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Rapid incision of the Colorado River in Glen Canyon – insights from channel profiles, local incision rates, and modeling of lithologic controls

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ABSTRACT: The Colorado River system in southern Utah and northern Arizona is continuing to adjust to the baselevel fall responsible for the carving of the Grand Canyon. Estimates of bedrock incision rates in this area vary widely, hinting at the transient state of the Colorado and its tributaries. In conjunction with these data, we use longitudinal profiles of the Colorado and tributaries between Marble Canyon and Cataract Canyon to investigate the incision history of the Colorado in this region. We find that almost all of the tributaries in this region steepen as they enter the Colorado River. The consistent presence of oversteepened reaches with similar elevation drops in the lower section of these channels, and their coincidence within a corridor of high local relief along the Colorado, suggest that the tributaries are steepening in response to an episode of increased incision rate on the mainstem. This analysis makes testable predictions about spatial variations in incision rates; these predictions are consistent with existing rate estimates and can be used to guide further studies. We also present cosmogenic nuclide data from the Henry Mountains of southern Utah. We measured *in situ* ^{10}Be concentrations on four gravel-covered strath surfaces elevated from 1 m to 110 m above Trachyte Creek. The surfaces yield exposure ages that range from approximately 2·5 ka to 267 ka and suggest incision rates that vary between 350 and 600 m/my. These incision rates are similar to other rates determined within the high-relief corridor. Available data thus support the interpretation that tributaries of the Colorado River upstream of the Grand Canyon are responding to a recent pulse of rapid incision on the Colorado. Numerical modeling of detachment-limited bedrock incision suggests that this incision pulse is likely related to the upstream-dipping lithologic boundary at the northern edge of the Kaibab upwarp. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: Colorado River; quaternary incision; Henry Mountains; cosmogenic nuclides

Introduction

The Grand Canyon is thought to be the result of baselevel fall caused by the integration of the Colorado River drainage system over the edge of the Colorado plateau. Although some authors suggest that incision in the western Grand Canyon began as early as 17 Ma (Polyak *et al.*, 2008), most evidence indicates that the incision of the Grand Canyon took place between ~6 and 1 Ma (Karlstrom *et al.*, 2008; Lucchitta, 1990; Hamblin, 1994). However, the extent to which this baselevel fall has affected the Colorado River upstream of the Grand Canyon is not clear. The Grand Canyon is considered to begin at Lee's Ferry, where the river leaves weaker Mesozoic sedimentary units and enters more resistant Paleozoic rocks and abruptly steepens. The large knickpoint at this transition is often interpreted as the upstream extent of Grand Canyon related incision, implying that the river upstream of the Lee's Ferry has not yet felt the effects of the large baselevel fall, and that the incision signal propagates upstream through the migration of this large knickpoint (e.g. Karlstrom and Kirby, 2004; Karlstrom, 2005; Wolkowinsky and Granger, 2004). In contrast, rapid incision in the Colorado River upstream of Lee's Ferry would suggest that the upper reaches of the Colorado are responding to the lowering in the Grand Canyon and that the knickpoint at Lee's Ferry is not the upstream extent of the incision signal, but may reflect a lithologic influence on channel gradient. Thus, the incision history of the region upstream of Lee's Ferry is critical for evaluating how the Colorado River is responding to the incision of the Grand Canyon, and may provide insight into how large river systems adjust to downstream perturbations.

The advent of surface and burial dating techniques using cosmogenic radionuclides has allowed estimates of incision rates from a number of sites on the Colorado River and its tributaries on the Colorado plateau. Comparing these rates with estimates of Quaternary incision from within the Grand Canyon should help to determine the nature of the knickpoint at Lee's Ferry and how the signal of Grand Canyon incision is transmitted upstream. However, reported rates vary widely, and their implications are difficult to determine without a regional framework to guide interpretation. In order to provide such a framework, we undertook an analysis of Colorado River incision between Lee's Ferry and Cataract Canyon based on tributary longitudinal profiles. This analysis, in combination with new incision rate estimates from a tributary to the Colorado River in the Henry Mountains, helps to resolve the regional incision pattern and demonstrates that a pulse of rapid incision has occurred upstream of the Lee's Ferry knickpoint since ~500 ka. We also present a simple model of detachment-limited bedrock incision that relates this incision pulse to the interaction between an upstream-dipping lithologic boundary at Lee's Ferry and the upstream propagation of Grand Canyon-related incision.

Grand Canyon and Southern Colorado Plateau Incision Rates

Incision rates have been measured within the Grand Canyon and in several places on the Colorado and its tributaries upstream of the Grand Canyon in northern Arizona and southern Utah (Figure 1, Table I; the following location numbers refer to Table I and the points marked on Figure 1). Within the Grand Canyon, incision rates range from ~140–160 m/my in the Eastern Grand Canyon (location 9) to <58–92 m/my west of the Hurricane/Toroweap Fault zone (location 11) (Pederson *et al.*, 2002, 2006; Karlstrom *et al.*, 2007). Lava flows on the upper Little Colorado River (location 8) suggest incision at

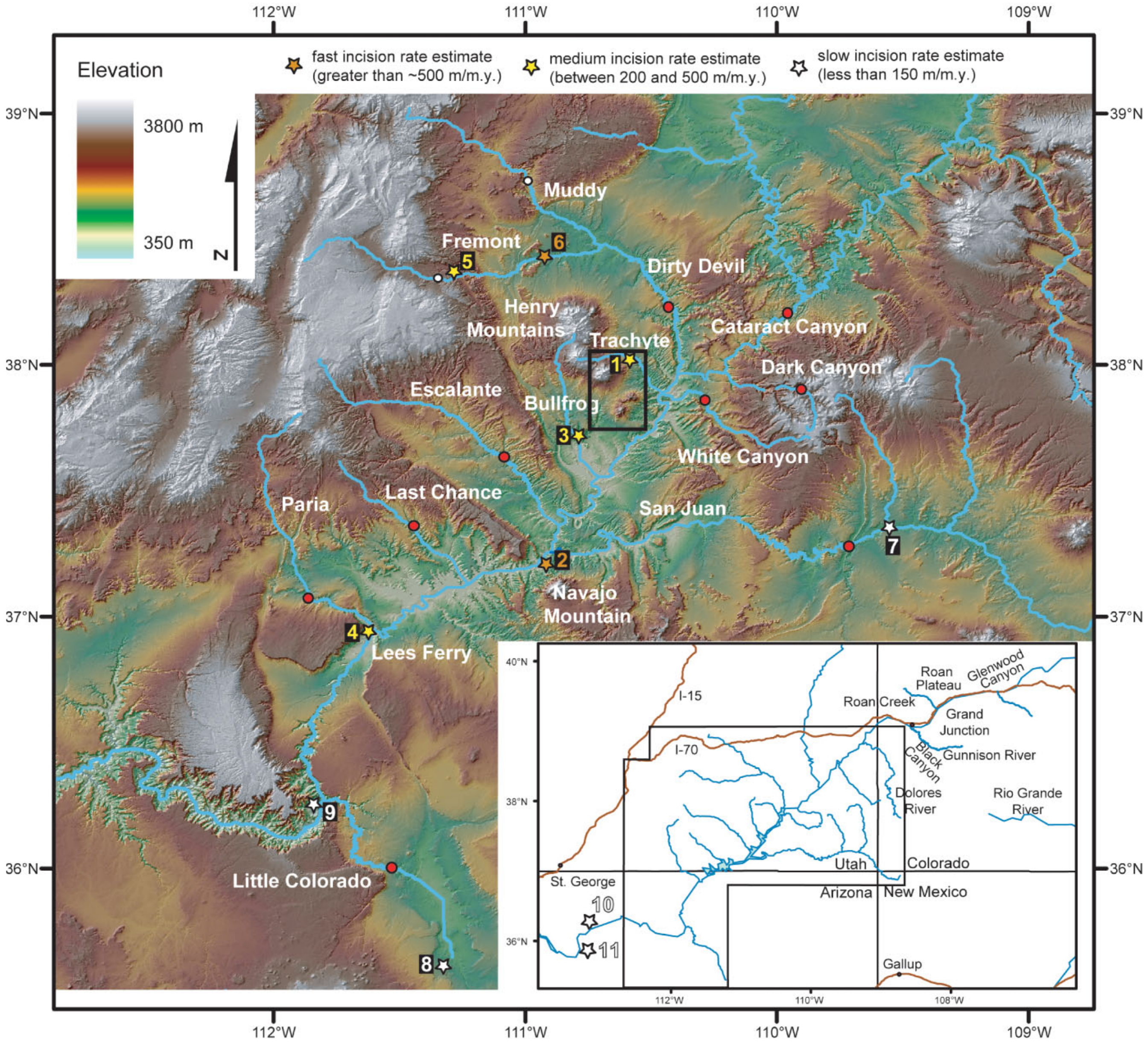

Figure 1. Overview of the studied portion of the Colorado River system and the surrounding region (inset). Highlighted and labeled tributaries indicate drainages for which long profiles were analyzed. Black circles mark the upstream extent of the steep reach on each tributary and correspond to the knickpoints shown in the channel profiles above. The circle on the Colorado marks the large knickpoint at Cataract Canyon. White circles mark the upper knickpoints on Muddy Creek and the Fremont River. The locations of existing incision rate estimates are indicated with stars; numbers correspond to location numbers in Table I and in the text, a black star indicates a fast rate (greater than ~500 m/my), a gray star a medium rate (between 200 and 500 m/my), and a white star a slow rate (less than 150 m/my). The black box indicates the location of the Henry Mountains pediment map. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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Table I. Incision rate data from the Colorado River and tributaries in the Grand Canyon and Glen Canyon regions

Location	Incsion rate (m/my)	Approximate time period (ka)	Source
1 Trachyte Creek	350 ± 30 to 540 ± 20	270–present	This study
2 Glen Canyon	700 ± 120; 830 ± 190	240–present	Garvin *et al.*, 2005
2 Glen Canyon – Oak Island – 4103 surface	420 ± 150	460–240	Garvin *et al.*, 2005
2 Glen Canyon – Rainbow Bridge Canyon	500 ± 110; 600 ± 140	120–present	Garvin *et al.*, 2005
2 Glen Canyon – Navajo Mountain	~500	500–present	Hanks *et al.*, 2001
3 Lake Powell – Bullfrog	418 ± 11	480–present	Davis *et al.*, 2001
4 Lees Ferry	~250	100–present	Lucchitta *et al.*, 2000
5 Fremont River – Carcass Creek/Johnson Mesa	380 to 470	200–present	Marchetti and Cerling, 2001
6 Fremont River – Caineville	300 to 850	150–present	Repka *et al.*, 1997
7 San Juan River – Bluff	110 ± 14	1360–present	Wolkowinsky and Granger, 2004
8 upper Little Colorado	103 ± 17	510–present	Damon *et al.*, 1974
8 upper Little Colorado	90 ± 12	240–present	Damon *et al.*, 1974
9 eastern Grand Canyon	135 ± 17; 144 ± 18	340,280–present	Pederson *et al.*, 2006
10 Grand Canyon – upstream of Toroweap Fault	133 ± 16	350–present	Pederson *et al.*, 2002
11 Grand Canyon – downstream of Toroweap Fault	72 to 92	510–present	Pederson *et al.*, 2002

90–100 m/my since 510 ka (Damon *et al.*, 1974). Terraces near Lee's Ferry (location 4) yield rates ranging from 310 m/my to 480 m/my over the past 80–500 ka (Lucchitta *et al.*, 2000). Cosmogenic exposure ages, pedogenic carbonate analyses, and paleomagnetic data from gravel covered pediment surfaces draping Navajo Mountain (location 2) suggest that the Colorado River cut most of Glen Canyon over the past ~500 ky at rates of 400 ± 150 to 700 ± 120 m/my (Garvin *et al.*, 2005; Hanks *et al.*, 2001). Terraces at Bullfrog Basin (location 3) suggest 418 ± 11 m/my over the past 480 ka (Davis *et al.*, 2001). Data from the Fremont River north of the Henry Mountains (locations 5 and 6) suggest rates of 300 to 850 m/my (Repka *et al.*, 1997; Marchetti and Cerling, 2001) over the past 150 to 200 ky In contrast, a much slower rate of 110 ± 14 m/my over the past 1·36 Ma was measured on the San Juan River near Bluff, Utah (location 7) (Wolkowinsky and Granger, 2004). This low rate, and its similarity to those from the upper Little Colorado (Damon *et al.*, 1974) was interpreted as evidence that the incision of the Grand Canyon has not yet affected the San Juan River. Farther up the system, on the Gunnison River near the Black Canyon of the Gunnison, incision rates range from ~300 m/my downstream of a significant knickpoint to ~100 m/my upstream of the knickpoint (Sandoval *et al.*, 2006). Basalt flows at Glenwood Canyon, farther to the north-east on the Colorado, suggest that the incision rate here has accelerated, increasing from 24 m/my between 7 and 3 Ma to 240 m/my averaged over the past 3 Ma (Kirkham *et al.*, 2001). These incision rate estimates are variable and the sites are geographically widely spaced, making it difficult to infer a coherent regional pattern. Each incision rate has at times been interpreted as representative of the entire region; however, the range of values highlights the non-uniform character of regional incision.

We note that these incision rate estimates may also have a high degree of epistemic uncertainty, as the rate that is obtained depends on the model used to interpret the data, and therefore a number of assumptions whose influence may be difficult to quantify. The rates cited earlier represent the interpretations preferred by the authors of each study.

Analysis of Regional Incision Pattern

In addition to measuring incision rates at individual sites, one can also investigate the degree of response throughout the system by examining topographic data and the longitudinal profile forms of channels. The form of a river's longitudinal profile may provide information about the presence of a transient response in the river. In a simple model of detachment-limited bedrock channel incision, the response of a channel to a sudden perturbation results in a knickpoint that migrates upstream (Howard, 1994; Whipple and Tucker, 2002). In this model, an increase in incision in the Colorado would result in a baselevel fall for its tributaries, which may be preserved in the long profiles of tributaries as knickpoints. The location of each knickpoint on the long profile will then mark the boundary between the adjusted and unadjusted reaches of the channel (e.g. Wobus *et al.*, 2006; Crosby and Whipple, 2006; Schoenbohm *et al.*, 2004).

In a real system, such as the Colorado River, a perturbation will likely result in a more complicated signal that may evolve in complex ways as the landscape continues to respond. The region of the Colorado Plateau that has potentially been affected by the behavior of the Colorado River is quite large and encompasses a range of lithologies, climatic conditions, and underlying structures. Differences in erosional efficiency due to climate, sediment load, or bedrock properties, as well as variations in uplift rate may also result in knickpoints in a channel profile. However, knickpoints due to baselevel fall may exhibit a systematic pattern in their distribution of elevations and the extent of their retreat along the tributaries (Wobus *et al.*, 2006).

We use the US Geological Society (USGS) Digital Elevation Models (DEMs) of the region with 90 m resolution to extract longitudinal profiles of the Colorado and its tributaries, and to characterize the distribution of relief and slopes throughout the region. The construction of the Glen Canyon dam and the presence of Lake Powell have obscured the channel profiles in a significant portion of the area studied. The DEMs do not provide any information about the former course of the Colorado and its tributaries underneath Lake Powell. To supplement these data, we used USGS 7·5 min topographic maps that show the bathymetry of the lake bottom along with topographic maps made prior to the construction of the dam to manually construct portions of the longitudinal profiles under the lake (Figure 2).

All channels extracted from the DEM were examined to ensure that the extraction algorithm did not cut off any meander bends and artificially steepen the profile. The two channels that failed this check were re-extracted using USGS 10 m and 30 m DEMs. A comparison between the Colorado, San Juan, and Green River profiles calculated from the 90 m DEM data and profiles that were manually surveyed in the

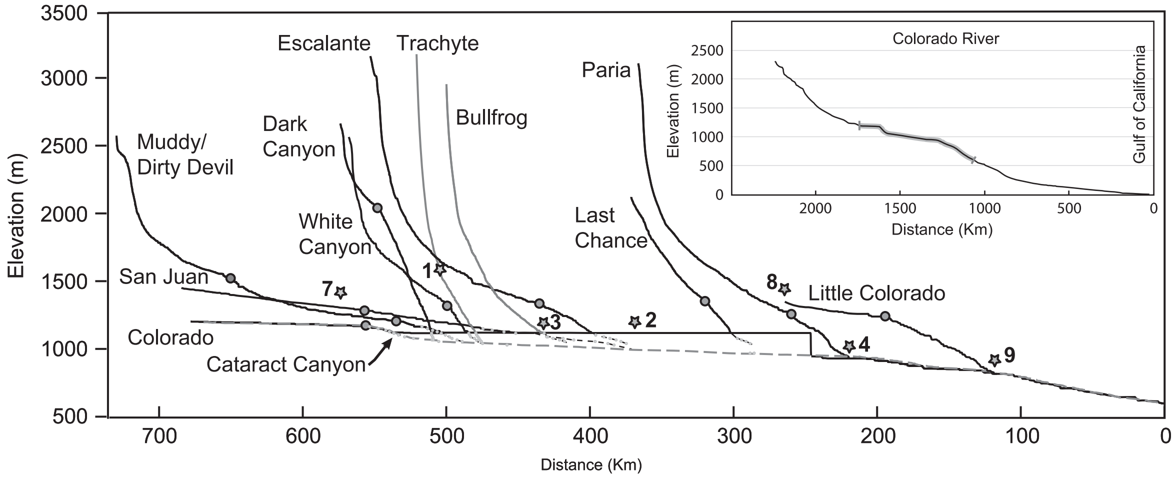

Figure 2. Longitudinal profiles of channels entering the Colorado River between the upper Grand Canyon and Cataract Canyon, obtained using 90 m USGS DEMs. The dashed gray line represents a manually surveyed profile of the Colorado River (1924 USGS river survey, B. Webb and T. Hanks personal communication, 2005). The gray dots and dashed black lines are channel positions obtained from USGS contour maps showing bathymetry of Lake Powell. The circles mark the beginning of the steep reach in each channel, and correspond to the knickpoints shown on the maps. The stars mark the locations of selected incision rate estimates, corresponding to the numbered stars in the overview map. The profiles of the San Juan and Little Colorado Rivers have been truncated and locations 5 and 6 are not shown for clarity. Inset shows the entire longitudinal profile of the Colorado River starting from the Gulf of California; the gray bar indicates the portion of the profile shown in the figure.

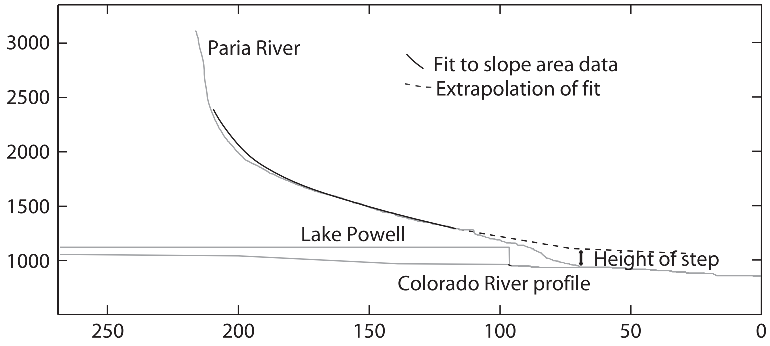

Figure 3. The Paria River example of a long profile fitting method. We fit concavity and steepness indices to the upper part of the profile, then extrapolate the fit downstream and measure the difference between the expected elevation and the actual elevation of the channel where it enters the Colorado.

field (1924 USGS river survey, B. Webb and T. Hanks, personal communication, 2005) shows that the two methods yield very similar profiles (Figure 2). Thus we are confident that the DEM-extracted profiles faithfully represent the channel forms at the scale of interest.

Morphology of Channel Profiles

As Figure 2 illustrates, the long profiles clearly indicate that most of the tributaries downstream of Cataract Canyon do not have the smoothly concave profile typically observed in well-adjusted channels (e.g. Mackin, 1948; Hack, 1957; Flint, 1974). Instead, most tributaries steepen prior to entering the Colorado, and the transition into the lower, oversteepened portion of each channel is marked by either a distinct knickpoint or a broad convex knickzone. The oversteepened reaches extend all the way to the confluence with the Colorado. The knickpoints discussed later and shown in Figures 1, 2, 4, and 5 mark the upstream extent of the oversteepened reach in each channel; these points were located using plots of slope versus drainage area for each profile. Increases in channel slope stand out clearly on slope versus drainage area plots, allowing us to locate convexities that may appear quite subtle on the channel profiles (such as the knickpoint on the San Juan River). The elevations of the knickpoints are remarkably similar, and are consistent with the pattern expected from a transient signal of baselevel fall (Wobus *et al.*, 2006). Notable exceptions to this pattern are the tributaries draining the Henry Mountains. These channels are smoothly concave all the way to the Colorado and will be discussed in more detail later.

In order to estimate the magnitude of incision represented by each knickpoint or convexity, we fit concavity and steepness indices (e.g. Wobus *et al.*, 2006; Schoenbohm *et al.*, 2004) to the upper unadjusted part of the profile, then extrapolate the fit downstream of the rollover and measure the difference between the reconstructed pre-incision elevation and the actual elevation of the channel where it joins the Colorado (Figure 3). The precision of these measurements is limited by the presence of Lake Powell. However, this method yields a consistent estimate of 150 to 190 m of recent incision for most of the drainages (Table II). The extremely large knickpoint in Dark Canyon is likely structurally controlled, as the steep section occurs where the channel follows the slope of the Monument Upwarp, and the abrupt change in slope corresponds to a change in the orientation of the channel relative to the underlying structure. The knickpoint on the Dirty Devil/Fremont River is at a slightly lower elevation than the other knickpoints and corresponds to a smaller magnitude of incision; this may be due to a more complicated incision signal, and will be discussed further later.

Table II. Knickzone properties

Tributary	Step length (km)	Step height (m)	Step elevation (m)
Little Colorado	75	386	1247
Paria	32	156	1258
Last Chance	35	189	1375
San Juan	165	150	1293
Escalante	59	147	1356
Bullfrog Creek	n/a	n/a	n/a
Trachyte Creek	n/a	n/a	n/a
White Canyon	22	182	1340
Fremont/Dirty Devil River	40	113	1204
Dark Canyon	39	769	2037

Note: n/a, not applicable.

Stationary knickpoints can also form due to differences in the strength or erodibility of the underlying bedrock. A geologic map of Utah (Hintze *et al.*, 2000) indicates that the steep sections do not consistently correspond to more resistant lithologies. On several channels the steep sections pass through a range of lithologies of varying strength, and the top of the knickzone often does not occur near a lithologic contact (Figure 4). For example, the knickpoint on Last Chance Creek is located within the Straight Cliffs Formation, far from the contact with the underlying Tropic Shale or the overlying Wahweap Sandstone (Figure 4B). The knickpoints occur in different lithologies in different tributaries, and it seems unlikely that the pattern observed could be due to lithology alone. It is likely that the lithology plays a role in determining the form of knickpoints and perhaps their propagation speed; however, the consistent presence and height of the convexities, and the lack of convincing correlation with lithology suggest that they are related to a pulse of incision on the Colorado and are not primarily an expression of lithologic contrasts.

The Little Colorado River provides useful point of comparison to the tributaries farther upstream, as the Little Colorado enters the Colorado River downstream of the large convexity at Lee’s Ferry, in a reach of the Colorado that has clearly experienced Grand Canyon-related incision. The similarity between the profile of the Little Colorado and the elevation of its knickpoint and the profiles and knickpoints of the tributaries upstream of Lee’s Ferry implies that both have been affected by the same process – the lowering of the Colorado River.

The extent to which the most recent pulse of incision has affected the landscape can be evaluated by examining the geographic pattern of the knickpoints and their relationship to topography and relief. The locations of the knickpoints superimposed on a map of local relief (calculated over a 1·5 km radius moving window) (Figure 5) show that for many drainages there is a correlation between the location of the knickpoint and the distribution of relief along the channel. The reaches downstream of the knickpoints are typically characterized by deeply incised canyons, while the top of the step often corresponds with a reduction in local relief.

Comparison with Published Incision Rate Estimates

When the incision rate estimates are re-examined in light of the regional incision pattern suggested by our analysis (Figure 1), some of the apparent discrepancies in rates can be resolved. Bluff is located upstream of the convexity in the San Juan, so the slow incision rates measured at Bluff (Wolkowinsky and Granger, 2004) are characteristic of a reach that has not experienced the recent incision pulse. In contrast, the rates from Glen Canyon near Navajo Mountain (Garvin *et al.*, 2005; Hanks *et al.*, 2001) were measured downstream of the knickpoint, and therefore reflect the passage of the incision pulse through these reaches.

The fast incision rates measured on the Fremont River (Repka *et al.*, 1997) are not as easily explained, as the knickpoint marked on Figures 1 and 2 is located downstream of the study site. However, as noted earlier, the size of this knickpoint is smaller than the rest, and there are additional knickpoints farther upstream on both the Fremont River and Muddy Creek. It is possible that the propagation of the signal up this drainage has been heavily influenced by lithology. The incision rates were obtained from a reach of the Fremont River that has incised into weak, easily erodable Mancos shale. The lower knickpoint may represent part of the signal that has hung up below the shale, while the rest of the incision may have propagated very rapidly upstream through the shale. Such a scenario is illustrated with our channel incision model and discussed further in that section. Additional incision rate estimates from Muddy Creek and the Fremont and Dirty Devil Rivers are required to evaluate this hypothesis. This style of knickzone separation into upper and lower steps has also been noted in other landscapes with perturbed channels in layered bedrock (e.g. Crosby and Whipple, 2006).

Trachyte Creek Incision Rates

Our simple stream profile analysis suggests that Colorado River in the region between Lee’s Ferry and Cataract Canyon (and perhaps farther upstream) has experienced a recent pulse of incision. However, as noted earlier, the profiles of Trachyte Creek and Bullfrog Creek are smoothly concave; unlike other tributaries in the region, these channels do not contain knickpoints. Trachyte Creek and Bullfrog Creek both drain the Henry Mountains [a group of five peaks formed by the mid-Tertiary intrusion of diorite laccoliths into sedimentary units of the Colorado Plateau (Jackson, 1997)], and enter the Colorado in Glen Canyon (Figures 1 and 2). Our stream profile analysis predicts that these channels have been affected by an increase in incision of the Colorado River, yet the profiles of the Henry Mountains channels show no evidence of a transient incision pulse. Knowledge of the incision rates on these tributaries will provide an important test of our proposed regional incision pattern, and may help to resolve the nature of response in these drainages. Fast

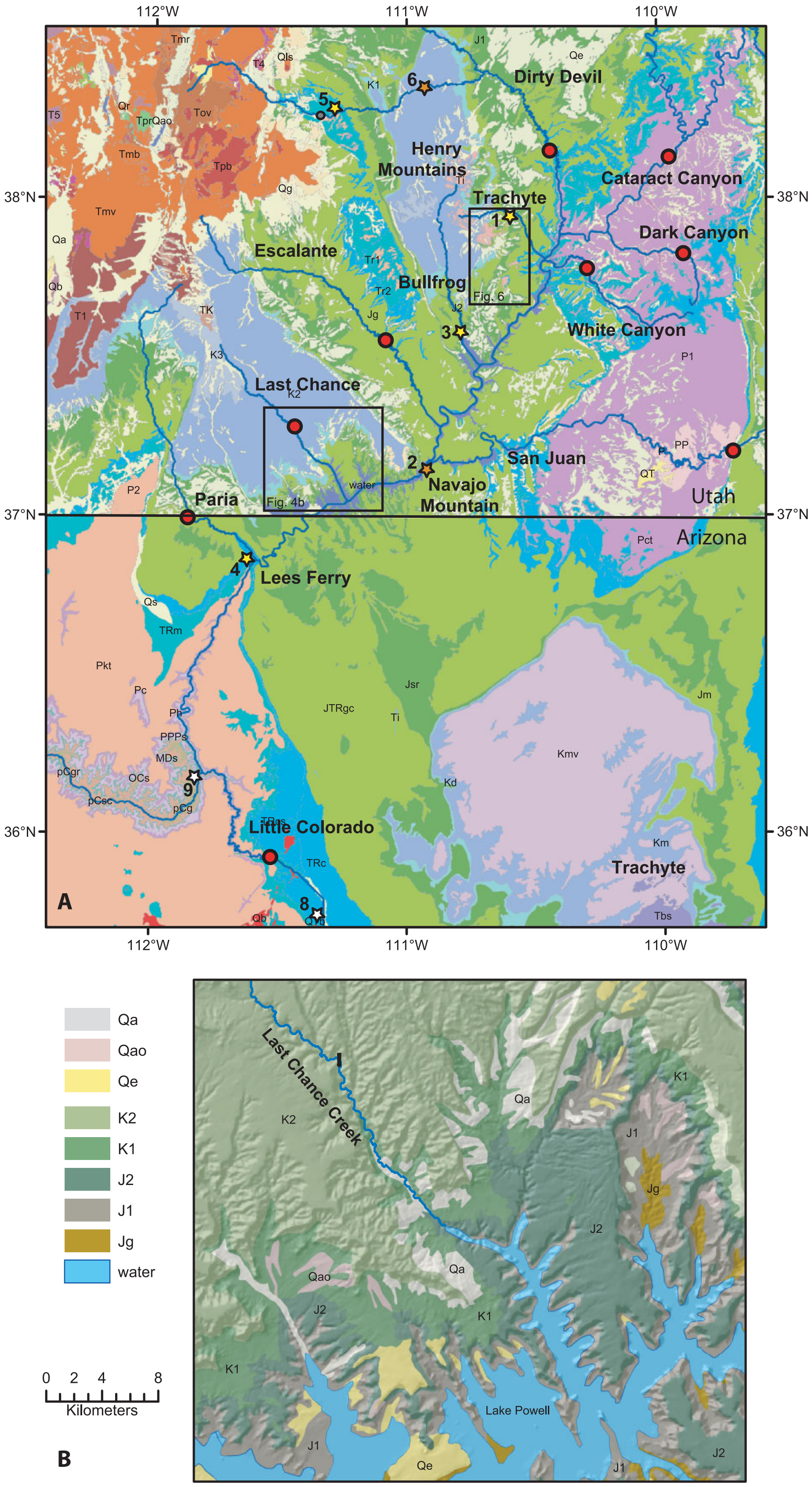

Figure 4. (A) Geologic map of northern Utah and southern Arizona, illustrating the location of the knickpoints relative to lithologic boundaries. Black boxes show the locations of Figures 4B and 6. Locations of selected incision rate estimates are marked; locations 7, 10, and 11 are off the map. Geology from USGS digital geologic maps of Utah (Hintze *et al.*, 2000) and Arizona (Hirschberg *et al.*, 2000). (B) Close-up of the geology near the knickpoint on Last Chance Creek. Qa: Quaternary, alluvium/colluvium; Qao: Quaternary, older alluvium/colluvium; Qe: Quaternary, eolian deposits; K2: Cretaceous, Wahweap Ss, Straight Cliffs Fm; K1: Cretaceous, Tropic Shale, Dakota Ss; J2: Jurassic, Morrison Fm; J1: Jurassic, Summerville Fm, Entrada Ss; Jg: Jurassic, Glen Canyon Group. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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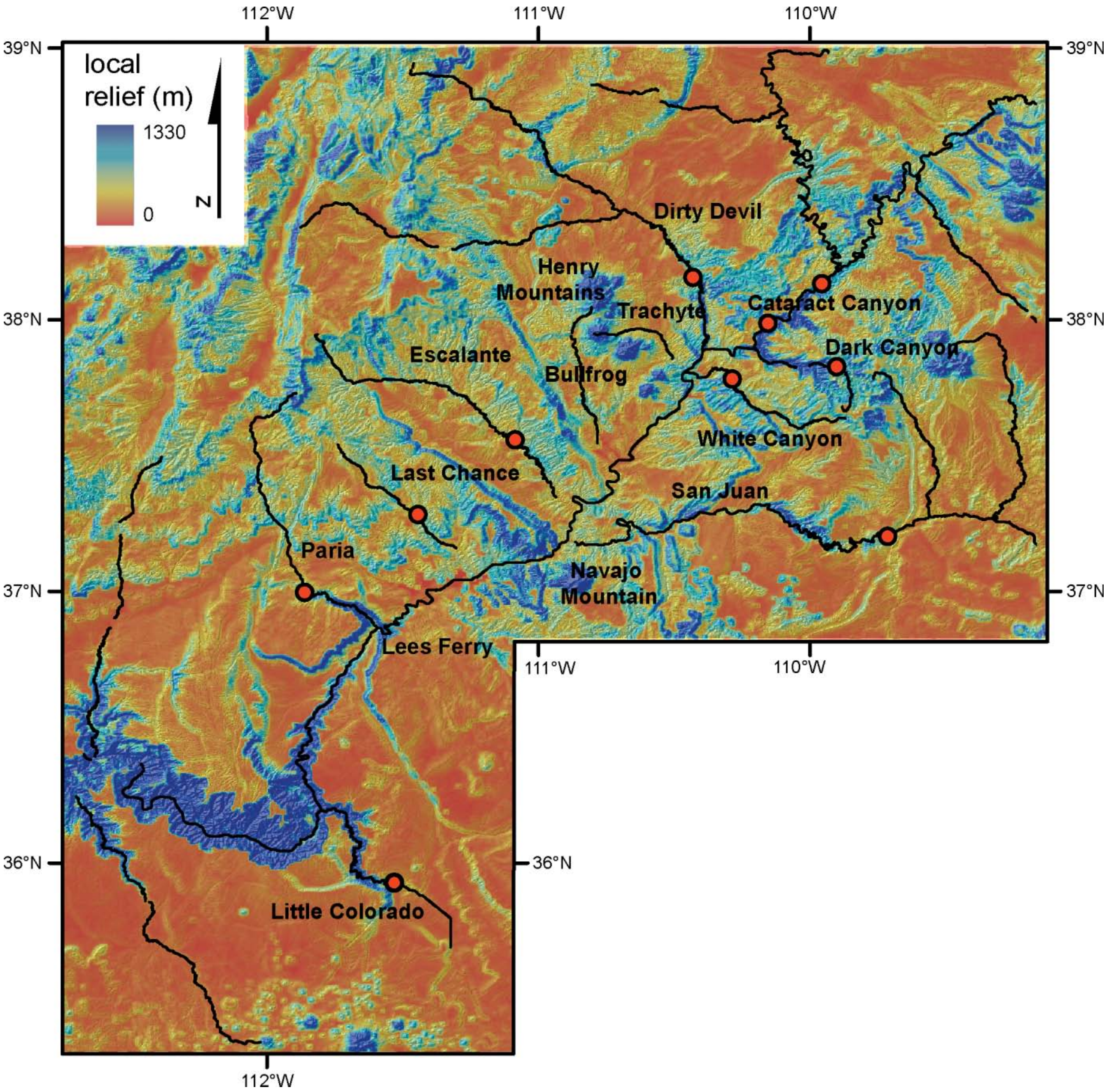

Figure 5. Map of local relief calculated over a circular 1·5 km radius moving window. Many of the knickpoints correspond to an increase in local relief near the channel. This figure is available in colour online at www.interscience.wiley.com/journal/espl

incision rates over recent timescales would imply that that the channels are currently responding to an incision pulse without the development of discrete knickpoints. Fast rates in the past and slow rates on more recent timescales would imply that the channels have fully responded. Slow rates over all time periods would suggest that the channels have not experienced an incision pulse and would contrast with the regional incision pattern developed earlier.

Trachyte Creek Surfaces

The Henry Mountains region was studied extensively by G. K. Gilbert (1877) and later Hunt (1953), who both noted that lower slopes flanking the mountains are covered with extensive gravel-covered pediment surfaces of varying height above adjacent channels (Figure 6). In addition, many of the drainages in the area are flanked by a series of smaller gravel-covered strath terraces. We use *in situ* cosmogenic nuclides to date the abandonment of a series of these surfaces and determine an incision rate for Trachyte Creek. The use of cosmogenic nuclides in measuring surface exposure ages has been developed by a number of authors (Anderson *et al.*, 1996; Bierman and Nichols, 2004; Granger and Muzikar, 2001; Hancock *et al.*, 1999; Repka *et al.*, 1997; Perg *et al.*, 2001; Gosse and Phillips, 2001), and these studies can be referred to for a detailed analysis of the methods and assumptions.

Samples for cosmogenic nuclide exposure age analysis were collected from a suite of four gravel-covered strath surfaces that rise from 1 m to 110 m above the bed of Trachyte Creek, an active stream channel that joins the Colorado river ~22 km downstream of the study area (Figure 7). The terraces are cut into Entrada sandstone, a cliff-forming fine-grained red sandstone, and the edges of each terrace remain well defined (Figure 7). The terraces consist of

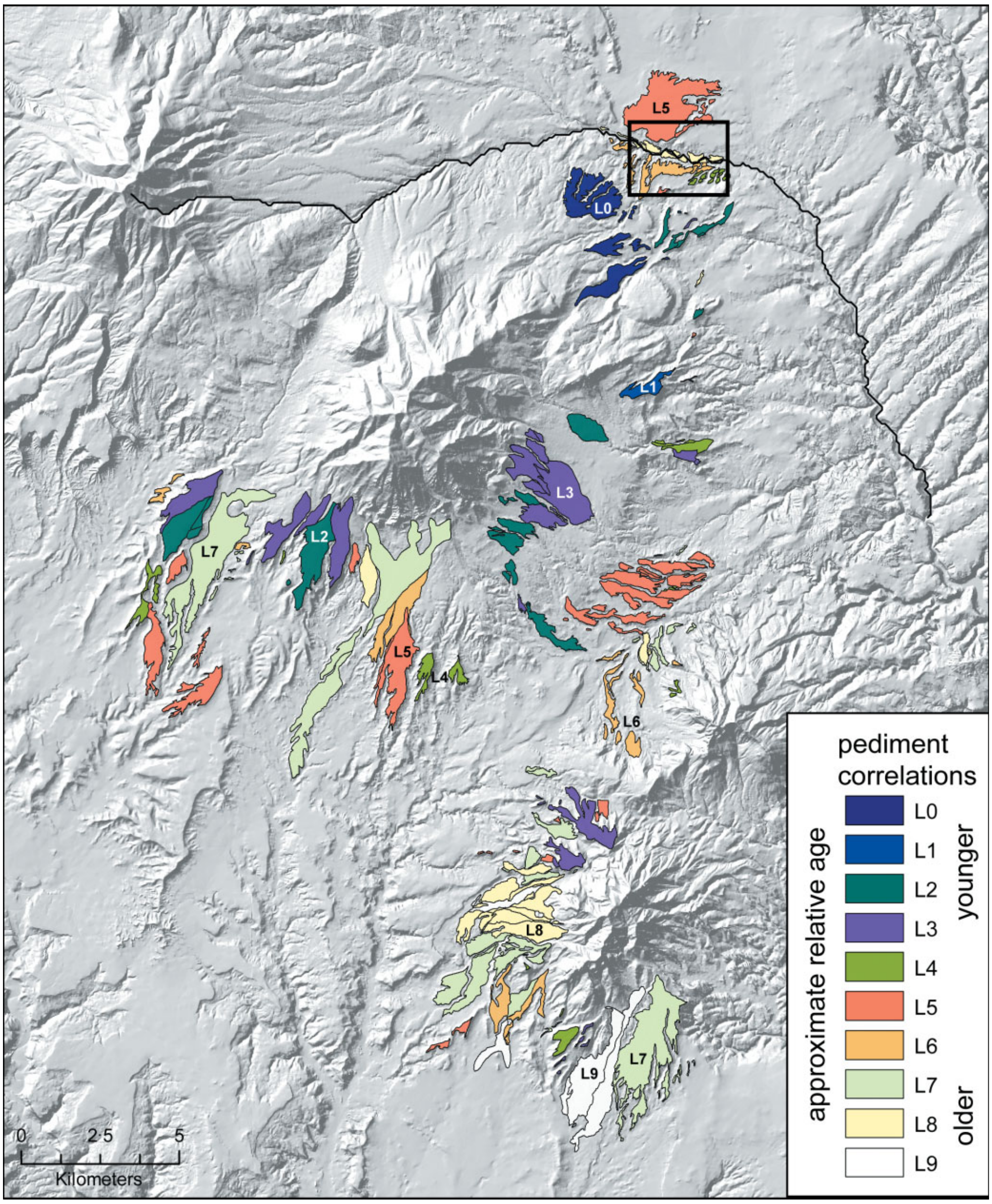

Figure 6. Map of the distribution and inferred relative ages of pediments in the Henry Mountains. Pediments decrease in age from L0 to L9. Mapping is based on aerial photographs and field observations. The black line marks Trachyte Creek, and the black box shows the location of the studied terraces. The terrace levels defined locally in our sturdy area correspond as follows: P1 corresponds to level L5, P2 to L6, and P3 to L9; P4 is too small in extent and too close to the channel in elevation to map at this scale. This figure is available in colour online at www.interscience.wiley.com/journal/espl

beveled bedrock surfaces covered with gravel deposits that range from 1 to 8 m thick (Figures 7B and 7D). The gravel deposits are primarily (up to 95%) diorite in composition, with some sandstone and quartzite clasts, and significant pedogenic carbonate in the older deposits. The clasts are poorly sorted, and range from fine-grained sand to boulders up to a meter in diameter. The surfaces show little evidence of deflation or erosion, particularly the lower two levels. This suite of terraces was selected for their high degree of preservation, their proximity to an active drainage of significant size, and the presence of four distinct levels, P1–P4, that can be visually correlated across several surface remnants (Figures 6, 7B and 7C).

We obtain a rough estimate of the minimum age of each gravel deposit from the degree of pedogenic carbonate development in the gravel using the classification scheme of Machette (1985) and the age estimates of Lucchitta *et al.* (2000). It should be noted that disturbance or stripping of part of the deposit can remove accumulated carbonate, so this method can yield only an approximate minimum age.

P1 is the highest level at ~110 m above creek and is covered with a gravel deposit up to 8 m thick. The gravel surface has moderate development of desert pavement. There is pedogenic carbonate lag present on the surface, suggesting that some deflation of the deposit has taken place. The gravel contains a thick layer (2–2·5 m) of well-cemented carbonate at the base of the deposit that appears to be related to groundwater, and therefore cannot be used to estimate deposit age. A correlative surface north of the creek contains carbonate classified as stage IV, indicating a minimum age between 250 ka and 525 ka (Machette, 1985; Lucchitta *et al.*, 2000).

The P2 surface covers a much larger area, and is ~62 m above the creek. Surfaces of this level can be correlated in several places south of Trachyte Creek, but are not observed north of the creek. The gravel deposit is several meters thick and contains a well developed carbonate horizon

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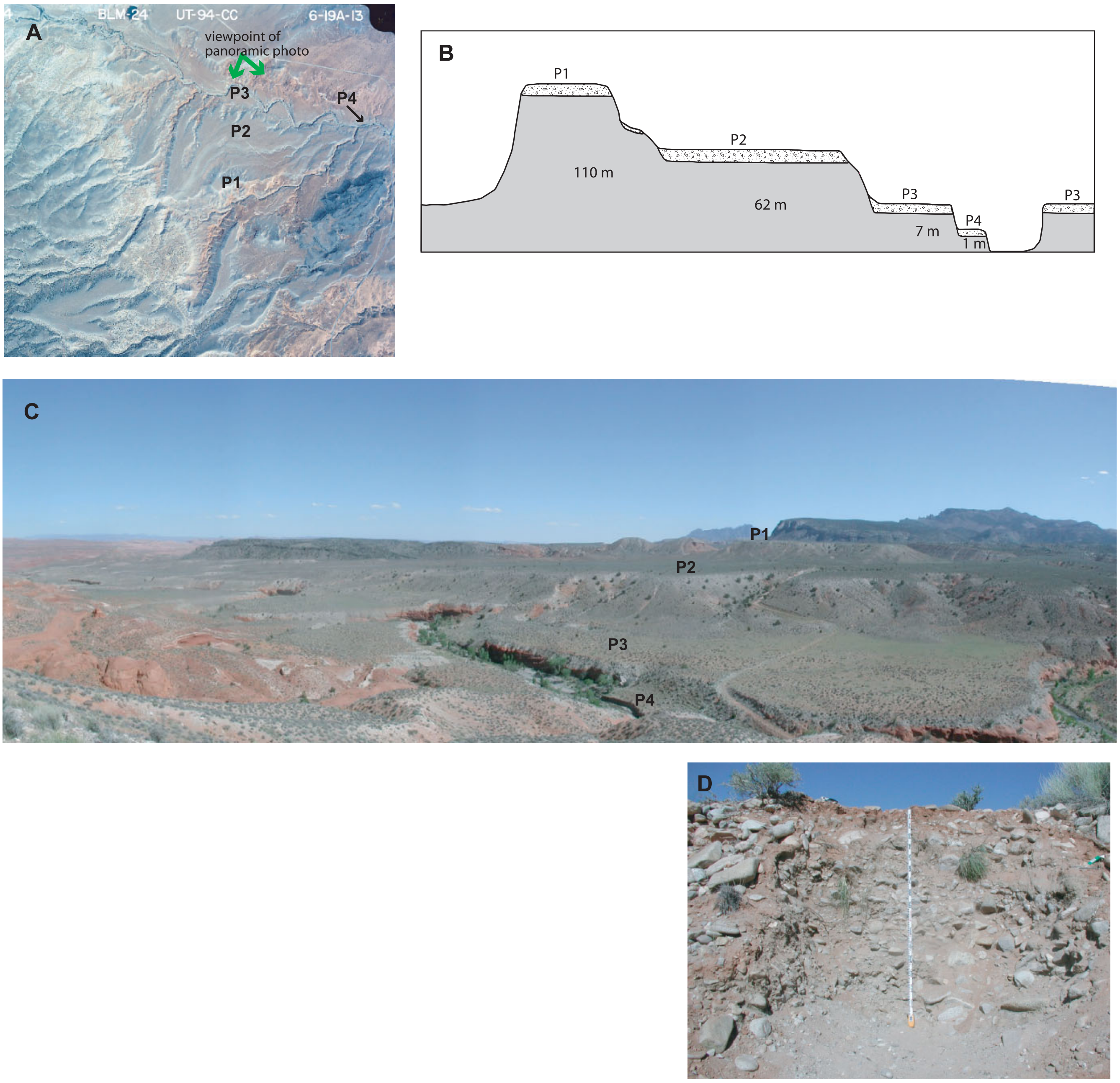

Figure 7. (A) Aerial view of studied surfaces. (B) Schematic cross-section of Trachyte Creek surfaces. Scale is approximate. (C) Panoramic view of Trachyte Creek surfaces. (D) The P3 gravel deposit where the depth profile samples were collected. Tape measure is 1·7 m long. This figure is available in colour online at www.interscience.wiley.com/journal/espl

that corresponds to stage III or incipient stage IV carbonate development and implies an approximate minimum age of 100 to 250 ka. The sampled pediment is quite flat, but there is evidence of deflation, as boulders and carbonate lag are present on the surface. The surface has a moderately well developed desert pavement, in which diorite clasts have accumulated desert varnish, indicating that recent disturbance has been minimal.

The P3 terraces define a laterally extensive level cut into bedrock about 7 m above Trachyte Creek. Surfaces of this level are present on both sides of the creek and can be visually correlated along much of the creek (Figures 6 and 7). The gravels vary in thickness, but are typically several meters thick. There is no evidence for deflation or erosion of the gravel deposit; however most of the surface is covered with several centimeters of red silt, indicating some inflation. There is slight carbonate development in the gravels, characteristic of a stage I carbonate, which suggests that this terrace level is less than 60,000 years old (Lucchitta *et al.*, 2000).

P4 denotes the lowest terrace level. The base of the ~1 m thick gravel deposit is about 1 m above modern Trachyte Creek. This level is fairly small in area, but can be visually correlated in several places along the creek. The top of the gravel surface is extremely flat and shows no evidence of deflation or erosion. In most places there is a layer of silt/fine sand deposited above the gravels, which increases in thickness away from the creek toward the base of the cliff on the edge of P3. The gravel contains no pedogenic carbonate.

Sample Collection and Analysis

We collected samples from surface boulders and cobbles on levels P1 and P2. Inherited ^{10}Be concentration in these

Table III. ^{10}Be data

Sample ID	Altitude (m)	Latitude	Depth (cm)	Production rate[a]	±[b]	^{10}Be (atoms/gm quartz)	±	Age (ky)	±
P2S1	1548	37·96	0	15·42	0·77	2·74E + 06	6·24E + 04	177·9	7·85
P2S2	1548	37·96	0	15·42	0·77	2·45E + 06	5·15E + 04	158·6	7·66
P2S3	1548	37·96	0	15·42	0·77	2·53E + 06	5·90E + 04	164·1	12·19
P1s6	1600	37·95	0	16·05	0·80	3·29E + 06	6·30E + 04	205·0	6·67
P1s4	1600	37·95	0	16·05	0·80	3·52E + 06	6·15E + 04	219·1	8·09
P1s7	1600	37·95	0	16·05	0·80	4·29E + 06	9·79E + 04	267·1	7·65
P4asurf	1451	37·96	0	14·30	0·71	1·41E + 05	4·15E + 03		
P4a2	1451	37·96	30	8·52	1·19	1·37E + 05	4·67E + 03		
P4a3	1451	37·96	56	5·44	0·51	1·16E + 05	2·84E + 03		
P4a4	1451	37·96	88	3·14	0·30	2·39E + 05	5·71E + 03		
P4aBr	1451	37·96	124	1·69	0·13	1·01E + 04	1·57E + 03		
P3asurf	1499	37·96	0	14·84	0·74	3·09E + 05	5·76E + 03		
P3a0	1499	37·96	15	11·46	1·81	2·22E + 05	5·73E + 03		
P3a1	1499	37·96	50	6·27	0·87	1·36E + 05	4·85E + 03		
P3a2	1499	37·96	85	3·43	0·84	1·90E + 05	5·26E + 03		
P3a3	1499	37·96	120	1·88	0·28	1·28E + 05	4·67E + 03		
P3a4	1499	37·96	165	0·86	0·13	1·22E + 05	2·46E + 03		
HmTc1[c]	1444	37·96	0	14·22	0·71	8·46E + 04	2·47E + 03	5·92	0·46

[a] We use the surface production rate of Stone (2000), corrected for altitude and latitude using Dunai (2000).
[b] Includes 5% error in surface production rate plus an uncertainty arising from an estimated depth range for each sample.
[c] Sample of modern sediment from Trachyte Creek.

samples is likely to be small compared to *in situ* ^{10}Be; the age estimates based on pedogenic carbonate development suggest that these terraces are older than 100 ka, while inheritance is likely to be at least an order of magnitude smaller. This assumption is supported by the relatively low concentration measured in modern river gravel (see later). We collected depth profiles from levels P3 and P4 since inheritance is likely to be significant for these lower surfaces relative to their abandonment ages. Each depth profile consists of four or five samples, where each sample is an amalgamation of at least 50 clasts (Repka *et al.*, 1997), taken at regular intervals from the surface to the base of the gravel deposit (P4) or a depth of 1·7 m (P3). We also collected a sample from the sandstone bedrock below the base of the P4 gravel, as well as two samples of active bedload from Trachyte Creek.

The extraction of ^{10}Be from the samples and accelerator mass spectrometry (AMS) target preparation was performed at the Cosmogenic Radionuclide Laboratory at Dartmouth College following the method of Heimsath *et al.* (2001). AMS analysis was done at Lawrence Livermore National Laboratory. We use the production rates of Stone (2000) corrected for latitude and elevation using the scaling factors of Dunai (2000). The shielding correction for the surfaces sampled was negligible (less than 1%).

Cosmogenic Data

Results from P1 and P2 surface samples are given in Table III. The three samples from the highest level, P1, range from 205 to 267 ky. We take the oldest of these as a minimum for the age of the surface. This minimum age of 267 ± 7·7 ka. is consistent with the 250–525 ka range estimated from pedogenic carbonate development in the gravel deposit. An age of 267 ka for this surface 110 m above the creek corresponds to a maximum incision rate of 412 ± 21 m/my.

The three surface samples from P2 yield ages ranging from 159 to 178 ka. The similarity between these ages suggests that inheritance is either relatively small, or is consistent between the samples. A minimum age of 178 ± 7·9 ka agrees with the 100 to 250 ka range suggested by observations of carbonate development and implies a maximum incision rate of 350 ± 28 m/my.

We calculate an age from the P3 depth profile by correcting the production rate for depth below the surface, using $P(d) = P_0 e^{-d\rho/\Lambda}$ with $\Lambda = 160$ g/cm^2 and a density of 2·5 g/cm^3 (where P is the production rate, d is depth below the surface, ρ is the density of the gravel, and Λ is the absorption mean-free path). For a profile with uniform age and average inheritance, the depth-corrected production rate and concentration should have a linear relationship; a fit to the data gives the age and average inherited concentration (Figure 8). The P3 profile suggests an age of 13·3 ± 1·1 ka and an average inheritance of 1·03e5 ± 5·3e3 atoms ^{10}Be/gm quartz. This age is consistent with the degree of carbonate development in the gravel and suggests an incision rate of 527 ± 86 m/my. The inherited concentration is equivalent to 6920 ± 496 years of exposure at the sample site, or an upstream basin-average paleo-erosion rate of 151 ± 15·3 m/my, assuming no exposure during fluvial transport (Bierman and Nichols, 2004; Granger *et al.*, 1996). The average inheritance obtained from this fit is similar to the 8·5e4 ± 2·5e3 atoms ^{10}Be/gm quartz measured in modern Trachyte Creek gravel. The ^{10}Be concentration in the creek gravel corresponds to an upstream basin-average paleo-erosion rate of 184 ± 14·5 m/my, or 5920 ± 455 years of exposure at the sample site.

The P4 depth profile does not exhibit any consistent relationship between concentration and depth and therefore cannot be used to calculate a reliable age for this surface (Figure 9). This depth profile suggests a more complicated exposure history or distribution of inherited nuclides, as the deepest sample has the highest concentration of ^{10}Be. The gravel deposit does not contain structures that would indicate multiple depositional or erosional events; however, a nearby fill terrace at a similar height above the channel provides evidence for an episode of aggradation and reincision. The deepest sample may therefore represent an earlier depositional event. The ^{10}Be concentration of the upper three samples is only slightly higher than the inherited concentration measured in P3 and the stream sediments, so inheritance is likely

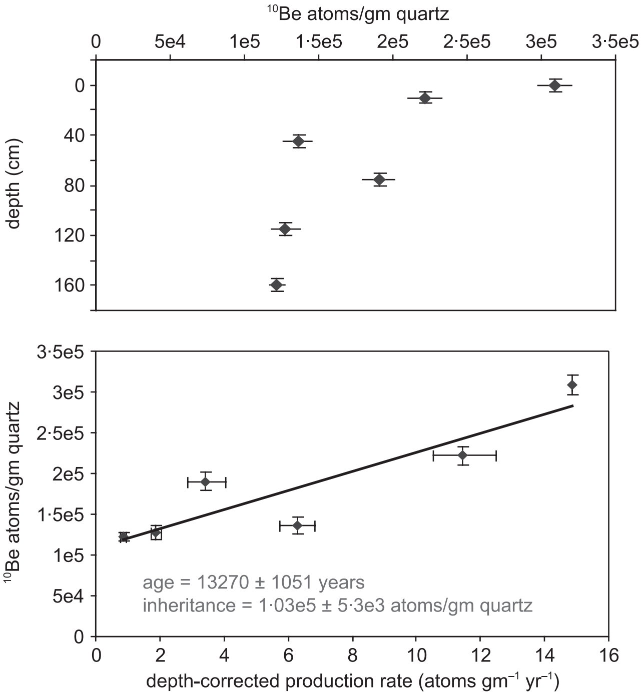

Figure 8. The P3 depth profile. A linear fit to depth-corrected production rate versus concentration suggests an exposure age of about 13 ky and an inherited concentration that is equivalent to approximately 7 ky of exposure.

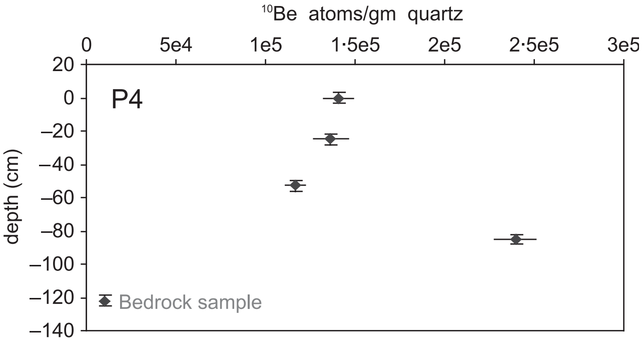

Figure 9. The P4 profile indicates a complicated exposure history or distribution of inherited nuclides, as concentration does not uniformly decrease with depth. The low concentration in the bedrock sample suggests a very young age for terrace formation.

overwhelming any age signal that may exist. Although the depth profile cannot be used to date the formation of terrace P4, the sample of bedrock at the base of the P4 gravel deposit yields an age of ~3 ka if no previous exposure and a constant burial depth is assumed. This suggests an upper constraint for the age of this terrace, although it is likely that the amount of gravel cover has varied. The concentration of ^{10}Be measured in the bedrock could accumulate in only ~700 y of exposure at the surface, so the terrace may be significantly younger than 3 ka. An age of 3 ka corresponds to a minimum incision rate of 330 m/my. Although the uncertainty in terrace age and the possible intervals of aggradation render this rate extremely unreliable, there are no data suggesting that channel incision during this most recent time period was significantly slower than the rates obtained from the older surfaces.

The ^{10}Be concentrations measured in the P3 depth profile also deviate slightly from the expected exponential profile, as ^{10}Be concentration does not uniformly decrease with depth. This suggests that either inheritance varies systematically with depth, or that inheritance is highly variable and the amalgamation technique was not sufficient to average out random variations. Recent studies have suggested that variability in ^{10}Be concentration in sediment samples collected from active channels is highly dependent on grain size. Samples made up of pebble sized clasts tend to have lower reproducibility than samples of sand sized sediment, as fewer total clasts are included in the analysis (Bierman *et al.*, 2001, Belmont *et al.*, 2006). The samples collected from the P3 gravel are likely to contain highly variable amounts of inheritance due to the heterogeneity of the gravel clasts. The quartz-bearing lithologies in the gravel include locally derived sandstone that breaks down rapidly in modern streams, as well as more resistant quartzite clasts sourced from farther upstream that may have been in the fluvial system for a longer period of time. Variations in the erosion rate of the source rock, as well as possible recycling of clasts from older terraces may also contribute to the variation in inheritance. The stratigraphy of the deposit does not indicate a change in composition or multiple episodes of deposition. It therefore seems unlikely that there is a systematic variation in inheritance, and suggests that the observed concentrations merely reflect the large random variability inherent in samples of heterogeneous clasts. Although the P3 deposit in Trachyte Creek does not show evidence of multiple deposition events, we did note the presence of fill terraces up to 10 m high in Trail Canyon, a channel that drains the Henry Mountains farther to the south and joins Trachyte Creek about 12 km downstream of our study site and 10 km upstream of the confluence with the Colorado River. Thus there has been aggradation elsewhere in the system, and we cannot rule out the possibility that the P3 gravels were deposited in a later depositional event and are younger than the terrace itself. The incision rate of 527 ± 86 m/my obtained from the P3 deposit should therefore be considered a maximum rate.

Implications for Trachyte Creek Incision

The surfaces range from at least 267 ka to ~3 ka, and exposure ages increase with elevation of the surfaces (Table IV). Although the ages for the upper two terraces are minimums and the lower two terraces yield approximate ages, the rates calculated are quite consistent, ranging from 350 m/my to 527 m/my (Figure 10). The presence of strath terraces along Trachyte Creek, and throughout the Henry Mountains, indicates that incision has been somewhat episodic during this time period. We suggest that these episodes can likely be attributed to climatic variations; the data indicate that the long-term net incision rate has been steady for the past ~270 ky.

The rates from Trachyte Creek are similar to those obtained nearby in Glen Canyon (Garvin *et al.*, 2005; Hanks *et al.*, 2001) and at Bullfrog Basin (Davis *et al.*, 2001), and

Table IV. Incision rates based on ^{10}Be surface ages

Surface	Age (ky)	Height (m)	Incision rate (m/my)	±
P1	267	110	412	21·4
P2	178	62	348	28·3
P3	13	7	527	8·4
P4	~3?	1	~330?	19·2

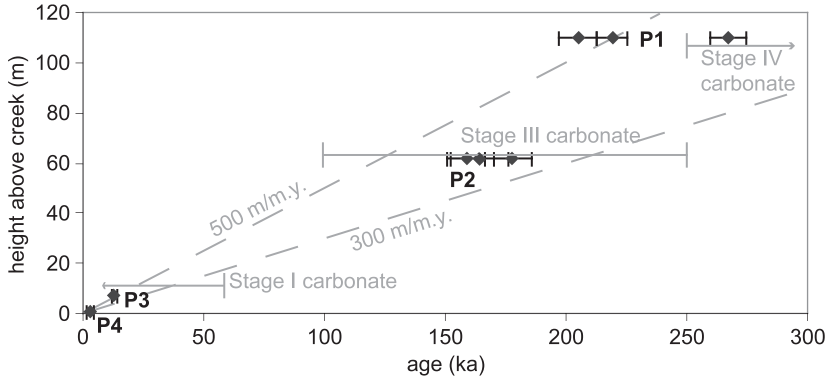

Figure 10. The age of each surface plotted against the amount of subsequent downcutting. Gray bars indicate predicted age ranges based on pedogenic carbonate development in the gravels. Dashed gray lines have slopes of 300 m/my and 500 m/my for comparison.

significantly higher than recent rates in the Grand Canyon (Pederson *et al.*, 2002) and at Bluff, Utah (Wolkowinsky and Granger, 2004). The relatively consistent, rapid incision rates estimated for Trachyte Creek suggest that this channel is in fact responding to the recent rapid incision of the Colorado River, and the lack of a knickpoint in the channel suggests that Trachyte Creek is responding to the incision pulse in a continuous way. The elevation at which these rates were measured also suggests that Trachyte Creek is not responding in a detachment-limited manner. Stream-power based incision models predict that the vertical migration rate of transient knickpoints should be uniform throughout a simple detachment-limited system (i.e. Niemann *et al.*, 2001; Whipple and Tucker, 2002). The study location on Trachyte Creek is at an elevation of ~1450 m – about 200 m higher than the knickpoints seen in the other channels in this region (Table II); the presence of rapid incision at this site since at least ~270 ka suggests that the incision pulse was able to rapidly advance up the channel without forming a discrete knickpoint. Both theory and landscape evolution models predict that transport limited, or dominantly alluvial, channels will rapidly smooth out knickpoints and maintain a regular, concave profile even as they respond to perturbations (Whipple and Tucker, 2002; Crosby *et al.*, 2007, Whipple, 2004) and that such perturbations will rapidly sweep upstream. The combination of extremely durable diorite gravel and weak, easily abraded bedrock in the Henry Mountains channels may drive them towards an essentially transport-limited condition (Johnson *et al.*, 2009). Johnson *et al.* (2009) refer to these channels as sediment-load dominated bedrock channels. Channels that tap into a source of diorite typically contain a high sediment load that is dominated by diorite clasts. Johnson *et al.* (2009) show that diorite-rich channels in the Henry Mountains tend to not have the knickpoints due to lithologic variations that are seen in nearby diorite free channels. We infer that knickpoints have likewise not formed in response to the recent pulse of baselevel fall on the Colorado river along these bedload-rich channels; with the greater availability of abrasion tools (hard diorite clasts i.e, Sklar and Dietrich, 2004) incision of these channels has been able to more closely keep pace with the rate of baselevel fall. This highlights the importance that sediment supply and lithology can have in determining the response of a channel to perturbations.

Channel Incision Model

To further investigate the interaction between lithologic variations and transient knickpoints, we follow an approach similar to that of Stock *et al.* (2004), and model channel evolution using a detachment-limited model of bedrock channel incision based on the equation $E = K_{\mathrm{eff}} A^m S^n$ (where E is the incision rate, A is the drainage area and S is the slope at each point). Our model includes both a critical shear stress and a stochastic distribution of precipitation and discharge through the K_{eff} term. K_{eff}, calculated each timestep at each point, is a complex function that incorporates a number of different parameters, including the critical shear stress, the frequency and magnitude of precipitation events, the slope at each point, and the effect of lithology on erodability [equation (7) in Snyder *et al.* (2003) and equation (23) in Tucker (2004)]. For a full derivation and discussion of the equations used in this model, see Tucker (2004).

We seek to illustrate how key elements of the Colorado River system are expected to influence both its longitudinal profile, the distribution of knickpoints in the Colorado and its tributaries, and the spatial and temporal variations in incision rate. Accordingly, we use the configuration of the Colorado River to guide model setup. However, we emphasize that our model is intentionally kept simple – sufficiently well elaborated to provide novel insight, but admittedly inadequate to accurately reproduce the modern river profile and its incision rate history. In other words, our modeling is exploratory in nature and we do not attempt to use observations to quantitatively constrain model parameters. We assign a simple distribution of lithologies; in the first case we use two flat-lying layers of different strengths, and in the second case a lithologic distribution suggested by sections along the Colorado River (i.e. Karlstrom, 2005). The initial channel profile was obtained by running the model with the given lithologic distribution until the profile reached a steady state and incision was balanced with a background uplift rate of 100 m/my. This uplift rate is suggested by incision rates on the upper Little Colorado (Damon *et al.*, 1974), the upper San Juan (Wolkowinsky and Granger, 2004) and recent rates within the Grand Canyon (Pederson *et al.*, 2002, 2006). We then impose an abrupt, discrete baselevel fall on the initial profile and allow the profile to adjust. Because several of the model parameters are amalgamations of different factors, their value is difficult to determine physically; we tuned the values of these parameters to best match the slope of the Colorado River and the rates of incision in the Glen Canyon region. Values for the parameters describing the stochastic distribution of precipitation were suggested by Tucker and Bras (2000).

As Figure 11(A) illustrates, a perturbation in layered rocks where the lower layer is more resistant than the upper layer can split into two discrete knickpoints that propagate

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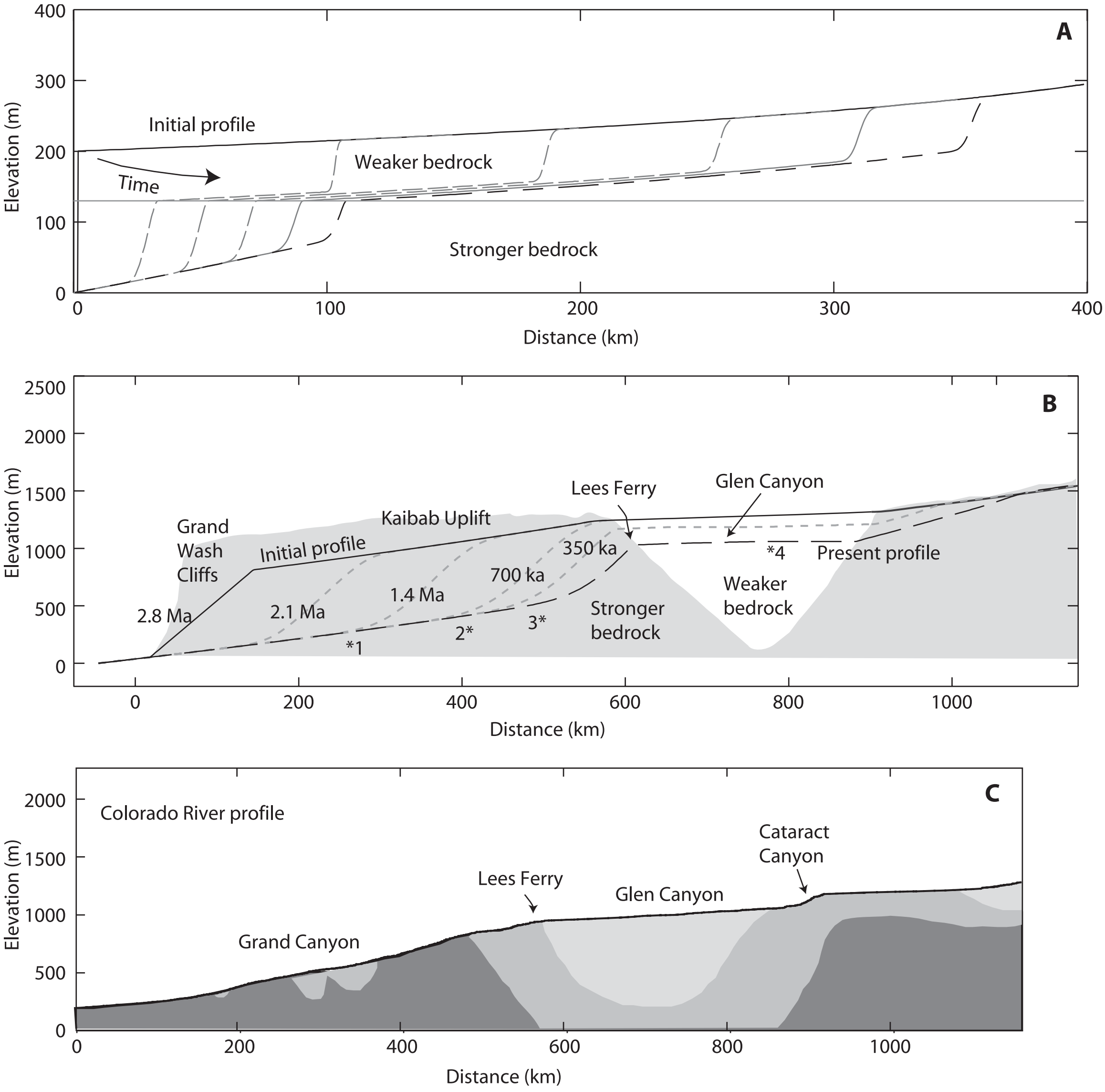

Figure 11. Numerical models of the evolution of a detachment-limited channel profile in response to a sudden base-level fall. The solid black line is the initial channel profile, and the dashed gray lines show how the profile evolves through time. In both models the background uplift rate is 100 m/my. (A) Evolution of a channel in flat-lying two-layer bedrock – above 130 m elevation, the bedrock is five times weaker (more erodable) than below 130 m. The channel experiences a sudden base-level fall of 200 m at the initiation of the model run. The dashed black line shows the profile after the upper knickpoint has swept through much of the system. Diffusion of the knickpoints is an artifact of the numerical model. This may be analogous to the Dirty Devil River. (B) Evolution of a channel in dipping bedrock. Setup is analogous to the Colorado River in the Grand Canyon region. The strong rocks of the Kaibab uplift dip under the Glen Canyon Group near Lee's Ferry, then resurface farther upstream. The channel experiences a sudden 650 m baselevel fall at the initiation of the model run, simulating Colorado River diversion or integration across the Grand Wash Cliffs. The dashed black line is analogous to the modern Colorado River. See text for further discussion. (C) Manually surveyed profile of the Colorado River for comparison (1924 USGS river survey, B. Webb and T. Hanks, personal communication). Simplified lithologic boundaries adapted from Karlstrom (2005).

upstream at different rates. The lower knickpoint is controlled by the lithologic boundary, and moves upstream much more slowly than the upper knickpoint, which can rapidly sweep upstream through the weaker rock. Because the knickpoints in this model are the response to a single discrete pulse of incision, rather than a lasting change in rock uplift rate or rate of baselevel fall, the portions of the channel above the upper knickpoint and below the lower knickpoint are incising at the same rate. This type of knickpoint partitioning may explain our observations of the Dirty Devil/Fremont River.

In the context of the Colorado Plateau, a more realistic scenario is the presence of an upstream-dipping lithologic contrast such as the contact between the resistant units of the Kaibab upwarp and the weaker rocks upstream (Figure 11B). In this case, a single knickpoint propagates upstream until it reaches the contact between rocks of contrasting strength. The signal is then divided into two parts. The lower knickpoint remains localized on the lithologic boundary, and because the boundary is dipping upstream, the knickpoint lowers in elevation as it moves upstream. This provides a prolonged signal of relative baselevel fall to the upper section of the channel. The upper knickpoint sweeps rapidly through the weaker bedrock until, in the model illustrated here, it encounters the more resistant bedrock again and propagation slows. As the profile evolves, the upper knickpoint grows while the lower knickpoint shrinks, and the incision rate in the reach between the two knickpoints remains high and is controlled by the retreat rate of the lower knickpoint and the dip of the resistant unit. This simple example illustrates that not only is the relative strength of the bedrock important, but that the orientation of strength contrasts also play a very important role in determining the way in which incision is distributed in space and time along the river. These results suggest that the late incision pulse (initiation at ~500 ky) we see upstream of Lee's Ferry is related to the interaction of a knickpoint propagating up through the Grand Canyon with the upstream-dipping boundary of the Kaibab uplift.

We reiterate that this modeling is not intended to reproduce the Colorado River and its incision history, or to predict incision rates, but instead to isolate and therefore illustrate the effect of dipping lithologic boundaries. The models illustrated in Figure 11 describe a strictly detachment-limited system; however the Colorado River contains reaches that are likely closer to a gravel-bedded transport-limited system. This could cause the incision pulse to diffuse out upstream of Lee's Ferry and prevent the formation of a discrete upper knickpoint, and may result in a steeper channel downstream of the lower knickpoint as incision is distributed over a broader zone. We also ignore a number of other factors that influence and tend to steepen the profile of the Colorado, particularly in the Grand Canyon region, including the effect of tributary debris flows (Hanks and Webb, 2006), possible lithologic effects associated with incision into crystalline basement, and motion along the Toroweap Fault (Pederson *et al.*, 2002).

Discussion

Timing and extent of incision pulse

Both the channel profiles and our new incision rates for Trachyte Creek indicate that the Colorado River in the Glen Canyon region has experienced a recent pulse of rapid incision. The timing of the incision pulse in this region is not well constrained. Surfaces as old as ~500 ka yield high incision rates, suggesting 500 ka as a minimum age for the onset of rapid incision (i.e. Hanks *et al.*, 2001). However, these rates are averaged over the age of the surfaces, and therefore do not preclude the possibility of a post-500 ka acceleration in incision. The initiation of rapid incision around 500 ka is consistent with the magnitude of the incision pulse that we see in the Glen Canyon region and the incision rate estimates in the region. Thus, 500 ky of incision at an average rate of 350 to 450 m/my results in a total of 175 to 225 m of incision. This is similar to the knickpoint heights of 150 to 200 m that we measured in our analysis of channel profiles, and further supports our interpretation that these knickpoints are related to a pulse of rapid incision in the past 500 ky, which our modeling suggests is the time when an advancing knickpoint associated with Grand Canyon incision breached the Kaibab Upwarp.

The upstream extent of this signal in the Colorado itself is unclear. There is a large knickpoint of similar size on the Colorado at Cataract Canyon; however, Webb *et al.* (2004) suggest that this knickpoint is the result of a rapid input of sediment due to frequent debris flows in the Holocene, and not due to transient bedrock incision. The relationship between the large knickpoint and relatively fast incision rates on the Gunnison River, a major tributary that enters the Colorado upstream of Cataract Canyon (Sandoval *et al.*, 2006) and the incision pulse in southern Utah is likewise unclear. The knickzone in the Black Canyon of the Gunnison is of similar magnitude (~200 m) and the incision rate is similar, but there is no corresponding knickpoint on the North Fork of the Gunnison and the Black Canyon knickzone may reflect local structural uplift (Sandoval *et al.*, 2006). Berlin and Anderson (2007) also note large knickpoints on tributaries to the Colorado draining the Roan Plateau. However, incision rates on these tributaries have not been directly measured. These knickpoints are heavily influenced by lithologic strength contrasts and are too large (~800 m above the Colorado) to be attributed solely to the incision pulse discussed here. In addition, the tributary reaches downstream of the knickpoints grade smoothly into the Colorado River (Berlin and Anderson, 2007). This suggests that these knickpoints are related to incision over a much longer timescale than the incision pulse seen farther downstream, as suggested by Berlin and Anderson (2007).

In order to further characterize the timing and spatial extent of this incision pulse and define its relationship to the knickpoints shown in Figures 1 and 2, more estimates of incision rates upstream and downstream of the knickpoints on these drainages are necessary. Our analysis provides a framework for the collection of further incision rate data from tributaries of the Colorado. Understanding the context of incision rate estimates is crucial for extrapolating those rates upstream/downstream or to other parts of the system.

Regional implications

As more incision data becomes available throughout the region, we can better constrain the spatial and temporal variations in incision rates, and can asses the importance of forcings such as localized deformation, regional uplift, baselevel fall, and climate. For example, Pederson *et al.* (2007) suggest that recent rapid incision on the Colorado Plateau is primarily related to a 'bullseye' of regional epeirogenic uplift, rather than the propagation of incision up the Colorado River. This assumes that the rivers are in equilibrium with the landscape, so that incision rates are in balance with uplift rates, but the pattern of knickpoints described earlier suggest that the upper and lower reaches of the channels are not in equilibrium and that the system is in a transient state. While regional uplift may be contributing to the incision on the Colorado Plateau, it does not explain the pattern that we observe in the channel profiles in southern Utah.

Our observations may also help resolve the nature of the large knickzone at Lee's Ferry – whether it is primarily a response to the transition from weak sedimentary rocks in the Glen Canyon region to the more resistant units of the Grand Canyon Group, or primarily a transient knickpoint that is sweeping upstream. The recognition of a recent pulse of incision on the Colorado immediately upstream of Lee's Ferry indicates that this reach of the Colorado River is responding to the incision of the Grand Canyon, and that the Lee's Ferry convexity does not represent the upstream extent of the incision signal. In addition, the difference in incision rates upstream and downstream of Lee's Ferry indicates that this reach of the Colorado River is not in equilibrium, and that the Lee's Ferry convexity is not a static knickpoint solely due to the presence of a resistant lithology. As the modeling results illustrate, the large convexity is likely due to a combination of transient and lithologic effects, where a portion, but not all, of the incision signal has become localized at the lithologic boundary near Lee's Ferry.

Our modeling also predicts a relationship between the initiation of rapid incision in Glen Canyon and the slowing of incision in the Grand Canyon. As Figure 12(A) illustrates, rapid incision upstream of Lee's Ferry does not begin until headward incision reaches the boundary between the

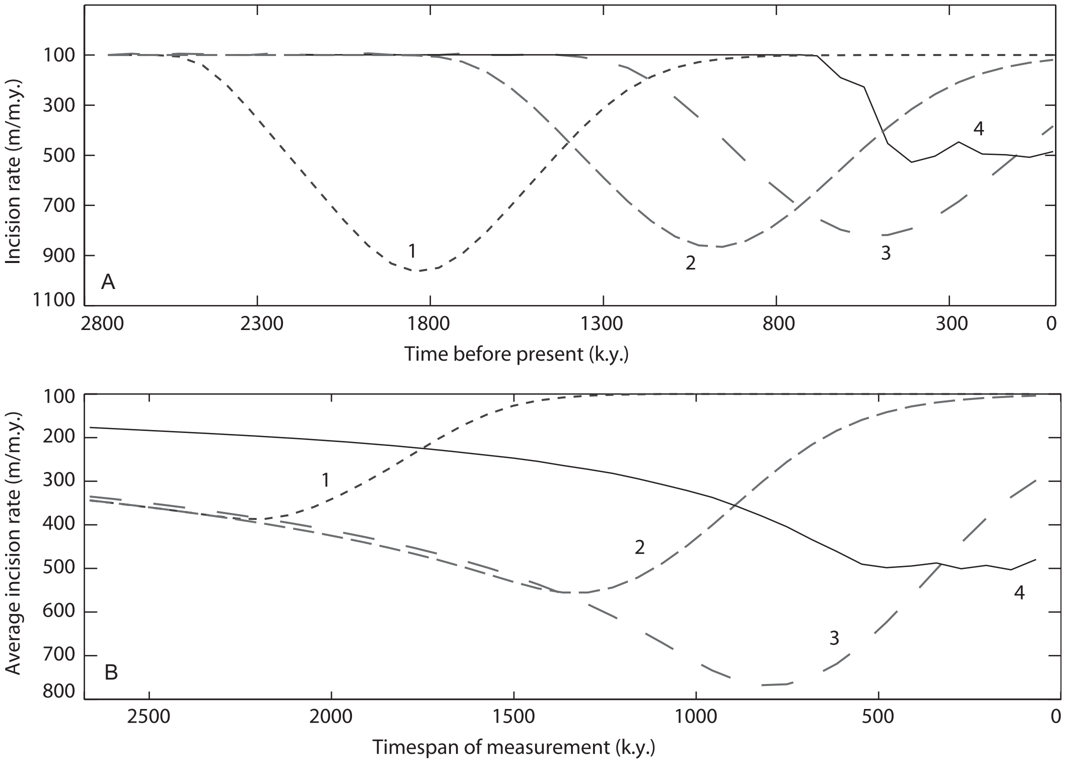

Figure 12. (A) Incision rates with time for the Colorado River incision model. Each numbered curve shows the incision rate at the corresponding point marked in Figure 11(B). The rates include a background uplift and incision rate of 100 m/my. (B) Rates at each point averaged between present and different times in the past. This is analogous to the rate one would estimate from the height of a terrace of a given age above the modern channel. Note that the maximum averaged rate is offset from the actual maximum rate in a manner that varies with position along the river profile.

resistant Kaibab Upwarp and the weaker rocks of the Glen Canyon Group. This corresponds to a slowing of incision in the Grand Canyon in the wake of the transient headward incision signal. After rapid incision in the Glen Canyon region begins, rates downstream of Lee's Ferry continue to drop, while the rates upstream of Lee's Ferry remain high and fairly constant, as the relative baselevel of the reach is controlled by the retreat rate of the knickpoint and the dip of the lithologic contact (each relatively constant).

Because we are only able to measure incision rates that are averaged over some length of time, it is important to understand how the variation in incision rates through time affects the average rate we measure, particularly in complex transient incision scenarios such as that predicted by our modeling. The curves in Figure 12(B) show the incision rate at each of the points in Figure 11(B) averaged between different times in the past and today, illustrating how the incision rate one would calculate at a particular point by measuring a feature, such as a fluvial terrace or cave deposit, varies with the age of that feature. The rates within the Grand Canyon region are highly dependent on the timespan over which they are averaged, reflecting the passage of a pulse of rapid incision associated with an upstream migrating knickpoint. The plot shows that, even though the absolute rate at point three (just downstream of Lee's Ferry) is near its maximum at the onset of Glen Canyon incision, the averaged rate has already substantially declined.

As even these simple models illustrate, in a real system, with spatial variations such as multiple lithologies and structures, as well as temporal variations such as climatic effects, the incision signal has the potential to become quite complicated. The variations that we see in the form of the knickzone throughout the study region, and the absence of a visible transient signal in the channels of the Henry Mountains highlight the complexity that results in large natural systems such as the Colorado River drainage.

Conclusions

The Colorado River in the Glen Canyon region has experienced a pulse of incision within the past ~500 ky. Tributaries to the Colorado are continuing to adjust to the more rapid incision of the main stem, as transient knickpoints are preserved at similar elevations in most of the channels. Incision rates measured below the knickpoints are rapid relative to recent incision rates of the Colorado in the Grand Canyon. Additional incision rates are needed both upstream and downstream of the knickpoints to corroborate our interpretation of the pattern observed in the channel profiles. Incision rates on Trachyte Creek, in the Henry Mountains, are of a similar magnitude to the rapid rates measured below the knickpoints in nearby channels, despite the absence of knickpoints in Trachyte Creek and many of the Henry Mountains channels.

Modeling suggests that the pulse of incision we observe upstream of the Grand Canyon may be related to the interaction between the propagation of headward incision through the Grand Canyon and the presence of an upstream-dipping lithologic boundary at Lee's Ferry. This suggests that the large knickpoint at Lee's Ferry is neither the upstream extent of Grand Canyon incision nor solely related to lithology, but instead results from a combination of lithologic and transient effects. These observations indicate that, upstream of the Grand Canyon, Colorado River is continuing to adjust in a complex way to the drainage integration and large baselevel fall responsible for the formation of the Grand Canyon.

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