increase in incision in their baselevel, the Colorado River. They suggest that this diffuse incision has progressed perhaps as far as the Cataract Canyon knickpoint.

Our data do not support the notion that there has been a large effect of rapid and young incision that far upstream from the main knickpoint, but it may help explain the different average rates at Bullfrog and Hite. For example, an increase in incision rate to 300 m/Ma in the last 0.5 Ma could change a nominal 50 m/Ma incision rate (since 3 Ma at Hite) to 125 m/Ma at Bullfrog. The transient incision shown in Figure 12, similar to the Cook et al. model, is envisioned to be diffusely bypassing the Lee’s Ferry knickpoint, and to have propagated to between Bullfrog and Hite.

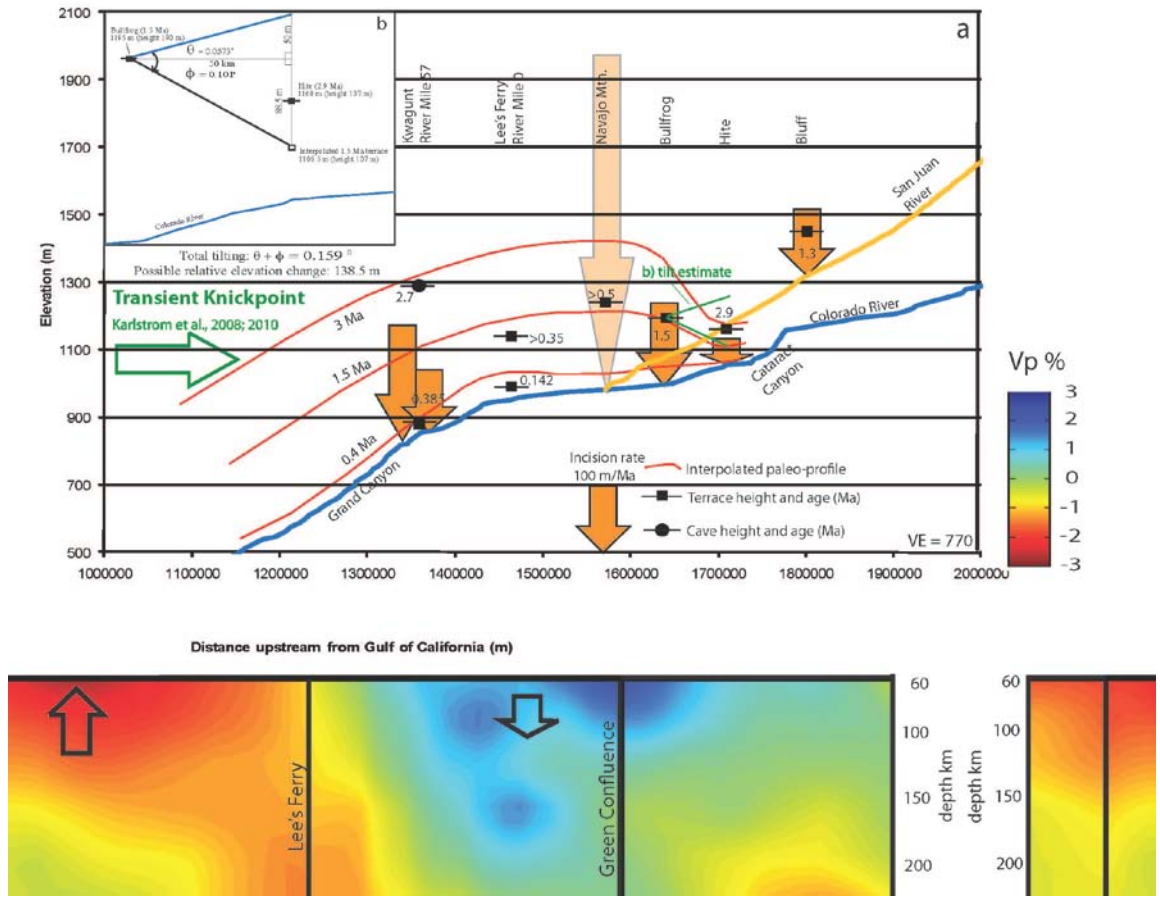


Figure 12. a) Incision constrains from eastern Grand Canyon and Glen Canyon from Hanks et al., (2001), Garvin et al., (2005), Cook et al., (2009), Pederson et al., (2010) and this volume. b) Methodology for determining a possible tilt of Glen Canyon to the east in the Quaternary drawn on the profile of the Colorado with known terrace elevations. Assumes slope of the paleo-CO-River to be equal to modern. Hite terrace is projected to the COR using the gradient of modern Dirty Devil, reducing elevation from Table 2 to seven meters. The 1.5 Ma terrace below Hite is interpolated assuming constant incision rate. Horizontal distance between terraces is measured as a straight line, not along the river channel. Mantle tomography beneath the profile (Schmandt and Humphreys, 2010) shows relative p-wave velocity under the Colorado plateau.

The more difficult problem is that the Bullfrog terrace (1.5 Ma) is at higher elevation (1195 m) than the Hite terrace (3 Ma, 1160 m when projected 4 km to the Colorado). It is geometrically difficult for an upstream terrace to be both lower in elevation and older than a downstream terrace in a generally eroding region. One solution to this problem is to invoke rock tilting between these two locations. These points are 50 km apart and figure 12b shows 1) the modern river gradient for reference (i.e. 50 m/50 km pinned by Bullfrog on the downstream end); 2) the upstream dip of the hypothetical geometry of the interpolated 1.5 Ma terrace, and 3) the 0.16 degree angle of tilt that would be inferred to explain the current 35 m of elevation difference over this 50 km distance due to East-tilting of the Hite point relative to the Bullfrog point.

Thus the observed differential incision could be driven by relatively short wavelength flexure of the earth's surface in the region of the Lee's Ferry knickpoint. The driving force for this flexure could be mantle buoyancy below the region (e.g. Karlstrom et al., 2008; Moucha et al., 2008; van Wijk et al., 2010). Figure 12 shows a tomographic cross section from directly below the river (Schmandt and Humpreys, 2010). High velocity mantle in the central portion of the Colorado Plateau and east of Lee's Ferry may be neutrally or negatively buoyant mantle compared to low velocity mantle below the Grand Canyon and the western Colorado Plateau. The observed 6-8 % contrast in mantle velocity requires sharp rheological and density contrasts and geodynamic models suggest these could produce on the order of 400 m of surface uplift. Given a flexural thickness of 25 km for the Colorado Plateau (Lowry et al., 2000), we propose that this could explain the postulated 140 m tilt (over 50 km and 1.5 Ma) needed to explain the data.

Hence, the combined hypothesis of Figure 12 is that the Lee's Ferry knickpoint is a transient that was set up at the time of integration of the Colorado River system across the Kaibab uplift and Grand Wash cliffs in the last 6 Ma (Karlstrom et al., 2008) and has been responding to both geomorphic and tectonic forcings that include migrating incision waves (including diffuse knickpoint propagation around a hard bedrock stratum), and differential rock uplift due to tilting driven by mantle flow.

UPPER COLORADO RIVER

Upper Colorado Burial Dating Results

Morrisania Mesa is an alluvial fan complex on the north flank of Battlement Mesa in Colorado which provided ideal shielding for a simple burial date from an amalgamation of quartz-rich drill-hole cuttings. Substantial drilling activity in oil and gas exploration has led to numerous drill holes that pierce high abandoned terraces and alluvial fans. The region surrounding Grand Mesa contains an extensive series of alluvial fan remnants which often bury Colorado River terraces (Yeend, 1969). Cuttings from a drill hole on Morrisania Mesa contained fragments of river gravel from a depth of 110 m which were analyzed assuming complete shielding.

Morrisania Mesa near Rifle Colorado yielded a simple burial date with assumed perfect shielding of 440 ka \pm 300 ka (Table 2). The terrace strath is approximately 94 m above the river and yields a poorly constrained incision rate of ca. 214 m/Ma (671-127 m/Ma; Table 2). This date is plotted alongside proximal incision rates from the literature in Figure 13. A simple linear regression of these incision rates and their height above the river reveal an apparently semi-constant incision rate of 168 m/Ma from 10 Ma basalt flows to the younger cosmogenic dates. Several other terraces buried by alluvial fans

exist in this region. Once their chronology is more closely constrained, this area may provide the evidence to support the trend that incision has, on average, remained constant for the last 10 Ma, or that it has accelerated from lower incision rates in the past to a rapid incision pulse (possibly a transient knickpoint) and then slowed down again before the Grass Mesa terrace was deposited. Also, several terraces are approximately the same height above the river and could further constrain the apparently ca. 1.8 Ma paleo-profile.

Significant incision (1500 m) has occurred around Grand Mesa basalt flows (extruded ~10 Ma; Kunk et al., 2002) at a mean rate of 150 m/Ma in western Colorado. Additional incision constraints from Lava Creek B ash yield a similar rate of around 150 m/Ma for locations close to Grand Mesa (Willis and Biek, 2001; Darling et al., 2009; Table 2). Substantial incision has occurred over long distances upstream at variable rates, but generally incision has occurred at 150 m/Ma around the broad western edge of the Rockies. Substantially down-dropped blocks due to evaporite dissolution/deformation reduce apparent incision rate substantially in central Colorado (Kirkham et al., 2000). The Gunnison River above the Black Canyon knickpoint is incising relatively slowly at 95 m/Ma since Lava Creek B time and at 64 m/Ma from basalt on top of Flattop Mountain dated to ~10 Ma (Aslan and Kirkham, 2007).

Remnant alluvial fan complexes like Morrisania Mesa around Battlement Mesa preserve underlying Colorado River gravel in several locations. Berlin et al., (2008) dated one of these fans at a height above the river of 227 m and calculated an age of $1.77 \pm 0.71/-0.51$ Ma which yields an incision rate between 92-180 m/Ma. This region is a prime location for attempting to date river gravel over a broad time frame (~10 Ma to

present), as these alluvial fans occur at several elevations and most of them contain river gravel (Yeend, 1969).

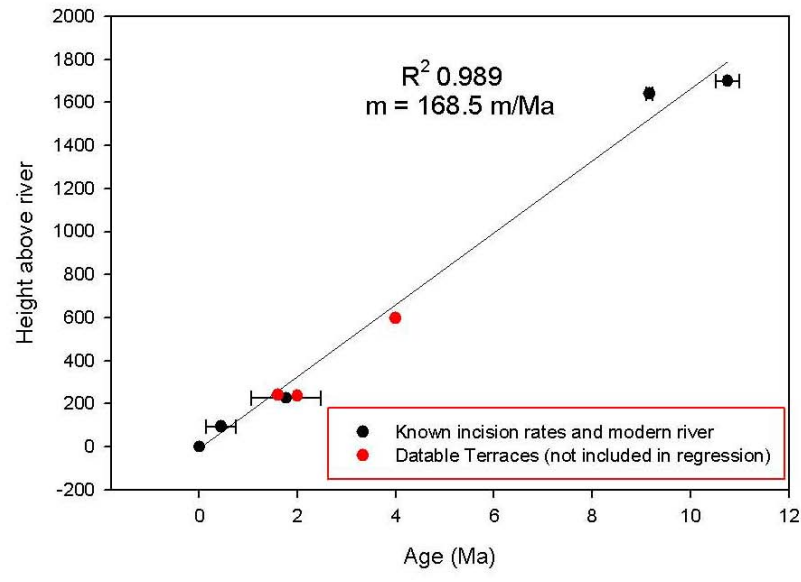


Figure 13. Plot of age vs height above the river for samples near Rifle, Colorado for four incision rate markers and the modern river. Heights of terraces that have not been dated are also shown. The data for this plot are listed in Table 2 for samples from Battlement, Grand, Grass, and Morrisania Mesas. Current data show semi-steady rates of incision in this region.

GREEN RIVER

Burial Dating Results

Tabyago Canyon of Desolation Canyon contains a large entrenched abandoned meander with a continuous gravel deposit (Fig. 14) currently overlain by locally derived colluvium and alluvium. Very recent tributary cut bank activity yielded an outcrop of river gravel (Fig. 15). Hand excavation down to the strath allowed us to sample clasts just above the strath. Burial depth of the sample was ~4 m below the surface, although the upper 0.5 m of this terrace consisted of reworked locally derived slope wash, colluvium and alluvium. Approximately 3.5 m of original depositional structures remained in the gravel deposit. Results for four clasts (Fig. 10) provide a calculated date of 1.48 +/- 0.12 Ma for this 60 m terrace. From these data we estimate an average incision rate of 40 m/Ma (Fig. 8).

Peru Bench near Green River, Wyoming consists of several flights of terraces up to ca. 180 m above the river with gravel pits in some of them. The 120 m terrace was sampled along the strath in a gravel pit for isochron burial dating with moderate burial depth (4 m) and resulted in a date of 1.2 +/- 0.3 Ma for Peru Bench, WY (Table 2, Fig. 1). This terrace date results in an average rate of 100 m/Ma (Fig. 8).

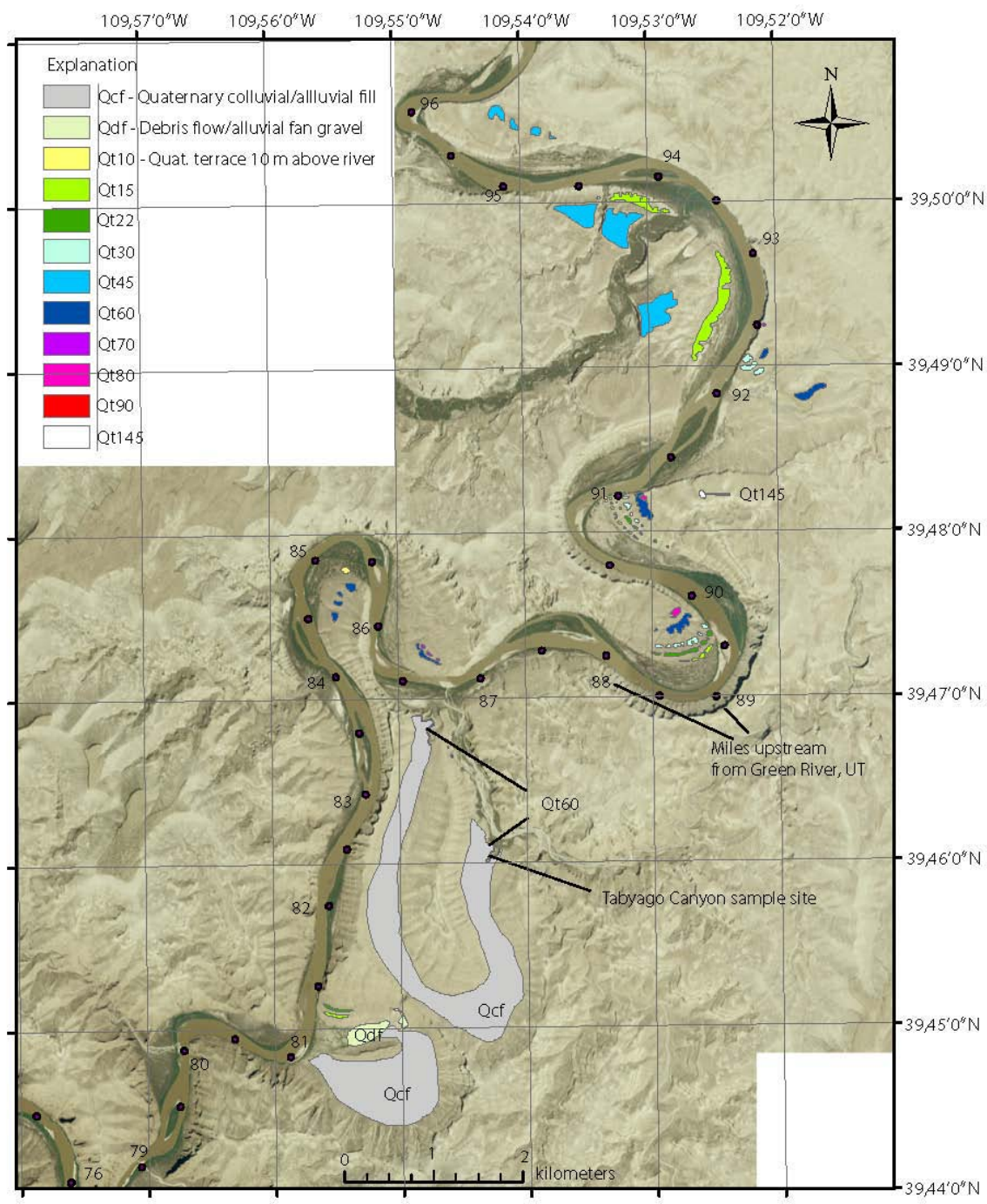


Figure 14. Map of Pleistocene terraces throughout Desolation Canyon. Sample location for new burial date for Tabyago Canyon is shown. Heights to terraces were measured with a laser range-finder.

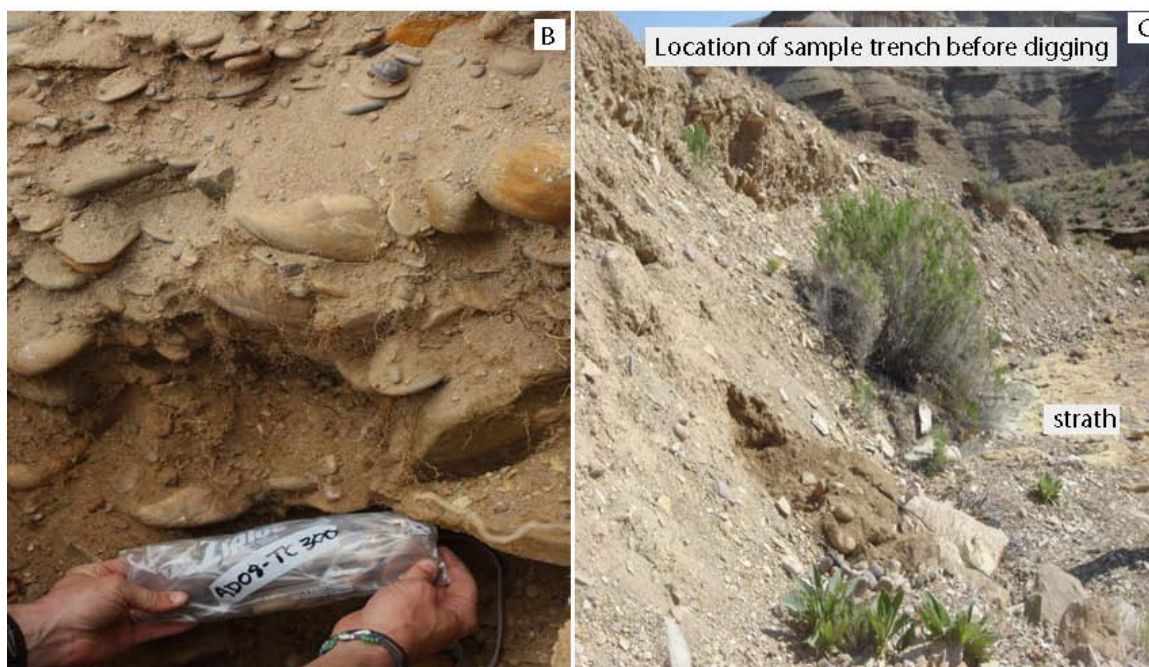


Figure 15. Collage of photos from Tabyago Canyon sample from Desolation Canyon. A) Bend in ephemeral stream with excavated hole; B) lower most gravel sample within the hole; C) profile photo of the cutbank, excavation of the pit is started in lower left corner. (Photos R. Crow).

Compilation Results

Work by Pederson et al. (2010) and Munroe et al., (2005) reports three incision rates on the Green River. One, from U-series dating of young travertine deposits along the Green just south of Green River, UT provides an incision rate of 300 m/Ma. A similar high rate of 400 m/Ma along the Green River near Canyon of Lodore is estimated from level of soil development as a guide to relative age, but these are not included in our incision rate database because of the lack of published geochronology. Munroe et al., (2005) describe briefly an incision rate of 90-115 m/Ma from a Lava Creek B ash site on a Green River terrace in western Brown's Park, and from their description it seems to be a reliable data point ("1"; Table 1). Thus in the area of the Canyon of Lodore the end of deposition within the Brown's Park Formation was <8.25 Ma with this ash and gravel within 50 m of the modern river (dated ash, Luft et al., 1985; Aslan et al., 2010). From these data incision has occurred at an average minimum rate of 6 m/Ma, and more recent incision has been much faster as the Green crossed the Uinta's in the late Neogene. We consider the Brown's park incision rate to be of moderate quality ("2") for bedrock river incision, which is the long term average of aggradation, incision and graben collapse in this basin. This point results in a minimum incision rate that clearly describes little bedrock incision. Lava Creek B ash reported by Izett and Wilcox, (1982) yielded a quality (1) incision rate near near the northern edge of the Green River Basin of 67 m/Ma (since 640 ka).

REGIONAL DISCUSSION

Comparison of the Colorado and Green River Systems

New cosmogenic incision rates along the Green River provide new controls for reconstructing 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 sedimentation <8.25 Ma and prior to terrace gravel deposition on Peru Bench at 1.5 Ma. Higher and older undated terraces along many portions of the whole Green River system suggest that our 1.5 Ma terrace date places a minimum date on postulated time of drainage reversal and development of a South-flowing Green River across the Uintas. Prior to this data Hansen (1986) suggested that the Green River flowed east away from the location of the town of Green River as recently as 640 ka based on the correlation of terraces at Peru Bench (Fig. 1) to terraces at the Rock Springs airport and terraces at Creston Junction on Interstate-80, which overlies Lava Creek B ash. In Hansen's model, capture of an east-flowing paleo-Green River that flowed over the modern Continental Divide initiated the present course of the Green River through the Gates of Lodore and across the Uinta uplift. However, the 640 ka Wyoming terrace gravels consist of angular, locally derived clasts unlike the rounded basement cobble deposits of Green River gravel (Ferguson, 2010). Thus the drainage changed from possibly flowing to the northwest (Ferguson, 2010), to the present southerly course after deposition of the Brown's Park Formation, after 8.25 Ma and before 1.5 Ma.

The steeper and older (to 10 Ma) Colorado River is either a result of uplift or resistant lithologies, and since incision rates are higher in the harder rock of the Colorado than the softer rock of the Green, it seems that rock type resisting erosion is not the main control. Because incision rates in the Uinta Basin are one third of the upper Colorado

rates, we infer that the Green River system is responding to different forces than the Colorado. These forces could be the result of transient incision as the Desolation knickpoint approaches the Uinta Basin, or differential tectonic uplift between the Green and the upper Colorado in the last ca.1.5 Ma or a combination thereof.

Isostatic Response and Incision Rates

The volume of denuded material on the Colorado Plateau and surrounding area show that the majority of erosion, and hence rock uplift from isostatic rebound, is centered around the middle of the Colorado Plateau (Pederson et al., 2002b; McMillan et al., 2006; Lazear et al., 2010) due to the large area over which a 1-2 km thick section of Mesozoic rock was removed from this region. Addition of Basin and Range extensional denudation as an additional cause of isostatic rebound modifies the inferred patterns of isostatic rock uplift (Roy et al., 2009) and timing of differential denudation also affects the isostatic calculations. These estimates for isostatic response are needed to determine if other sources of rock uplift have occurred.

We use a map of calculated isostatic rebound magnitude compared to incision rates does not reveal a direct correlation (Fig. 16). Rates of rebound used below assume rock uplift is averaged over 6 Ma, the best estimate for onset of erosion in the central Colorado Plateau as determined by low-temperature thermochronometry (Kelley and Blackwell (Kelley and Blackwell, 1990; Hoffman et al., 2010) and earliest sediment from a mostly or completely integrated Colorado River in the Gulf of California (Dorsey et al., 2010.).

Figure 16 plots incision rates on a map of isostatic response calculations to test whether the differential incision we observe is reasonably explained only by isostatic response or whether tectonic uplift is a possible explanation. Through Grand Canyon incision rates are greater than estimated rebound rates by about 100 m/Ma and imply a rock uplift component that is not isostatic (Karlstrom et al., 2008; Moucha et al., 2008). Central Colorado Plateau rate estimates are maximum rates and only sampled from the last 300 ka in few locations, however high rates may correlate with large magnitude rebound in this area and coincide with the region presumably affected by transient incision above Lee's Ferry (Cook et al., 2009). Along the Green River the incision rate at Tabyago Canyon is 75 m/Ma lower than estimated rebound, implying either that the Plateau has net negative rock uplift or that the Desolation Canyon knickpoint is transient. Reliable rates along the Green below Desolation Canyon are needed to assess this region further, however the maximum rate of 300 m/Ma from Pederson et al., (2010), seems to imply transient incision in Desolation Canyon, although the rate is not from within the canyon. Estimates of rebound throughout the Colorado Rockies are less than observed incision by 100-250 m/Ma, with the greatest difference around the San Juan Mountains and maintaining 100 m/Ma or more to the north side of the Colorado River. The Peru Bench incision rate is 84 m/Ma higher than estimated rebound and implies recent uplift of southwest Wyoming, corroborated by studies of tectonically tilted Ogallala Formation further east (McMillan et al., 2002).

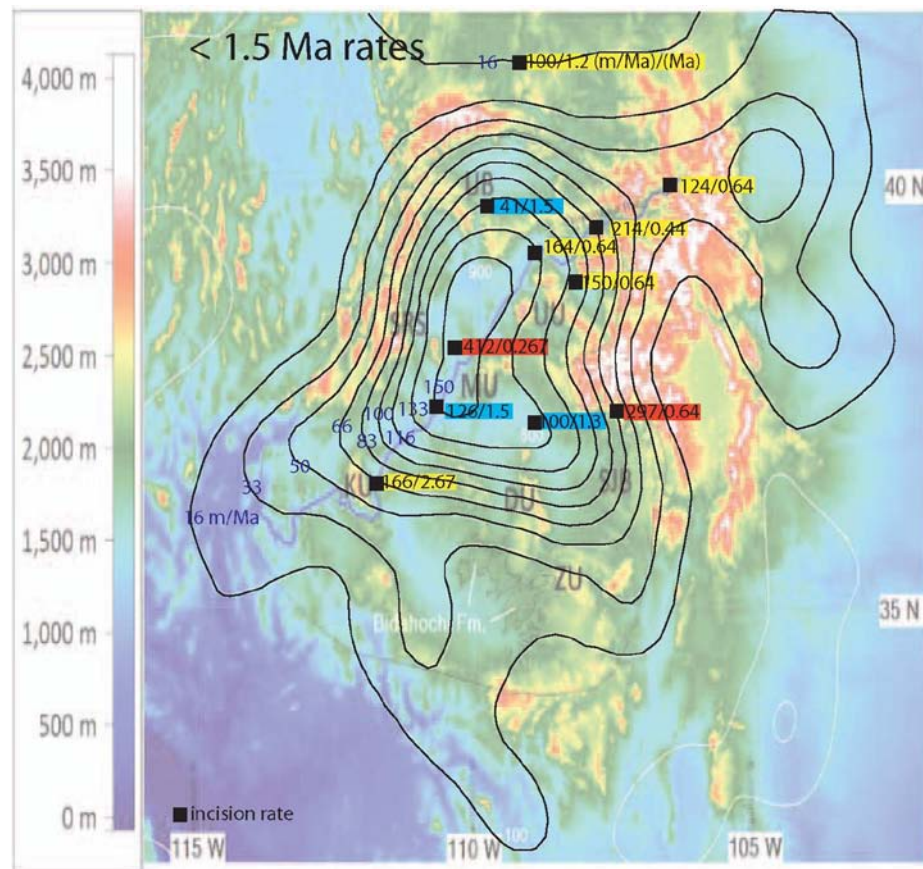


Figure 16. Isostatic rebound on the Colorado Plateau compared to incision rates, modified from Lazear (2010). Rebound rate contours (in m/Ma) are calculated average rates from estimated rebound magnitude and assumed uniform 6 Ma onset of exhumation. Incision rates are reported as incision rate over measured time and includes only rates from 1.5 Ma or younger (i.e. (m/Ma)/Ma). Red incision rates are much higher than estimated rebound, yellow are higher than rebound, and blue are less than rebound.

Origin and Evolution of Knickpoints

Figure 17 shows a regional view of the bedrock substrate of the Colorado River and Green River systems. Note that in order of “erodibility”, Precambrian basement is harder than Paleozoic rocks (which have abundant carbonate facies in this region), which, in turn, are harder than Mesozoic rocks (abundant shale and less indurated sandstone), and Tertiary sandstone and shale is generally weakest (Pederson et al., 2010). Rivers commonly develop steeper gradients to incise through harder rocks (Duvall et al., 2004), but the relative importance of bedrock control versus incision transients as the primary explanation for Colorado River knickpoints is debated (Cook et al., 2009; Pederson, 2010).

An empirical comparison of bedrock and knickpoints along the Colorado River system is useful. Several reaches in the upper Colorado and Green river systems are underlain by crystalline basement rock (Fig. 17); some are prominent knickzones and others are not. Grand Canyon’s overall steepness (1.5 m/km) could be attributed to hard bedrock that underlies approximately 50% of the river (Mackley and Pederson, 2004), but is interpreted by others as a transient feature (Karlstrom et al., 2008; Cook et al., 2009; Pelletier, 2010). At small scales, basement reaches are a few percent steeper than sedimentary reaches in Grand Canyon (Hanks and Webb, 2006). Westwater Canyon is also a reach with crystalline basement rock, but it produces a very small knickpoint (not noticeable on Figure 17). Instead its gradient (1.9 m/km) is only 2-3 times higher than gradients in the adjacent Paleozoic (0.65 m/km) and Mesozoic strata (0.9 m/Ma), which contrasts with the >30m/km gradient through the Gunnison knickzones, a remarkable difference in slope given similar rock.

Other major knickzones are not underlain by basement rock. Cataract Canyon, for example, has a high gradient reach within Paleozoic rock and the steep gradient has been attributed to debris flows and landslides in a region with active salt-tectonism and shallow normal faulting (Huntoon, 1988 and references therein). Desolation Canyon on the Green River is a large knickzone underlain by Tertiary sandstone and shale layers with a gradient just below the knickpoint of about 2.3 m/km (steeper than Westwater). This knickpoint closely corresponds with the transition from weak Green River Formation shale to somewhat more resistant Wasatch Formation sandstone, perhaps partly explaining the knickpoint. However, since the Green flows low resistance rock and is steeper through this reach, these canyons seem to be counter examples to bedrock being the primary control on steep gradients.

The Uinta Mountain knickzone (2.7 m/km) is probably also of composite origin. It is partly due to debris flow and rockslide sediment accumulation (Grams and Schmidt, 1999), with the hard quartzite of the Uinta Mountain Group contributing to resistant substrate, channel banks and boulders in the channel. Drilling data show the knickpoints in quartzite bedrock beneath the river in Canyon of Lodore and Flaming Gorge, (Fig. 18; Woolley, 1930) suggesting bedrock influences as well as sediment input. Young deformation also possibly affects the profile (Hansen, 1986). In addition, the young piracy of a post-8 Ma north-flowing river to the current channel position (Hansen, 1986; Pederson, 2010; Ferguson, 2010) might have produced a transient incision wave or waves.

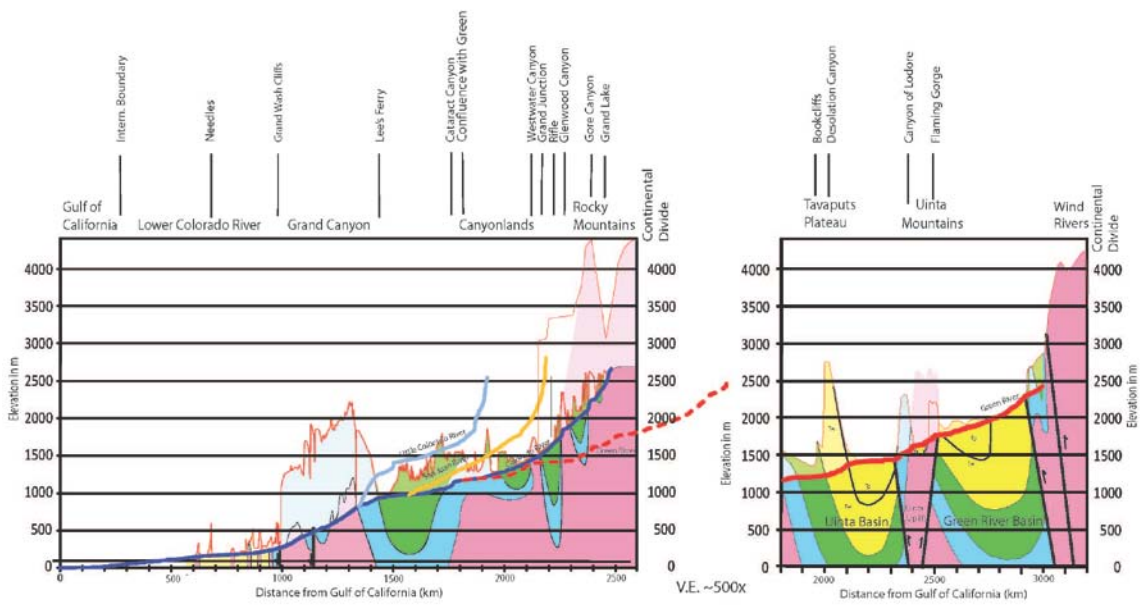


Figure 17. Longitudinal profiles with schematic bedrock geology and canyon names. V.E. ~500x. Yellow = Tertiary sedimentary rocks, Green = Mesozoic sedimentary rocks, Blue = Paleozoic sedimentary rocks, Pink = Precambrian igneous and metamorphic rocks.

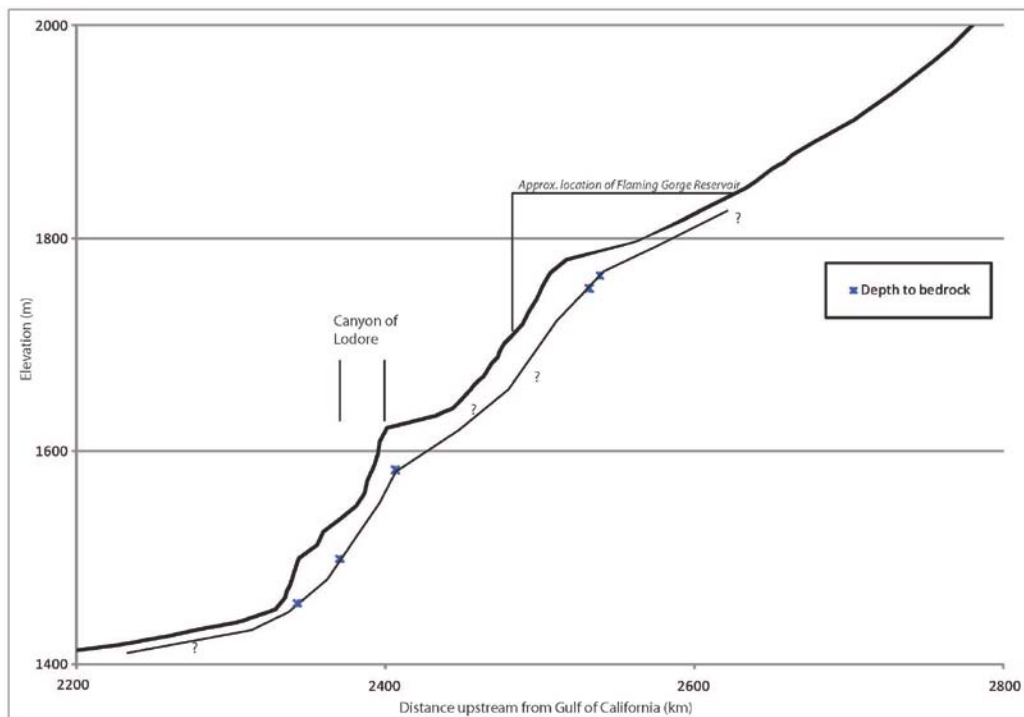


Figure 18. Depth to bedrock from borehole data in Canyon of Lodore/Flaming Gorge. These data show the knickpoints in the bedrock long profile, the river surface profile, and the thickness of sediment plus water.

CONCLUSIONS

Transient Incision

1) Our new burial dates placed in the context of existing incision rates lead to the following conclusions. Based on differential incision data, the knickpoint at Lee's Ferry is transient, and the knickpoint in Desolation Canyon may be transient. Other knickpoints in the system are yet to be determined to be transient. Knickpoints migrating upstream may move at rates 2-3 orders of magnitude greater than incision rates on the Colorado Plateau. This result implies that those knickpoints that are shown to be transient within the Colorado River system are recent (<6 Ma) and mobile phenomena, and must result from recent tectonic and integration related perturbations.

2) The hypothesis of a transient knickpoint at Lee's Ferry is further supported by our data, and more detailed patterns are currently explained by a combination of diffuse incision bypassing the knickpoint (modified from Cook et al., 2009) and tectonic forcing above a mantle velocity gradient that underlies Lees Ferry. The speed of recent rapid incision estimated by young dates is probably exaggerated by minimum age estimates however this pulse may still be contributing to canyon cutting in the last few hundred thousand years.

3) Green and Colorado Rivers comparison suggests regional rock uplift of the Rockies in last 6-10 Ma. The Green River integrated across the Uinta Mountains prior to 1.5 Ma and incision has proceeded differentially throughout the river. The rates of 40 m/Ma above Desolation Canyon imply that this section of the Green is different from the Colorado which has been incising at 150 m/Ma as seen in long and short term rates since 10 Ma (Figs.7 and 8). The differential incision rates of the upper Colorado River system

imply differential rock uplift of the Colorado Rockies and the Wyoming Rockies relative to the Colorado Plateau.

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APPENDIX AND TABLES

APPENDIX 1

AMS results used to calculate cosmogenic burial dates

Darling, 2010 UNM	[10Be]	unc	[26Al]	unc
	atoms/g qtz		atoms/g qtz	
Isochron Data				
Bullfrog terrace				
BF 1	644049.6	22704.53	2063041	93940.97
BF 2	149948.7	11702.61	645638.7	81136.41
BF 3	106388.1	7090.566	418395.2	32634.82
BF 5	133693.9	7773.876	570618	79886.51
BF 6	239903.2	15092.56	1009466	97918.17
BF 7	125356.9	6861.348	497818.7	508204.1
Hite terrace				
Hut 1	196291.3	7059.704	341629.8	64636.13
Hut 4	18134.17	1937.237	140785	84776.38
Hut 5	17383.82	1968.691	-12327.2	47483.2
Hut 6	33798.89	3264.399	82941.92	66844.02
Tabyago Canyon				
TC 1	117765	4943.002	465979	139264
TC 2	1314548	21003.52	4462084	294448.1
TC 3	4592.644	3680.544	89038.07	102100.1
TC 5	115625	5337.377	481060.7	69655.36
Peru Bench				
PWY 1	128423.3	14436.14	494947.6	118511.6
PWY 2	867591.9	18734.88	3370666	290719.8
PWY 3	295507.5	9600.891	1380436	193058.6
PWY 4	331360.9	10901.02	955580.6	239256.3
Bostwick Park				
BP 3	10862.91	795.138	25997.11	25672.32
BP 5	10548.87	738.9501	49980.88	15711.02
BP 6	98738.21	2862.177	443831.3	49969.85
BP 7	8027.217	772.7415	56145.49	29957.38

Sample Number/Source	Dating Method	Exposure/ Collapse?	Geographic Location	Nearest River	Incision Rate	Max Rate	Min Rate	Measured Age (Ma)	Error (std dev.)	(+ Error) (- Error)	Depth (m)	Height (m)	Lat	Long	Sample Material	Geochronology Notes	Field Notes	Other Comments	
Carriv et al., 2005	¹⁴ C exposure		2 1/3 surface	Cobaco	459	591	375	0.567	0.127	0.127	0.127	261	125	37.12000	-110.98000	Boulder	Array of surface ages reported, oldest reported here. Minimum age.		
Munk et al., 2002	⁴⁰ Ar/ ³⁹ Ar		2 Basal Mountain CO	Cobaco	105	106	104	10.49 (0.07 Z sigma)	0.07	0.07	1102	2870	39.40349	-108.99244	Basalt	Shield volcano that does not have any known relationship to river gravel			
Beffert et al., 2008	⁴⁰ Ar/ ³⁹ Ar		2 Battered Mesa, CO	Cobaco	179	180	178	9.16 (0.06 Z sigma)	0.06	0.06	1640	3200	36.38638	-107.86663	Basalt	Not sure of source of Ar/Ar date.			
Mokwinsky and Granger, 2004	Cosmogenic burial		1 Bullfrog, UT	San Juan	110	129	99	1.38 (0.150.2)	0.15	0.2	150	1450	37.29264	-108.54538	Quartz, rich cobbles	Cosmogenic burial date from vertical profile through gravel in a Nevada Nation quarry.			
Dering et al., this volume	Isotchon Cosmogenic burial		1 Bostwick Park CO	Garrison	385	515	307	0.87	0.22	0.22	0.22	335	2073	38.49415	-107.72873	Quartz, rich cobbles	Reported 1980's by Diersen on to include Mesa Falls ash. Chemical studies (USGS) were not conclusive as to the identity of 'Mesa Falls sample'. Cosmogenic is younger than Mesa Falls by at least 200 ka, hence in line with Mesa Falls ash.		
Carriv et al., 2005	¹⁰ Be exposure		2 Bridge, UT	Rainbow Bridges Creek	492	632	403	0.122	0.027	0.027	60	60	37.07000	-110.94000	Boulder	Array of surface ages reported, oldest reported here. Minimum age.			
Munroe et al., 2005	Tephrochronology		2 Brown's Park, UT	Green	102	115	90	0.84	0.04	0.04	65	1685	40.91320	-108.30498	Ash	Ash age given, deposits are reworked tal deposits presumed to be all post-date tal.		Little Hole Day use area 10 km downstream of Framing Gorge Dam. Details in Counts, 2005 Utah State Thesis	
Devis et al., 2001	Cosmogenic surface		3 Bullfrog, UT	Cobaco	395	465	365	0.479	0.012	0.012	189	189	37.51000	-110.89800	Boulder	Cosmogenic surface date on the same terrace as our Bullfrog date, surface date is 13 as old.			
Dering et al., this volume	Isotchon Cosmogenic burial		1 Bullfrog, UT	Cobaco	126	138	116	1.50	0.13	0.13	7	189	1195	37.51000	-110.69949	Quartz, rich cobbles	Mess was used scarp yields fresh exposure for sampling. Isotchon shows good linearity with 6 cists. Region contains relatively vast deposits of river gravel.		Elevation of river bottom taken from 1971 survey.
Replea et al., 1997	¹⁰ Be cosmogenic exposure profile		2 Carvelle Peaseau, UT	Fremont	881	1024	743	0.151 (0.24?)	0.024	0.024	130	130	38.34775	-110.98518	Quartz, rich gravel			Late location & approximate	
Replea et al., 1997	¹⁰ Be cosmogenic exposure profile		2 Carvelle Peaseau, UT	Fremont	333	392	290	0.06 (0.09?)	0.009	0.009	20	20	38.34775	-110.98518	Quartz, rich gravel			Late location & approximate	
Asken et al., 2008	Tephrochronology	yes	3 Caronvale, CO	Rearring Fork	86	86	86	0.639 (0.2 Z sigma)	0.002	0.002	55	55	39.39454	-107.23571	Ash	Ash age given, deposits are reworked tal deposits presumed to be all post-date tal.		This sample is within Eagle Valley evaporite collapse region	
Brown et al., 2007	Tephrochronology		1 Diersen, CO	Cobaco	133	133	133	0.639 (0.2 Z sigma)	0.002	0.002	85	1950	39.64601	-107.08393	Ash	Ash age given, deposits are reworked tal deposits presumed to be all post-date tal.		Site has no locations of LOB ash, one appears to have eroded down by landsliding. Rate is for higher, non-sterilized block with ash.	
Patton et al., 1991	Tephrochronology	no	1 Durango, CO	Arimas	297	298	296	0.639 (0.2 Z sigma)	0.002	0.002	190	190	37.21671	-107.84738	Ash	Ash age given, deposits are reworked tal deposits presumed to be all post-date tal.		Preserved in large outwash gravel deposit	
Asken et al., 2008	Tephrochronology		1 Eagle, CO	Eagle	100	100	100	0.639 (0.2 Z sigma)	0.002	0.002	64	2100	39.65385	-108.79110	Ash	Ash age given, deposits are reworked tal deposits presumed to be all post-date tal.			

Table 2. Page 1 of 3. Incision rates compiled throughout the Colorado River system on the Colorado Plateau and Colorado Rockies. Qualitative assessment of reliability is ranked 1 through 3, 1 being most reliable.

Lurt, 1985	Zircon FissionTrack		3 East Bone Draw, UT	Utah State	27	30	25		8.6(0.8 ?)	0.8	0.8	232	1982	40.64108	-108.53654	Ash in Browns Park. Not a true incision rate although shows that landscape has not denuded much.	
Asian et al., 2008	Tephrochronology		1 Elk Creek CO	Yampa	102	102	101		0.639 (0.02 (2sigma))	0.002	0.002	65		40.53789	-107.42653	Ash age given, deposits are reworked tal deposits presumed to be ash post-date tal.	
Asian and Kirkham, 2007; Sotik et al., ?	40K/39Ar	no	2 Flat Top Mountain, CO	Gunnison	64	64	64	10		0.7	0.7	640	378	38.88320	-108.89700	Basal on river gravel, cists derived from eroded basement rocks from the Central Rockies.	
Lurt, 1985	Zircon FissionTrack		3 Goshute Gulch, UT	Green	6	7	6		8.25(0.7 ?)	0.24	0.24	52	1683	40.82883	-108.90809	Ash in Browns Park	
Asian et al., 2007; Kunk et al., 2002	40Ar/39Ar	no	1 Grand Mesa, CO	Covardo	144	148	141		10.76(0.24 (2sigma))	0.24	0.24	1554	2335	39.04464	-108.21477		
Beiring et al., 2008	Burial Cosmogenic	no	2 Cross Mesa, CO	Covardo	128	180	92		1.77(0.7) (0.51)	0.71	0.51	1	227	38.53934	-107.78633	1 m tunnel, modeled age expressed in abstract and student (W. Beiring) did not continue work in this area.	
Deiring et al. this volume	Isotchron Burial Cosmogenic		1 Hite, UT	Dry Devil	37	45	30		2.90(0.7) (0.5)	0.70	0.50	6	107	37.91741	-110.38806	Isotchron data with slope controlled by one data point - needs verification.	Terrace near the confluence of Dry Devil and Colorado. Sample taken from 1 of two road cuts. More COR terraces South, across COR. Projecting this terrace to COR (~1053 m), yields height still 107 and but elevation 1161
Merchell et al., 2005	Exposure		2 Ivy Canyon, UT	Fremont	238	310	221	0.6		0.1	0.1	155	2565	38.55451	-111.58089	Detailed chronology notes in Merchell et al., 2005.	
Winkler, 1970; Dennon, 1970	40K/39Ar		3 Jesse Eving Crn, WY	Green	4	4	4	11.8	0.4	0.4	49	1708	40.91357	-108.14773	Ash in Browns Park		
Harden et al., 1985	Paleomagnetism		3 Keg Knoll, UT	Green	290	571	160	1.6	0.9	0.9	400	1620	38.54600	-110.02979	Fact of magnetically reversed only allows the assumption of an age bracket. In comparison with a good date may be helpful.		
Hansen, 1980's; Asian et al., 2008	Tephrochronology		1 Lake Fork, CO	Gunnison	95	98	95		0.639 (0.02 (2sigma))	0.002	0.002	61	2354	38.44820	-107.28884	Ash age given, deposits are reworked tal deposits presumed to be ash post-date tal.	
Peelerson et al., 2010	OSL		1 Lees Ferry	Covardo	150	150	150	0.12			18			38.65397	-111.60519	Multiple chronology points reported, we chose to report those closest to the stream in the terrace and report the rate to 300 m/s water level	Lat Long location is approximate
Peelerson et al., 2010	OSL		1 Lees Ferry	Covardo	289	289	289	0.142			41			38.65397	-111.60519	Multiple chronology points reported, we chose to report those closest to the stream and report the rate to 300 m/s water level	Lat Long location is approximate
Peelerson et al., 2010	OSL		1 Lees Ferry	Covardo	221	221	221	0.077			17			38.65397	-111.60519	Multiple chronology points reported, we chose to report those closest to the stream and report the rate to 300 m/s water level	Lat Long location is approximate
Kunk et al., 2002	40Ar/39Ar	no	2 Little Baby Mtn, CO	Covardo	115	116	114	10.38(0.12 (2sigma))	0.12	0.12	1192	2300	38.42489	-107.46706			
Brown et al., 2007; Kunk et al., 2002	40K/39Ar	no	2 Little Grand Mesa, CO	Covardo	114	115	113	7.74(0.06 (2sigma))	0.06	0.06	884	2652	38.57542	-107.15434			
Brown et al., 2007; Kunk et al., 2002	40Ar/39Ar	yes	3 Lookout Mountain, CO	Covardo	75	75	75	9.72(0.05 (2sigma))	0.05	0.05	730	2500	38.54197	-107.26658			
Larson et al., 1975; Asian et al., 2007	Tephrochronology	no	1 McCoy, CO	Covardo	124	124	123	0.639 (0.02 (2sigma))	0.002	0.002	79	2103	39.82803	-106.74453	Ash age given, deposits are reworked tal deposits presumed to be ash post-date tal.		
Asian et al., 2008	Tephrochronology		1 Meeker, CO	White	141	141	140	0.639 (0.02 (2sigma))	0.002	0.002	90			40.06638	-108.01984	Ash age given, deposits are reworked tal deposits presumed to be ash post-date tal.	
Deiring et al. this volume	Burial Date	no	1 Montezuma Mesa, CO	Covardo	214	671	127	0.4(0.3 ?)	0.30	0.30	110	94	1655	39.46654	-107.98882	Nicely shielded however poor precision. Combining this with other bore hole samples would be very helpful.	

Table 2. Page 2 of 3. Incision rates compiled throughout the Colorado River system on the Colorado Plateau and Colorado Rockies. Qualitative assessment of reliability is ranked 1 through 3, 1 being most reliable.

Coa, 2010 open file report																			Basalt on river gravel, gravelly mainly volcanics from west side mountains. Sparse quartzite, granite and schist debris well from central rocks.	
	40Ar/39Ar	1 Mt. Defiance, CO	N. Fork of Garrison	171	171	1038														
Harris, 2010	²⁶ Al/ ¹⁰ Be cosmogenic exposure	2 Navajo Mountain, AZ	San Juan	500	625	477	0.5	0.1	0.1	0.1									One surface projected toward the river, the top of the canyon walls at 4100 ft. Compared to date or height, this date is very young (probably close to 2 Ma in reality) and the rate is doubtful.	
Geniv et al., 2005	¹⁰ Be exposure	2 Oak Island, UT	Coeur d'Alene	639	825	521	0.266	0.06	0.06	0.06									Area of surface ages reported, oldest reported here. Minimum age.	
Darling et al., this volume	Isotchron Cosmogenic burial	1 Penn Bench, WY	Green	92	121	73	1.20	0.30	0.30	0.30	4	1101865							One terrace via suite of terraces. Cosmogenic samples are from the bottom of a gravel pit.	
Wills and Bek, 2001; Asan et al., 2007	Tephrochronology	1 Prairie On McDonald Cr, CO	Colorado	164	165	164	0.639 (0.2) (sigma)	0.002	0.002	0.002		1051426							Ash deposit is upstream of McDonald Creek. The same terrace appears to be preserved most of the way down into the river, terrace height is projected to river from there.	
Sardoval, 2017	Tephrochronology	1 Petroco Canyon, CO	Garrison	509	510	507	0.639 (0.2) (sigma)	0.002	0.002	0.002		3252200							Ash age given deposits are reworked (all deposits presumed to closely post-date fall.	
Darling et al., 2009	Tephrochronology	1 Sawmill Mesa, CO	Garrison	150	151	150	0.639 (0.2) (sigma)	0.002	0.002	0.002		961571							Ash age given deposits are reworked (all deposits presumed to closely post-date fall. Age compared to Bosworth Park burial age. Time span of gravel deposition, abandonment and ash deposits is ~200-400 ka.	
Brown et al., 2007; Kuk et al., 2002	40K/39Ar	no	no	107	108	107	7.80 (0.4) (2 sigma)	0.04	0.04	0.04		8372655							Weakly preserved ash fall in the graded sediment below locally derived gravel. This package is on top of Uncompaghe River the gravel close to the modern incision line.	
Kuk et al., 2002	40Ar/39Ar	no	no	88	88	87	15.6 (0.9) (2 sigma)	0.09	0.09	0.09		13692833							Probably debris flow basalt boulders, reported as a terrace with channels cut in by Kirkham et al., 2002.	
Kuk et al., 2002	40Ar/39Ar	no	no	114	117	111	10.4 (0.26) (2 sigma)	0.26	0.26	0.26		11502926							Pan. Tops, Wilderness Area, No river gravel.	
Darling et al., this volume	Isotchron Cosmogenic burial	1 Tanager Canyon, UT	Green	41	44	38	1.48	0.12	0.12	0.12	4	601475							Probably outside of salt collapse, no gravel.	
Cook et al., 2009	²⁶ Al/ ¹⁰ Be cosmogenic exposure profile	2 Trachyte Creek, UT	Trachyte	412	448	381	0.267 (0.4) (?)	0.0214	0.0214	0.0214		110							Abandoned meander ~80 m above Green River. Sample location for the burial date is a cutbank in an ephemeral channel that recently cut into the terrace. Upper portion of preserved deposits is reworked locally derived gravel (~1.5m), sitting on top of ~3m of river material.	
Cook et al., 2009	²⁶ Al/ ¹⁰ Be cosmogenic exposure profile	2 Trachyte Creek, UT	Trachyte	348	414	301	0.178 (0.23) (?)	0.0283	0.0283	0.0283		62							Four data points isotchron. Date very good nearby.	
Cook et al., 2009	²⁶ Al/ ¹⁰ Be cosmogenic exposure profile	2 Trachyte Creek, UT	Trachyte	538	1521	327	0.0130 (0.084) (?)	0.0084	0.0084	0.0084	7								Mean of 2 burial dates, original result reported in Asan GSA Abstract, 2007.	
Asan et al., 2010 update	Cosmogenic burial	1 Wenasop Canyon, CO	Colorado	564	802	453	0.81	0.24	0.24	0.24		4571884							Ash in Brown's Park.	
Beck, 1975; Nasser et al., 1980	Zircon Fission Track	3 Vermilion Cr, UT	Green	14	15	14	9.9 (0.4) (?)	0.4	0.4	0.4		1401768								
Beck and Wilcox, 1982 WY #2	Tephrochronology	1 W. of Prehalek, WY	Green	52	53	53	0.639 (0.2) (sigma)	0.002	0.002	0.002		942294								

Table 2. Page 3 of 3. Incision rates compiled throughout the Colorado River system on the Colorado Plateau and Colorado Rockies. Qualitative assessment of reliability is ranked 1 through 3, 1 being most reliable.