JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, F02003, doi:10.1029/2004JF000201, 2006

# Using fill terraces to understand incision rates and evolution of the Colorado River in eastern Grand Canyon, Arizona

Joel L. Pederson,[1] Matt D. Anders,[1] Tammy M. Rittenhour,[2,3] Warren D. Sharp,[4]
John C. Gosse,[5] and Karl E. Karlstrom[6]

Received 6 July 2004; revised 6 July 2005; accepted 20 December 2005; published 26 April 2006.

[1] The incision and aggradation of the Colorado River in eastern Grand Canyon through middle to late Quaternary time can be traced in detail using well-exposed fill terraces dated by a combination of optically stimulated luminescence, uranium series, and cosmogenic nuclide dating. This fluvial history provides the best bedrock incision rate for this important landscape and highlights the complications and advantages of fill terrace records for understanding river long-profile evolution and incision. The use of fill terraces, as distinct from strath terraces, for calculating incision rates is complicated by the cyclic alluviation and incision they record. In the example of the Grand Canyon this has led to various rates being reported by different workers and rates that tend to be overestimates in shorter records. We illustrate that a meaningful long-term bedrock incision rate of ~140 m/m.y. can be extracted from the Grand Canyon record by linking episodes when the Colorado River is floored on bedrock. Variable incision rates reported in the greater region may be, to some degree, due to inconsistent calculations. Our data also highlight that the Colorado River has been a mixed alluvial-bedrock river through both time and space and has been a bedrock river for less than half of its Pleistocene history. This strong temporal variation, combined with the varying bedrock the river encounters on its path, heightens the challenge of understanding the tectonic, climatic, and drainage integration controls on the form and evolution of the Colorado River's long profile.

**Citation:** Pederson, J. L., M. D. Anders, T. M. Rittenhour, W. D. Sharp, J. C. Gosse, and K. E. Karlstrom (2006), Using fill terraces to understand incision rates and evolution of the Colorado River in eastern Grand Canyon, Arizona, *J. Geophys. Res.*, *111*, F02003, doi:10.1029/2004JF000201.

## 1. Introduction

[2] Stream terraces are geomorphically important because they and their associated deposits provide information about a drainage's sedimentologic, hydrologic, and erosional history. As such, they are key to understanding the influence of tectonics, varying climate, and base level change on landscapes, and they can provide important information on incision rates when they can be numerically dated. A stratigraphy of river terraces is formed and preserved as a stream changes activity between incision, lateral planation, and alluviation. These changes are commonly thought of in terms of the balance between the driving forces of available stream power and the resisting forces that must be overcome to transport the sediment load [*Bull*, 1979]. A river is in equilibrium or a "graded" state when these forces are balanced such that it neither aggrades nor incises [*Mackin*, 1937; *Leopold and Bull*, 1979], and it takes on its characteristic longitudinal profile [*Knox*, 1975]. Stratigraphic markers of these past equilibria in a river's history are ideal for calculating incision rates and are recorded in stream terraces by their treads, abandoned after the stream crosses this equilibrium threshold and begins incising, and by their basal straths, buried as a river crosses the threshold between erosion and aggradation [*Bull*, 1991; *Pazzaglia et al.*, 1998].

[3] Of the two end member types, strath (erosional) terraces have been the focus of recent research for their utility in measuring bedrock incision, typically in areas of active tectonics [e.g., *Merritts et al.*, 1994; *Burbank et al.*, 1996; *Pazzaglia and Brandon*, 2001; *Hancock and Anderson*, 2002]. Fill (depositional) terraces, despite being very common, are more problematic for calculating consistent incision rates because of the cyclic nature of their formation through both incision and alluviation. Our focus in this paper is on fill terraces. The examples in eastern Grand Canyon are

---

[1] Department of Geology, Utah State University, Logan, Utah, USA.
[2] Department of Geosciences, University of Nebraska-Lincoln, Lincoln, Nebraska, USA.
[3] Now at Department of Geology, Utah State University, Logan, Utah, USA.
[4] Berkeley Geochronology Center, Berkeley, California, USA.
[5] Earth Sciences Department, Dalhousie University, Halifax, Nova Scotia, Canada.
[6] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico, USA.

0148-0227/06/2004JF000201

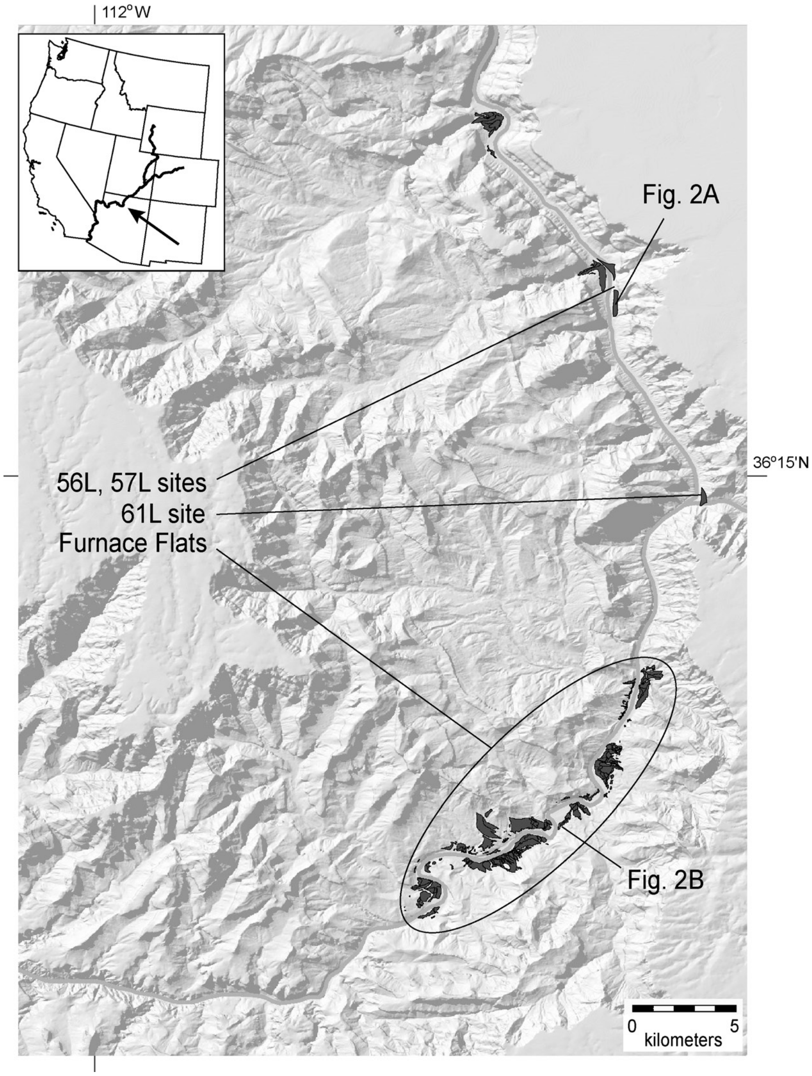

**Figure 1.** Location of eastern Grand Canyon study area along the Colorado River corridor. Select main stem Colorado River–associated Pleistocene map units are shown in dark gray (for complete mapping of both tributary drainages and the main stem corridor, see *Anders* [2003]), and locations of key study sites are labeled.

underlain by thick alluvium and have a sedimentary architecture indicating aggradation of more than a single channel depth, but they also have planar or stepped basal contacts or bedrock straths that are useful for tracking bedrock incision. Because these fill terraces are a relatively complete record of both incision and deposition, are well exposed, and can be dated by multiple methods, they can be used to understand both responses to climate and the long-term bedrock incision that such responses are superimposed upon. We discuss elsewhere the response of both the main stem Colorado River and local catchments to climate change and the specifics of the timing of terrace genesis in this setting [*Anders et al.*, 2005]. In this paper, we integrate the straths, treads, and deposits of the fill terraces with multiple dating methods to reconstruct the fluvial history in eastern Grand Canyon and to extract meaningful bedrock incision rates. This example provides a key data point for the ongoing debate about the tectonic and erosional evolution of the interior western United States and illustrates the timescale and space-scale complexities in understanding the controls on long-profile evolution of mixed bedrock-alluvial rivers.

## 2. Grand Canyon Background

[4] The study area includes 34 km of the Colorado River corridor in eastern Grand Canyon (Figure 1). The river is confined to a relatively narrow, steep-walled canyon in the Paleozoic sedimentary bedrock of the upper part of the study area, and then it flows in a broader canyon through the Furnace Flats reach, which is underlain by Proterozoic sedimentary and volcanic bedrock. The modern Colorado River receives negligible inputs of water from the arid Grand Canyon region, but tributaries provide significant sediment and the coarse debris fans at tributary confluences have controlled the river's hydraulic geometry over Holocene time [e.g., *Leopold*, 1969; *Schmidt and Rubin*, 1995]. The Pleistocene fill deposits studied here are generally 30–50 m thick and are composed of thin-to-thick crossbeds of

clast-supported, imbricated, pebble-to-boulder gravel with lenses of gravelly sand (Figure 2). All researchers who have studied this stratigraphy of inset deposits and terraces have attributed the cycles of deposition and incision that formed it to the effects of glacial-interglacial climate changes on the sediment load and water discharge of the Colorado River [*Machette and Rosholt*, 1991; *Lucchitta et al.*, 1995, 2000; *Pederson et al.*, 2002; *Anders et al.*, 2005].

[5] In terms of longer landscape evolution, incision of Grand Canyon began ~6 Ma driven by an unknown and debated combination of integration of the Colorado River off the Colorado Plateau and epeirogenic uplift [e.g., *Blackwelder*, 1934; *Lucchitta*, 1972; *Pederson et al.*, 2002]. *Hamblin* [1994] noted that incision was largely complete prior to the emplacement of lavas that flowed into the canyon and now lie along the present-day river in western Grand Canyon. Recent evidence suggests these lava flows are significantly younger than was first determined and that incision is still occurring throughout the canyon, but at a lower rate in western Grand Canyon, because of active slip along the Hurricane-Toroweap fault zone [*Lucchitta et al.*, 2000; *Fenton et al.*, 2001; *Pederson et al.*, 2002]. This picture of landscape evolution and differential incision is clouded by a dearth of information about incision along the Colorado River. Confusion also arises from the wide range of incision rates reported in places that have been studied, such as eastern Grand Canyon. *Machette and Rosholt* [1991] identified seven fill terraces in eastern Grand Canyon and concluded that the rate of incision increased from 100 to 700 m/m.y. over the last 700 kyr on the basis of five U trend analyses (as distinct from the U series dating we report here). *Lucchitta et al.* [1995, 2000] determined that these terraces were deposited between 525 and 26 ka and calculated an incision rate of 300–500 m/m.y. This was based on cosmogenic exposure dates from boulders on terrace treads as well as age extrapolation from western Grand Canyon based on soil-carbonate morphology. Finally, *Pederson et al.* [2002], using fewer data and a different approach to calculating rates than we employ here, reported a minimum bedrock incision rate of ~140 m/m.y. using the same deposits in eastern Grand Canyon. Part of our goal in this paper is to explore the origins of these variable conclusions derived from the same record.

## 3. Stratigraphic and Chronologic Data

### 3.1. Methods

[6] Surficial deposits and terraces of the tributary and main stem canyons of a ~300 km$^2$ area of greater eastern Grand Canyon have been mapped at a scale of 1:12,000 [*Anders*, 2003], and both main stem Colorado River and tributary deposits have been dated by multiple chronometers. Only the main stem Colorado River stratigraphy and geochronology is utilized here. The height of dated samples, terrace treads, and straths were surveyed relative to a local reference river stage of 283 m$^3$/s (10,000 ft$^3$/s), and terrace deposits were correlated on the basis of landscape position, tread and soil characteristics, and absolute dating (Figure 3). Ages are provided by three complementary methods: (1) optically stimulated luminescence (OSL), (2) uranium series dating, and (3) terrestrial cosmogenic nuclide (TCN) dating corrected for inheritance. An important advantage of utilizing these multiple dating methods is our ability to obtain dates from different levels within fill deposits as well as from terrace treads, recording different stages of deposition (OSL and U series), minimum ages for abandonment of terraces (TCN), and potentially even incision through U series dating of travertine precipitated locally during overall erosion.

[7] Samples of fine- to medium-grained sand from terrace deposits were dated using single-aliquot regenerative optically stimulated luminescence (Table 1). Samples were collected in aluminum tubes, with depth, elevation, and latitude/longitude noted for calculation of cosmic contribution [*Prescott and Hutton*, 1994]. Representative samples for the determination of water content and dose rate were collected from within 30 cm of the tubes, though most samples were desiccated in the field and so a water content of 0.5 ± 3.0% by weight was assumed. The bulk sediment concentration of K, Rb, U, and Th was measured using ICP-MS and ICP-AES techniques, with duplicates checked for complete dissolution using a fusion-flux dissolution technique. Dose rates incorporating water content, chemistry, and cosmic contribution were then calculated using the methods of *Aitken* [1998] and *Prescott and Hutton* [1994]. For optical measurements the 90–150 $\mu$m quartz fraction was isolated, treated, and mounted for analysis on a RISO TL/OSL-DA-15B/C reader with blue-green light stimulation (470 nm, Hoya U340 filter) using the single aliquot regenerative (SAR) protocol of *Murray and Wintle* [2000]. Forty to eighty aliquots were measured from each sample. To help identify partial bleaching, small aliquots of sand (~100 grains) were used to approach single-grain distributions [*Olley et al.*, 1999]. Aliquots with obvious signs of partial bleaching were removed and the optical ages were calculated from the mean equivalent dose. Total 2$\sigma$ errors in Table 1 include combined random and systematic errors calculated using the methods of *Aitken and Alldred* [1972] and *Aitken* [1976]. Examples of the random errors are those in dose rate measurement and calculation, whereas system-

**Figure 2.** (a) Overview of the 57L site with relatively planar basal straths of fill terrace deposits preserved below river gravels that are interfingered with U series–dated travertine. The upper parts of deposits and the terrace treads have been removed by subsequent hillslope processes. (b) Example of the M3 Colorado River deposit in Furnace Flats where the timing of deposition is known from optically stimulated luminescence dates in the deposit and a minimum age for the abandonment of a fill cut terrace is given by a terrestrial cosmogenic nuclide date corrected for inheritance. (c) Composite Colorado River stratigraphy of eastern Grand Canyon with a range of sample ages from Table 4. This is compiled from the correlation of individual deposits that vary in height and thicknesses over the 34 km long study reach because of partial preservation in this steep canyon landscape. An obscured deposit (not shown here) may exist bracketed by a 280 ± 9 ka basal U series age (seen in Figure 2a) and a 161 ± 34 ka cosmogenic date. M1 represents fine-grained Holocene deposits, and we hypothesize that a younger Pleistocene deposit (M2) may underlie the modern channel.

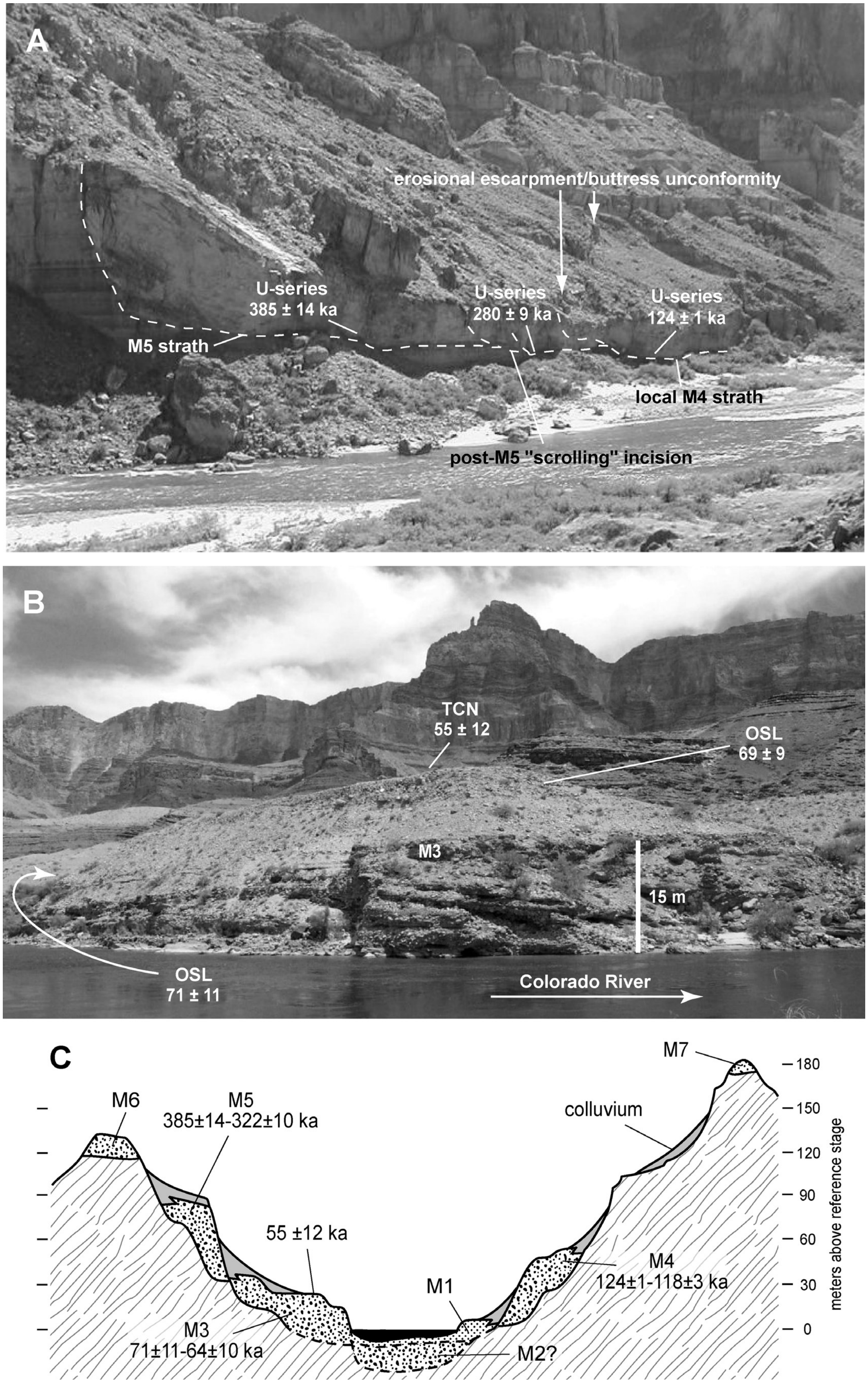
A
erosional escarpment/buttress unconformity
U-series
385 ± 14 ka
U-series
280 ± 9 ka
U-series
124 ± 1 ka
M5 strath
local M4 strath
post-M5 "scrolling" incision
B
TCN
55 ± 12
OSL
69 ± 9
M3
15 m
OSL
71 ± 11
Colorado River
C
M7
M6
M5
385±14-322±10 ka
colluvium
55 ±12 ka
M1
M4
124±1-118±3 ka
M3
71±11-64±10 ka
M2?
180
150
120
90
60
30
0
meters above reference stage

Figure 2

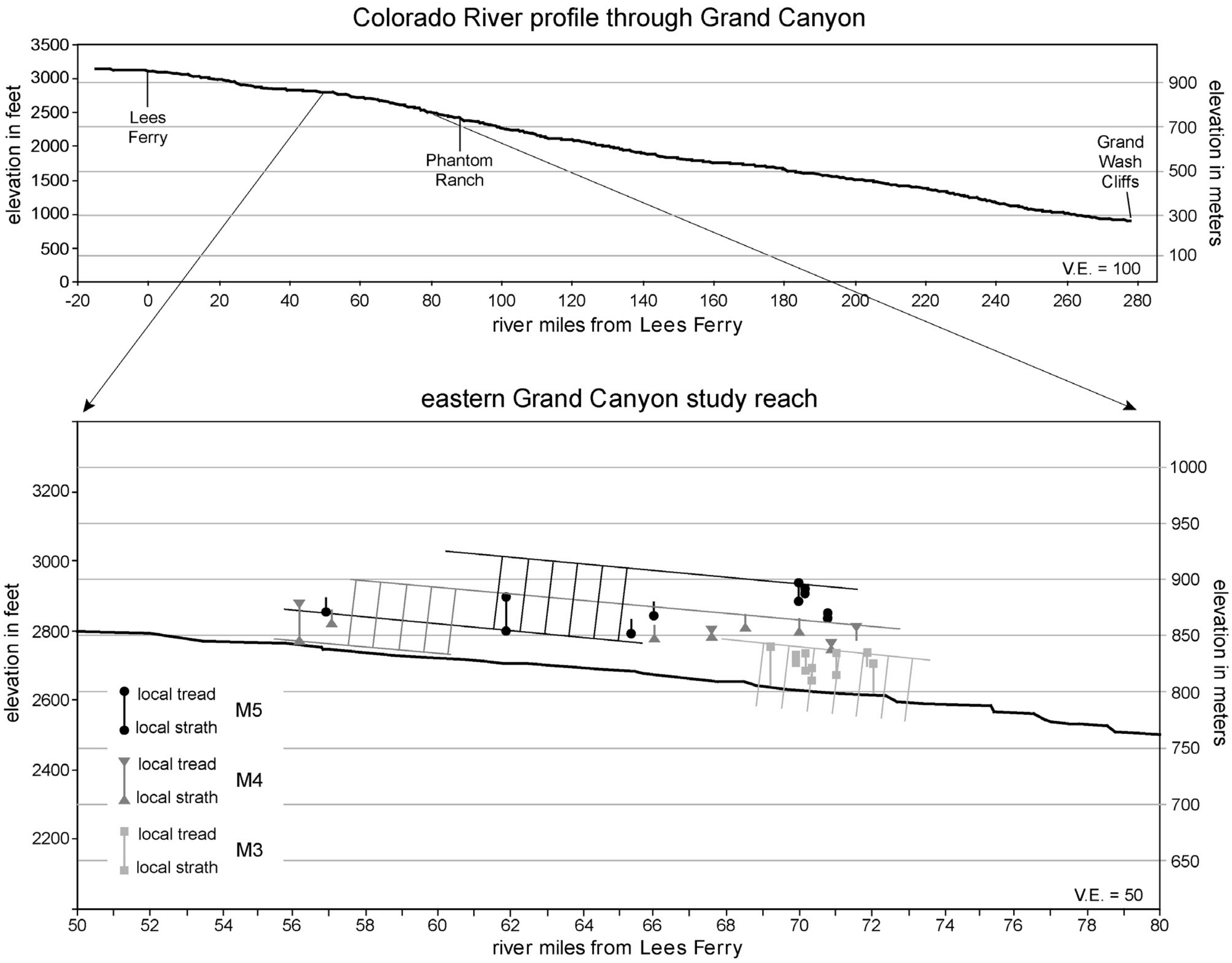

**Figure 3.** Eastern Grand Canyon study reach in the context of the longitudinal profile of the Colorado River, with water surface elevations taken from the work of *Birdseye* [1924]. Locations of major study outcrops where survey and geochronologic samples were obtained are illustrated with data points for local base and top of deposit. Only the three major dated fill deposits are shown. Preservation and exposure vary because of steep canyon topography and erosion in this setting, resulting in local bases of outcrops that do not reflect the total thickness of the unit. Likewise, local terrace treads, if preserved, can be degradational (fill cut) terraces that do not record the true top of the original deposit. Thus careful mapping and correlations based on geochronology are necessary. Dashed curves and hachures tie the isolated remnants into the overall interpretation shown in Figures 2c and 4.

atic errors include calibration of the OSL reader and $^{90}$Sr irradiation source.

[8] Uranium series dating focused on travertine spring deposits that interfinger with and drape alluvium, and thus are not a secondary cement, and results are interpreted as ages of crystallization for the travertine (Tables 2 and 3). Samples were dissolved in concentrated $HNO_3$-HF together with a mixed $^{233}$U-$^{236}$U-$^{229}$Th spike. U and Th were then separated using conventional ion exchange methods and loaded as a colloidal graphite sandwich onto single rhenium filaments [*Chen et al.*, 1986; *Edwards et al.*, 1987]. Isotopic analyses were done on a Micromass Sector-54 TIMS

**Table 1.** Data for Optical Dating of Eastern Grand Canyon

| Deposit, Location[a] | Sample | Depth, m | U, ppm | Th, ppm | $K_2O$, wt % | $Rb_2O$, ppm | Cosmic, Gy/ka | Dose Rate, Gy/ka | De, Gy | Age ±2σ Error, ka |
|---|---|---|---|---|---|---|---|---|---|---|
| M3, 69.5L | GC-09-04-22 | 13.5 | 1.4 ± 0.1 | 3.0 ± 0.3 | 1.22 ± 0.12 | 38.3 ± 3.8 | 0.05 | 1.54 ± 0.09 | 110.10 ± 16.15 | 71.3 ± 10.9 |
| M3, 69.5L | GC-09-04-21 | 5 | 1.4 ± 0.1 | 3.0 ± 0.3 | 1.52 ± 0.15 | 48.1 ± 4.8 | 0.13 | 1.85 ± 0.11 | 128.00 ± 16.04 | 69.2 ± 9.2 |
| M3, 67L | GC-09-04-18 | 21 | 1.4 ± 0.1 | 5.8 ± 0.6 | 2.06 ± 0.21 | 58.9 ± 5.9 | 0.03 | 2.41 ± 0.15 | 164.34 ± 26.95 | 68.1 ± 11.6 |
| M3, 72L | GC-09-04-23 | 2 | 1.5 ± 0.2 | 3.0 ± 0.3 | 1.41 ± 0.14 | 44.4 ± 4.4 | 0.19 | 1.85 ± 0.10 | 123.43 ± 19.47 | 66.9 ± 10.8 |
| M3, 67L | GC-09-04-19 | 16 | 2.4 ± 0.2 | 8.4 ± 0.8 | 2.12 ± 0.21 | 68.9 ± 6.9 | 0.04 | 2.90 ± 0.17 | 185.08 ± 27.24 | 63.7 ± 9.8 |

[a] Shown here are river miles (RM) below Lees Ferry. L and R are left and right riverbank, respectively, when facing downstream.

**Table 2.** Data for U Series Dating of Travertines in Eastern Grand Canyon[a]

| Deposit, Location[b] | Sample | $^{238}$U, ppm | $^{232}$Th, ppm | $^{230}$Th/$^{232}$Th | Measured $^{230}$Th/$^{238}$U ±2σ | Measured $^{234}$U/$^{238}$U ±2σ | Age, ka | Initial $^{234}$U/$^{238}$U[c] |
|---|---|---|---|---|---|---|---|---|
| 2 m above M5 strath, 57L | K02-056-2A | 2.82 | 0.101 | 125.2 | 1.478 ± 0.68 | 1.378 ± 0.12 | 400 ± 20 | 2.182 ± 0.066 |
| 2 m above M5 strath, 57L | K02-056-2B | 2.87 | 0.129 | 99.5 | 1.470 ± 0.60 | 1.383 ± 0.38 | 375 ± 18 | 2.118 ± 0.050 |
| 2 m above M5 strath, 57L | K02-056-4A | 0.64 | 0.163 | 20.4 | 1.720 ± 1.13 | 1.569 ± 0.18 | 379 ± 29 | 2.787 ± 0.153 |
| 2 m above M5 strath, 57L | K02-056-4B | 0.74 | 0.124 | 30.5 | 1.680 ± 1.12 | 1.567 ± 0.12 | 338 ± 20 | 2.543 ± 0.089 |
| 20 m above M5 strath, 61L | LCR | 1.77 | 0.045 | 206.2 | 1.710 ± 0.56 | 1.602 ± 0.56 | 326 ± 13 | 2.523 ± 0.041 |
| Between M5 and M4, 57L | GC5/01-57L-E | 2.21 | 0.238 | 43.2 | 1.534 ± 1.22 | 1.504 ± 0.45 | 283 ± 14 | 2.154 ± 0.045 |
| On slope under M4, 56L | 56L-3A-1 | 0.74 | 0.147 | 22.1 | 1.444 ± 1.75 | 1.768 ± 0.36 | 151 ± 5.6 | 2.242 ± 0.037 |
| On slope under M4, 56L | 56L-3A-2 | 0.69 | 0.053 | 59.5 | 1.507 ± 1.49 | 1.782 ± 1.30 | 163 ± 6.8 | 2.265 ± 0.030 |
| On slope under M4, 56L | 56L-3B-1 | 1.69 | 0.010 | 768.7 | 1.455 ± 1.13 | 1.780 ± 0.21 | 153 ± 3.4 | 2.205 ± 0.012 |
| On slope under M4, 56L | 56L-3B-2 | 1.54 | 0.010 | 649.6 | 1.438 ± 1.43 | 1.785 ± 0.13 | 149 ± 4.0 | 2.197 ± 0.014 |
| On slope under M4, 56L | GC9/01-56L-A2 | 0.77 | 0.053 | 62.2 | 1.409 ± 1.32 | 1.732 ± 0.40 | 152 ± 4.1 | 2.145 ± 0.017 |
| On slope under M4, 56L | GC9/01-56L-B1 | 0.88 | 0.087 | 43.3 | 1.420 ± 0.85 | 1.729 ± 0.38 | 154 ± 3.0 | 2.158 ± 0.018 |
| Above local M4 base, 57L | K02-056-6A | 1.07 | 0.021 | 220.1 | 1.434 ± 1.61 | 1.960 ± 0.13 | 124 ± 3.4 | 2.369 ± 0.014 |
| Above local M4 base, 57L | K02-056-6B | 1.08 | 0.022 | 212.9 | 1.445 ± 0.97 | 1.958 ± 0.09 | 126 ± 2.1 | 2.373 ± 0.009 |
| 26 m above M4 strath, 56L | GC5/01-56L-A2 | 2.03 | 0.224 | 37.0 | 1.350 ± 0.72 | 1.888 ± 0.22 | 119 ± 1.7 | 2.279 ± 0.019 |
| 26 m above M4 strath, 56L | GC5/01-56L-B1 | 2.96 | 0.277 | 44.3 | 1.367 ± 1.71 | 1.913 ± 0.17 | 118 ± 3.5 | 2.309 ± 0.020 |
| 26 m above M4 strath, 56L | GC5/01-56L-A1 | 1.66 | 0.248 | 26.0 | 1.276 ± 2.01 | 1.873 ± 0.16 | 109 ± 3.7 | 2.238 ± 0.027 |

[a] Age and initial $^{234}$U/$^{238}$U errors are 95% confidence intervals. Isotope ratios are given as activity ratios.

[b] Shown here are river miles (RM) below Lees Ferry. L and R are left and right riverbank, respectively, when facing downstream.

[c] Back calculated from present-day, detritus-corrected $^{234}$U/$^{238}$U and the $^{230}$Th/U age.

equipped with a wide-angle-retarding potential energy filter and Daly-type ion counter. Mass discrimination for U was corrected using the spike $^{233}$U/$^{236}$U, whereas thorium ratios were uncorrected. Corrections for detrital U and Th were made using $^{232}$Th as an index, and assuming that the detritus has $^{232}$Th/$^{238}$U = 1.2 ± 0.6 and $^{230}$Th/$^{238}$U = $^{234}$U/$^{238}$U = 1.0 ± 0.1. Decay constants used for $^{230}$Th and $^{234}$U are those of *Cheng et al.* [2000]. Final ages reported (as in Table 4) are the mean age of up to six subsamples added in quadrature. Analyses of modern Grand Canyon travertine (grown on artificial substrates) indicate that nondetrital initial $^{230}$Th is negligible. Moreover, the assumption of a closed U-Th system is supported by selection of samples that preserve primary textures, agreement of subsample ages, and preservation of outcrop and map-scale relative age relations where observable.

[9] TCN dating of terraces is the most labor- and cost-intensive of our dating methods, as well as the most difficult to interpret geomorphically. Thus we report only two TCN dates, and they have relatively large 2σ errors (Table 3). Samples taken for TCN dating were of amalgamated ($n$ > 40) quartzite, vein quartz, and chert pebbles collected from the most stable surfaces with well-developed desert pavements at the center of terraces. Samples required no correction for shielding (less than 1% effect) or surface geometry. The inheritance correction for the M3 degradational terrace (24% of the measured concentration) utilized a shielded sample at 5.2 m depth, and the final age is corrected for the estimated amount of in situ production from fast neutrons and muons [*Anderson et al.*, 1996; *Gosse and Phillips*, 2001]. The other reported TCN age is for a terrace with equivocal mapping correlations (perhaps an obscured de-

**Table 3.** Data for TCN Dating in Eastern Grand Canyon

| Terrace, Location | Sample ID[a] Field | Sample ID[a] Laboratory | Production Rate,[b] atoms/g/yr | Concentration,[c] atom/g | Inherited,[d] atom/g | Age, kyr | 2σ Uncertainty,[e] kyr Precision | 2σ Uncertainty,[e] kyr Accuracy |
|---|---|---|---|---|---|---|---|---|
| M3 fill cut, 69.5L | BAS-119 | 354-be | 8.74 | $62.1 \times 10^4$ | $14.7 \times 10^4$ | 55 | 3.3 | 11.5 |
| M3 fill cut, 69.5L | BAS-120 | 355-be | 0.12 | $15.4 \times 10^4$ | $14.7 \times 10^4$ | NA[f] | | |
| M4? fill cut, 73R | UNK-123 | 350-be | 8.82 | $137 \times 10^4$ | $1.13 \times 10^4$ | 161 | 9.4 | 33.6 |
| M4? fill cut, 73R | UNK-124 | 351-be | 3.61 | $54.9 \times 10^4$ | $1.13 \times 10^4$ | 157 | 9.4 | 32.8 |

[a] BAS-119 and BAS-120 (36.10°N, 111.84°W, 840 m) comprise >50 amalgamated 2–2.5 cm diameter desert pavement clasts and a subsurface sample (below the mixed zone at 5.18 m depth) to estimate inheritance. UNK-123 and UNK-124 (36.07°N, 111.88°W, 850 m) comprise 40 amalgamated quartzite clasts (1.5–3 cm diameter) in desert pavement and a subsurface sample (below the mixed zone at 80 cm depth in a stage 2 petrocalcic horizon, 30 quartzite pebbles), respectively.

[b] Production rates are scaled from 5.1 atom $g^{-1}yr^{-1}$ at sea level high latitude with 2.2% muonic contribution, according to *Lal* [1991] and *Stone* [2000]. Production rates for subsurface samples assume a 1.83 g $cm^{-3}$ bulk density for cobbly gravel, and they ignore the <1% topographic shielding at these locations and changes to the bulk density over time due to pedogenic processes. No corrections for erosion were attempted because the pavements are well developed and the vegetation cover is currently sparse.

[c] Chemistry was completed at the University of Kansas, and accelerator mass spectrometry (AMS) was completed at Lawrence Livermore National Laboratory, with 1σ precisions of 3% or better, using KNSTD549 and normal LLNL standards, assuming $^{10}$Be half-life of $1.5 \times 10^6$ years. Concentrations were corrected for geochemical plus AMS background of $3.12 \times 10^6$ atoms $^{10}$Be which was 2% or less of the measured atoms for each sample, except for the deep sample BAS-120 for which the subtraction was 7%.

[d] Inheritance for the BAS site was calculated iteratively by subtracting an in situ component from the subsurface sample until both samples agreed within 1σ uncertainty. Inheritance for the UNK site was estimated with a least mean squares approach until the ages of the pavement and subsurface samples were within 1σ uncertainty.

[e] Precision is the 2σ AMS uncertainty. Accuracy at 2σ includes a 20% estimate for the total random and systematic errors but does not include the contribution to uncertainty in the age from error in inheritance or the effect of erosion.

[f] This is a sample for inheritance.

**Table 4.** Data for Colorado River Curve of Figure 4

| Data Point Description[a] | Height,[b] m | Age,[c] ka | Dating Method |
|---|---|---|---|
| Holocene flood deposits[d] | 0–8 | | various |
| RM 69.5L, degradational terrace on M3 | 24 | 55 ± 12 | TCN[e] |
| RM 72L, surveyed T3 terrace tread | 38 | | |
| RM 67L, sand lens in M3 fill | 37 | 64 ± 10 | OSL |
| RM 72L, sand lens in M3 fill | 36 | 67 ± 11 | OSL |
| RM 67L, sand lens in M3 fill | 36 | 68 ± 12 | OSL |
| RM 69.5L, sand lens in M3 fill | 19 | 69 ± 9 | OSL |
| RM 69.5L, sand lens in M3 fill | 11 | 71 ± 11 | OSL |
| mean surveyed M4 top | 52 | | |
| RM 56L, travertine in M4 gravel[f] | 26 | 119 ± 2 | U series |
| RM 57L, travertine flowstone drape in M4 gravel | 22 | 125 ± 2 | U series |
| RM 56L, travertine on bedrock, M4 strath[f] | 0 | 153 ± 2 | U series |
| RM 73R, degradational terrace on uncorrelated deposit | 44 | 161 ± 34 | TCN[e] |
| RM 57L, travertine in gravel, post-M5 incision | 22 | 283 ± 14 | U series |
| RM 70.5R, surveyed M5 top | 94 | | |
| RM 61L, travertine in M5 fill | 52 | 326 ± 13 | U series |
| RM 57L, travertine in gravel, 2 m above M5 strath[f] | 33 | 385 ± 14 | U series |

[a] Shown here are river miles (RM) below Lees Ferry. L and R are left and right riverbank, respectively, when facing downstream.

[b] Height is referenced to a local river stage of 283 $m^3/s$.

[c] The $2\sigma$ errors are given.

[d] Deposits are fine-grained Holocene overbank sediments of Colorado River in study reach [*Lucchitta et al.*, 1995; *Hereford*, 1996].

[e] TCN is terrestrial cosmogenic nuclide date of surface sample corrected for inheritance with shielded sample, interpreted as minimum age for terrace abandonment.

[f] Age is different than that reported by *Pederson et al.* [2002, 2003a] because of subsequent analysis of superior samples or duplicates.

posit stratigraphically between M4 and M5). It was calculated using a two-sample profile over the upper 80 cm of the deposit, with ages converging at ~160 ka and negligible inheritance. The 80 cm sample unit had original sedimentary structures and no signs of bioturbation. For subsubsurface samples, bulk densities integrated over shallow and deep gravel depths are 1.83 and 2.00 g $cm^{-3}$, and average density of the surface pavement pebbles is 2.6 g $cm^{-3}$. Production rates were calculated according to *Lal* [1991], *Gosse and Phillips* [2001], and *Stone* [2000], assuming 2.2% muonic contribution of the 5.1 atoms $^{10}$Be $g^{-1}$ quartz $yr^{-1}$ produced at sea level and high latitude and fast neutron and muonic average absorption lengths in rock of 160 and 1300 g $cm^{-2}$. The error reported for the TCN ages includes the AMS precisions and other random errors added in quadrature, which is used in comparing individual TCN ages. The $2\sigma$ accuracy reflects the $2\sigma$ precision and an estimated 20% systematic error added in quadrature [*Gosse and Phillips*, 2001], primarily because of uncertainty in production rate scaling and bulk density. We use this accuracy when comparing the TCN ages with OSL or U series ages.

## 3.2. Results

[10] A challenge of mapping and correlations in this steep canyon setting is the high relief, buttressed, and incomplete nature of outcrops (Figure 2a). The full thickness of a fill deposit is seldom preserved at a single location, multiple deposits can be found at a given height, and varying preservation of these erosional remnants along with the presence of degradational terraces create local bases and treads that do not necessarily record the true strath or top of the deposit (Figure 3). As a result, some correlations rely upon absolute dating, and it requires careful field study of the full 34 km study reach to compile a record of the fluvial stratigraphy. Of the seven Colorado River deposits in our mapped stratigraphy (main stem deposits "M1–M7"), M5, M4, M3, and M1 are dated at this time (Figure 2).

[11] M1 is a series of finer-grained Holocene deposits that have been well studied by other researchers [e.g., *Hereford et al.*, 1996] but are not a focus of our effort. M2 is a late Pleistocene deposit that we hypothesize lies mostly below the grade of the modern river [*Pederson et al.*, 2003a; *Anders et al.*, 2005], and thus is not a source of data. Also, one or more obscured deposits may lie stratigraphically between M4 and M5 [*Anders*, 2003; *Pederson et al.*, 2003a]. The major preserved and exposed deposits, M3–M7, typically have two or more terrace treads cut on each deposit, and the relief along the base of deposits includes planar or stepped bedrock straths (Figure 2c).

[12] The combination of this stratigraphy and our chronology developed thus far allows construction of a curve tracing the vertical path of the river channel through time in the study area (a similar example is given by *Bull* [1991]) (Figure 4). The major oscillations of channel elevation through time represent sedimentary-geomorphic cycles associated with fill terrace formation, whereas the overall background trend of incision can be measured only by connecting analogous positions in each cycle. In this case, a net bedrock incision rate of 142 m/m.y. is extracted using the slope of a linear regression through the dated and surveyed points when the river was in contact with bedrock, either during incision or along the basal straths of fill deposits (Figure 4). This is the best estimate for the long-term rate of bedrock incision of eastern Grand Canyon, driven by base level fall that is independent of a given Quaternary climate oscillation.

[13] The curve of Figure 4 helps illustrate potential pitfalls in calculating incision rates, particularly with fill terraces. A common method for estimating incision rate has been to simply compare the tread height of a prominent

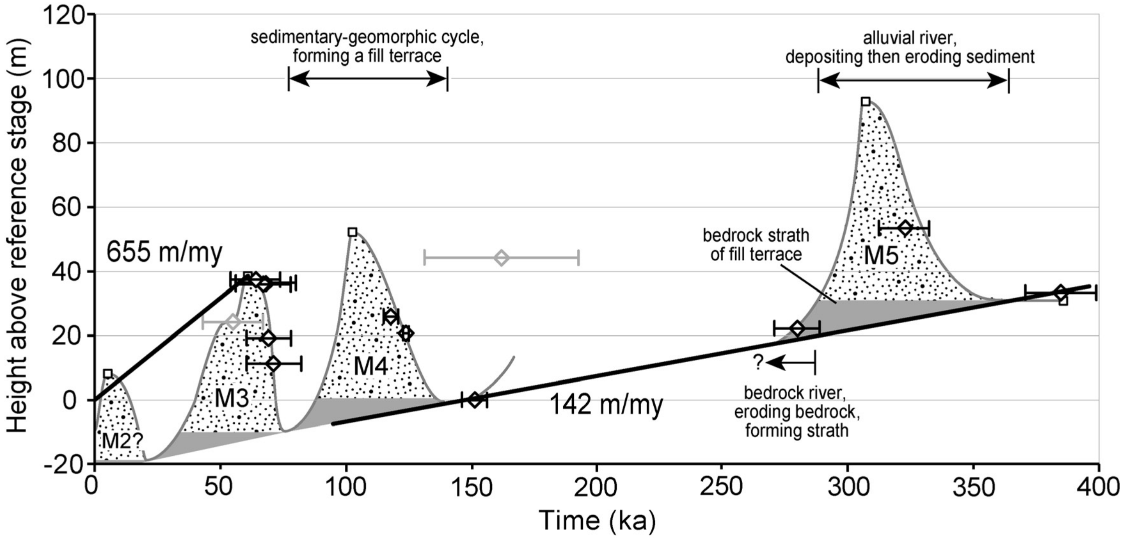

**Figure 4.** Curve representing the height of the Colorado River's bed through time, tracing sedimentary-geomorphic cycles of deposition and incision superimposed upon overall trend of incision. Stippled pattern represents fill deposits, and gray areas represent bedrock cut during the troughs of cycles. Diamonds and brackets mark chronologic sample heights, dates, and 2σ errors from Table 4, with less certain cosmogenic dates in gray. Squares represent field measurements not associated with a numerical date. The slopes of black curves are incision rates based on bedrock strath data points (142 m/m.y.) and, for illustration purposes, the height of the most prominent terrace relative to modern river stage (655 m/m.y.). The former gives the long-term bedrock incision rate for eastern Grand Canyon.

terrace to some modern river stage, and previous work in Grand Canyon is an example. This will almost always result in an erroneous estimate for net bedrock incision. For example, an incision rate estimate from our eastern Grand Canyon record using the top of the best preserved (M3) deposit relative to the present water surface results in a rate of 655 m/m.y. (Figure 4). This high, short-term alluvial incision rate does not match long-term bedrock incision because, first, it utilizes points within the river's history that are not analogous in terms of their position amongst the peaks and troughs of the path through time. In this case, the high estimate compares the peak of the M3 sedimentary-geomorphic cycle to the present-day river, which we interpret as being in the midst of overall incision. Second, this estimate is over one cycle at most, thereby making the value dependent upon the amplitude of the latest oscillation and not necessarily representative of the rate integrated over the length of cycles [*Wegmann and Pazzaglia*, 2002]. Because many other study areas may have relatively limited exposure or employ the dating of treads only, it may be necessary to resort to connecting terrace treads through time instead of straths. The case of eastern Grand Canyon is cautionary though, because this results in a moderate overestimate of long-term bedrock incision rate (225 m/m.y.) as fill thickness is interpreted to decrease from M5 to M3 (Figure 4).

## 4. Discussion

[14] The present-day Colorado River in Grand Canyon is an alluvial river in some reaches and perhaps a mixed bedrock-alluvial river in others, but it has obviously incised bedrock over time and has been a bedrock river during past episodes [see *Howard*, 1998; *Pederson et al.*, 2003b]. To what degree can research on purely bedrock streams, especially in tectonically active and relatively humid areas, inform us about mixed systems like the Colorado River in Grand Canyon? Using the better constrained last 150 kyr of our fluvial history as a guide, episodes of bedrock incision or planation probably cover 1/4–1/2 of the Colorado River's history relative to episodes when the river is alluvial and either aggrading or incising through its own sediment (Figure 4). Similarly, the amplitude of sedimentary-geomorphic cycles of the Colorado River in eastern Grand Canyon is high relative to the net bedrock incision that is accomplished. For a given cycle, the river incises through about five times the thickness of its own sediment as it does bedrock. In the case of the Colorado River the influence of these bedrock episodes on long-term landscape evolution may be discernable because, during those times, the geomorphic template for the river in terms of valley width and gradient must have been influenced by bedrock properties. The hydrologic and sediment load controls that dominate the alluvial episodes of the river, as in the Holocene, may be superimposed upon this template or may obscure it completely, depending upon the spatial scale of interest. These alluvial versus bedrock timescale and space-scale complexities on long-profile evolution may be especially confounding in the case of rivers draining regions that are only moderately to weakly tectonically active like the Colorado Plateau. This is not only because their gradient and profile may be more influenced by knickzones and bedrock properties due to relatively low stream power [*Pazzaglia et al.*, 1998] but also because of the proportionately shorter time they apply their power to bedrock.

[15] It is worth noting the contrast between our fill terrace record and the strath terrace records that have been a recent focus of research for calculating bedrock incision rates and interpreting rock uplift [e.g., *Burbank et al.*, 1996;

*Pazzaglia and Brandon*, 2001]. *Hancock and Anderson* [2002], comparing a numerical model of strath terrace formation to the Wind River record [*Chadwick et al.*, 1997], *Wegmann and Pazzaglia*'s [2002] study of the Clearwater River, and *Pan et al.*'s [2003] study in northwest China, conclude that the lateral planation of the bedrock strath occurs during cold-wet episodes of relatively high sediment flux. These workers all interpret that incision, conversely, happens during warm episodes when stream transport capacity exceeds a decreased sediment supply. These studies reveal that much of a river's history may be spent cutting a broad strath that is diachronous across the valley floor, which can be a problem for calculating incision rates, especially over shorter timescales [cf. *Hancock and Anderson*, 2002; *Wegmann and Pazzaglia*, 2002]. In contrast to this issue with strath terraces, the lateral planation of basal straths may represent relatively little time during the formation of fill terraces. Fill terrace records therefore may be advantageous for bedrock incision rates, but only if the true straths can be identified within the more complicated geometry of the deposits.

[16] The eastern Grand Canyon record illustrates that calculating incision rates from fill terrace records requires that the position of data points be carefully considered within the context of cyclic aggradation and incision. It is especially difficult to use the modern river as a datum, inasmuch as present rivers may be incising or aggrading and not in a graded state analogous to when the river formed terrace treads or straths in the past. Fill terraces also represent a prime example of an unsteady process that will produce apparently higher incision rates when calculated over shorter time intervals [*Gardner et al.*, 1987]. The curve of Figure 4 illustrates how, if connecting lines are drawn between successively younger terrace treads and the modern river, progressively higher incision rates (slopes of the lines) are derived. This artifact of the rate calculation method has led to interpretations of increasing overall incision rates through Quaternary time in Grand Canyon and elsewhere [e.g., *Machette and Rosholt*, 1991].

[17] Our bedrock incision rate for eastern Grand Canyon of ~140 m/m.y. is generally within the range of rates from major rivers across much of the interior western United States [e.g., *Dethier*, 2001]. On the other hand, it is greater than rates from the hanging wall of the Hurricane and Toroweap faults in western Grand Canyon [cf. *Lucchitta et al.*, 2000; *Pederson et al.*, 2002] but less than the long-term incision rates of 180–300 m/m.y. reported upstream in and near western Colorado [*Hanson*, 1987; *Kirkham et al.*, 2001; *Willis and Biek*, 2001; *Marchetti et al.*, 2005]. This increase in rate upstream could be due to (1) a differential uplift in Colorado, (2) a knickzone passing through the system from the major drainage integration and base level fall ~6 Ma at the southwestern edge of the Colorado Plateau, or (3) different timescales and methods of rate calculation. This last problem, as described above, may explain the moderately slower incision rate of 110 m/m.y. over the past ~1.3 m.y. that *Wolkowinsky and Granger* [2004] calculate on the San Juan tributary upstream. More data, and more consistent data, are needed about bedrock incision along the profile of this major river to investigate the influences of potential epeirogeny, drainage changes, and changing alluvial versus bedrock modes of the river through time on the sculpting of the western United States.

[18] **Acknowledgments.** Funding was provided by NSF EAR-0107065 to J. L. Pederson and K. E. Karlstrom and Geological Society of America awards provided to J. L. Pederson and M. D. Anders. We would like to thank the Grand Canyon National Park officials for permission to access and sample the study area. Helpful reviews were provided by Frank Pazzaglia, Ellen Wohl, Mark Brandon, Dave Dethier, and Darryl Granger.

## References

Aitken, M. J. (1976), Thermoluminescent age evaluation and assessment of error limits: Revised system, *Archaeometry*, *18*, 233–238.

Aitken, M. J. (1998), *An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence*, Oxford Univ. Press, New York.

Aitken, M. J., and J. C. Alldred (1972), The assessment of error limits in thermoluminescent dating, *Archaeometry*, *14*, 257–267.

Anders, M. D. (2003), Quaternary geology and landscape evolution of eastern Grand Canyon, Arizona, M.S. thesis, 153 pp., Utah State Univ., Logan.

Anders, M. D., J. L. Pederson, T. M. Rittenour, W. D. Sharp, J. C. Gosse, K. E. Karlstrom, L. D. Crossey, R. J. Goble, L. Stockli, and G. Yang (2005), Pleistocene geomorphology and geochronology of eastern Grand Canyon: Linkages of landscape components during climate change, *Quat. Sci. Rev.*, *24*, 2428–2448.

Anderson, R. S., J. L. Repka, and G. S. Dick (1996), Explicit treatment of inheritance in dating depositional surfaces using in situ $^{10}$Be and $^{26}$Al, *Geology*, *24*, 47–51.

Birdseye, C. H. (1924), Plan and profile of the Colorado River from Lees Ferry, Arizona, to Black Canyon, Arizona-Nevada, and the Virgin River, Nevada, map, scale 1:36,680, 21 sheets, U.S. Geol. Surv., Reston, Va.

Blackwelder, E. (1934), Origin of the Colorado River, *Geol. Soc. Am. Bull.*, *45*, 551–565.

Bull, W. B. (1979), Threshold of critical power in streams, *Geol. Soc. Am. Bull.*, *90*, 453–464.

Bull, W. B. (1991), *Geomorphic Responses to Climate Change*, 326 pp., Oxford Univ. Press, New York.

Burbank, D. W., J. Leland, E. Fielding, R. S. Anderson, N. Brozovic, M. R. Ried, and C. Duncan (1996), Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas, *Nature*, *379*, 505–510.

Chadwick, O. A., R. D. Hall, and F. M. Phillips (1997), Chronology of Pleistocene glacial advances in the central Rocky Mountains, *Geol. Soc. Am. Bull.*, *109*, 1443–1452.

Chen, J. H., R. L. Edwards, and G. J. Wasserburg (1986), $^{238}$U, $^{234}$U, and $^{232}$Th in seawater, *Earth Planet. Sci. Lett.*, *80*, 241–251.

Cheng, H., R. L. Edwards, J. Hoff, C. D. Gallup, D. A. Richards, and Y. Asmerom (2000), The half-lives of uranium-234 and thorium-230, *Chem. Geol.*, *169*, 17–33.

Dethier, D. P. (2001), Pleistocene incision rates in the western United States calibrated using Lava Creek B tephra, *Geology*, *29*, 783–786.

Edwards, R. L., J. H. Chen, and G. J. Wasserburg (1987), $^{238}$U–$^{234}$U–$^{230}$Th–$^{232}$Th systematics and the precise measurement of time over the past 500,000 years, *Earth Planet. Sci. Lett.*, *81*, 175–192.

Fenton, C. R., R. H. Webb, P. A. Pearthree, T. E. Cerling, and R. J. Poreda (2001), Displacement rates on the Toroweap and Hurricane faults: Implications for Quaternary downcutting in Grand Canyon, Arizona, *Geology*, *29*, 1035–1038.

Gardner, T. W., D. W. Jorgensen, C. Shuman, and C. R. Lemieux (1987), Geomorphic and tectonic process rates: Effects of measured time interval, *Geology*, *15*, 259–261.

Gosse, J. C., and F. M. Phillips (2001), Terrestrial in situ cosmogenic nuclides: Theory and applications, *Quat. Sci. Rev.*, *20*, 1475–1560.

Hamblin, W. K. (1994), *Late Cenozoic Lava Dams in the Western Grand Canyon*, *Mem. Geol. Soc. Am.*, *183*, 139 pp.

Hancock, G. S., and R. S. Anderson (2002), Numerical modeling of fluvial strath-terrace formation in response to oscillating climate, *Geol. Soc. Am. Bull.*, *114*, 1131–1142.

Hanson, W. R. (1987), The Black Canyon of the Gunnison, Colorado, in *Centennial Field Guide*, vol. 2, *Rocky Mountain Section of the Geological Society of America*, edited by S. S. Beus, pp. 321–324, Geol. Soc. of Am., Boulder, Colo.

Hereford, R. (1996), Map showing surficial geology and geomorphology of the Palisades Creek area, Grand Canyon National Park, Arizona, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2449*.

Hereford, R., K. S. Thompson, K. J. Burke, and H. C. Fairley (1996), Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona, *Geol. Soc. Am. Bull.*, *108*, 3–19.

Howard, A. D. (1998), Long profile development of bedrock channels: Interaction of weathering, mass wasting, bed erosion, and sediment transport, in *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, *Geophys. Monogr. Ser.*, vol. 107, edited by K. J. Tinkler and E. E. Wohl, pp. 297–319, AGU, Washington, D. C.

Kirkham, R. M., M. J. Kunk, B. Bryant, and R. K. Streufert (2001), Constraints on timing and rates of late Cenozoic incision by the Colorado River in Glenwood Canyon, Colorado—A preliminary synopsis, in *The Colorado River: Origin and Evolution*, *Monogr. Ser.*, vol. 12, edited by R. A. Young and E. E. Spamer, pp. 113–118, Grand Canyon Assoc., Grand Canyon, Ariz.

Knox, J. C. (1975), Concept of the graded stream, in *Theories of Landform Development: A Proceedings Volume of the Sixth Annual Geomorphology Symposia Series Held at Binghamton, New York, September 26–27, 1975*, edited by W. N. Melhorn and R. C. Flemal, pp. 169–198, State Univ. of N. Y., Binghamton.

Lal, D. (1991), Cosmic ray labeling of erosion surfaces: In situ nuclide production rates and erosion models, *Earth Planet. Sci. Lett.*, *104*, 424–439.

Leopold, L. B. (1969), The rapids and the pools—Grand Canyon, in *The Colorado River Region and John Wesley Powell*, *U.S. Geol. Surv. Prof. Pap.*, *669-D*, 131–145.

Leopold, L. B., and W. B. Bull (1979), Base level, aggradation, and grade, *Proc. Am. Philos. Soc.*, *123*, 168–202.

Lucchitta, I. (1972), Early history of the Colorado River in the basin and range province, *Geol. Soc. Am. Bull.*, *83*, 1933–1947.

Lucchitta, I., C. M. Dehler, M. E. Davis, P. G. Basdekas, and K. J. Burke (1995), Quaternary geologic map of the Palisades Creek–Comanche Creek area, eastern Grand Canyon, Arizona, *U.S. Geol. Surv. Open File Rep*, *95-832*, 39 pp.

Lucchitta, I., G. H. Curtis, M. E. Davis, S. W. Davis, and B. Turrin (2000), Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil carbonate stages in western Grand Canyon, Arizona, *Quat. Res.*, *53*, 23–33.

Machette, M. N., and J. N. Rosholt (1991), Quaternary geology of the Grand Canyon, in *The Geology of North America*, vol. K-2, *Quaternary Nonglacial Geology: Conterminous U.S.*, edited by R. B. Morrison, pp. 397–401, Geol. Soc. of Am., Boulder, Colo.

Mackin, J. H. (1937), Erosional history of the Big Horn Basin, Wyoming, *Geol. Soc. Am. Bull.*, *48*, 813–893.

Marchetti, D. W., J. C. Dohrenwend, and T. E. Cerling (2005), Geomorphology and rates of landscape change in the Fremont River drainage, northwestern Colorado Plateau, in *Interior Western United States*, *Field Guide Ser.*, vol. 6, edited by J. L. Pederson and C. M. Dehler, pp. 79–100, Geol. Soc. of Am., Boulder, Colo.

Merritts, D. J., K. R. Vincent, and E. E. Wohl (1994), Long river profiles, tectonism, and eustasy: A guide to interpreting fluvial terraces, *J. Geophys. Res.*, *99*, 14,031–14,050.

Murray, A. S., and A. G. Wintle (2000), Luminescence dating of quartz using an improved single aliquot regenerative-dose protocol, *Radiat. Meas.*, *32*, 57–73.

Olley, J., G. Caitcheon, and R. G. Roberts (1999), The origin of dose distributions in fluvial sediments, and the prospect of dating single grains from fluvial deposits using optically stimulated luminescence, *Radiat. Meas.*, *30*, 207–217.

Pan, B., D. Burbank, Y. Wang, G. Wu, J. Li, and Q. Guan (2003), A 900 k.y. record of strath terrace formation during glacial-interglacial transitions in northwest China, *Geology*, *31*, 957–960.

Pazzaglia, F. J., and M. T. Brandon (2001), A fluvial record of long-term steady state uplift and erosion across the Cascadia forearc high, western Washington State, *Am. J. Sci.*, *301*, 385–431.

Pazzaglia, F. J., T. W. Gardner, and D. J. Merritts (1998), Bedrock fluvial incision and longitudinal profile development over geologic timescales determined by fluvial terraces, in *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, *Geophys. Monogr. Ser.*, vol. 107, edited by K. J. Tinkler and E. E. Wohl, pp. 207–235, AGU, Washington, D. C.

Pederson, J., K. Karlstrom, W. Sharp, and W. McIntosh (2002), Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U series and Ar/Ar dating, *Geology*, *30*, 739–742.

Pederson, J. L., J. C. Schmidt, and M. D. Anders (2003a), Pleistocene and Holocene geomorphology of Marble and Grand canyons, canyon cutting to adaptive management, in *Field Trip Guidebook for the XVIth INQUA Congress*, edited by D. J. Easterbrook, pp. 407–438, Geol. Soc. of Am., Boulder, Colo.

Pederson, J., K. Karlstrom, W. Sharp, and W. McIntosh (2003b), Reply to comment by T. C. Hanks and J. L. Blair on Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U series and Ar/Ar dating, *Geology*, *31*, e16–e17, doi:10.1130/0091-7613(2003)31.

Prescott, J. R., and J. T. Hutton (1994), Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations, *Radiat. Meas.*, *23*, 497–500.

Schmidt, J. C., and D. M. Rubin (1995), Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, in *Natural and Anthropogenic Influences in Fluvial Geomorphology*, *Geophys. Monogr. Ser.*, vol. 89, edited by J. E. Costa et al., pp. 177–195, AGU, Washington D. C.

Stone, J. O. (2000), Air pressure and cosmogenic isotope production, *J. Geophys. Res.*, *105*, 23,753–23,759.

Wegmann, K. W., and F. J. Pazzaglia (2002), Holocene strath terraces, climate change, and active tectonics: The Clearwater River Basin, Olympic Peninsula, Washington State, *Geol. Soc. Am. Bull.*, *114*, 731–744.

Willis, G. C., and R. F. Biek (2001), Quaternary incision rates of the Colorado River and major tributaries in the Colorado Plateau, Utah, in *The Colorado River: Origin and Evolution*, *Monogr. Ser.*, vol. 12, edited by R. A. Young and E. E. Spamer, pp. 119–124, Grand Canyon Assoc., Grand Canyon, Ariz.

Wolkowinsky, A. J., and D. E. Granger (2004), Early Pleistocene incision of the San Juan River, Utah, dated with $^{26}$Al and $^{10}$Be, *Geology*, *32*, 749–752.

---

M. D. Anders, J. L. Pederson, and T. M. Rittenhour, Department of Geology, Utah State University, Logan, UT 84322, USA. (bolo@cc.usu.edu)

J. C. Gosse, Earth Sciences Department, Dalhousie University, Halifax, NS, Canada B3H 4R2.

K. E. Karlstrom, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA.

W. D. Sharp, Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA.