

# Episodic incision of the Colorado River in Glen Canyon, Utah

Cristofer D. Garvin,<sup>1\*</sup> Thomas C. Hanks,<sup>2</sup> Robert C. Finkel<sup>3</sup> and Arjun M. Heimsath<sup>1</sup>

<sup>1</sup> Dartmouth College, Earth Science Department, Hanover, New Hampshire, USA

<sup>2</sup> United States Geological Survey, Menlo Park, California, USA

<sup>3</sup> Lawrence Livermore National Laboratories, Livermore, California, USA

\*Correspondence to:

C. D. Garvin, Earth Science  
Department, Dartmouth  
College, Hanover, New  
Hampshire 03755-3571,  
USA. E-mail:  
CDGarvin@Alum.Dartmouth.org

## Abstract

Incision rates of the Colorado River are integral to understanding the development of the Colorado Plateau. Here we calculate episodic incision rates of the Colorado River based on absolute ages of two levels of Quaternary deposits adjacent to Glen Canyon, Utah, along the north flank of Navajo Mountain. Minimum surface ages are determined by a combination of cosmogenic radionuclide surface exposure ages, uranium series and soil-development formation times. Bedrock incision rates of the Colorado River between *c.* 500 ka and *c.* 250 ka, and *c.* 250 ka to present are *c.* 0.4 m ka<sup>-1</sup> and *c.* 0.7 m ka<sup>-1</sup>, respectively. These rates are more than double the rates reported in the Grand Canyon, suggesting that the Colorado River above Lees Ferry is out of equilibrium with the lower section of the river. We also determine incision rates of two tributaries to the Colorado River. Oak Creek and Bridge Creek flow off Navajo Mountain into Glen Canyon from the southeast. Oak Creek and Bridge Creek both have incision rates of *c.* 0.6 m ka<sup>-1</sup> over the past *c.* 100 ka at points about 9 km away from the main stem of the Colorado River. Copyright © 2005 John Wiley & Sons, Ltd.

**Keywords:** Colorado River; Glen Canyon; Navajo Mountain; episodic Quaternary incision

Received 1 September 2004;  
Revised 28 February 2005;  
Accepted 17 March 2005

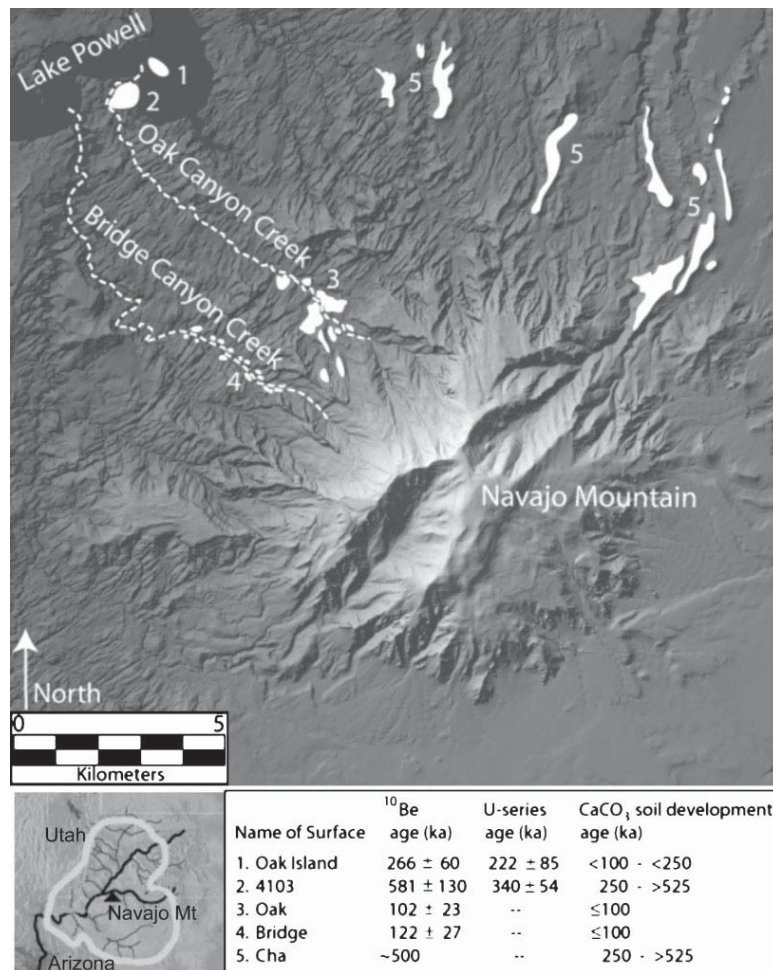
## Introduction

Ever since John Wesley Powell's epic voyage of discovery in 1869, the origin and evolution of the Colorado River has been the centrepiece of Earth science studies in the American Southwest. A remarkable number of incision rates for the main stem and its tributaries on the Colorado Plateau were available by 1980 and were published in Woodward-Clyde Consultants (1983); more readily available is the reproduction of these data by Willis and Biek (2001). Many of these earlier studies were confounded by poor age resolution, however, leading to a wide range of incision rates.

Like many other areas of Quaternary geology and geomorphology, the mid- to late Quaternary history of the Colorado River is now being revealed by advanced geochemical techniques, specifically age determinations now available from the abundance of 'cosmogenic' isotopes and uranium-series disequilibria. We use both of these techniques in this investigation of the incision of Glen Canyon by the Colorado River near Navajo Mountain in southern Utah (Figure 1).

Hanks *et al.* (2001) found that the 250 m deep modern slot of Glen Canyon truncating the north flank of Navajo Mountain was cut in the past *c.* 500 ka, at an average incision rate of *c.* 0.5 m ka<sup>-1</sup>. This is among the largest incision rates ever reported for the Colorado River over a significant time-period of >100 ka (Table I; Willis and Biek, 2001). Comparable incision rates, however, have been reported by Lucchitta *et al.* (2000) for a site near Lees Ferry, by Marchetti and Cerling (2001) for the Fremont River near Capitol Reef National Park, and by Willis and Biek (2001) for the Virgin River. A comparison of incision rates along the length of the Colorado River shows a dramatic increase in downcutting rates upstream from the Grand Canyon, which in turn suggests disequilibrium between the upper and lower reaches of the river.

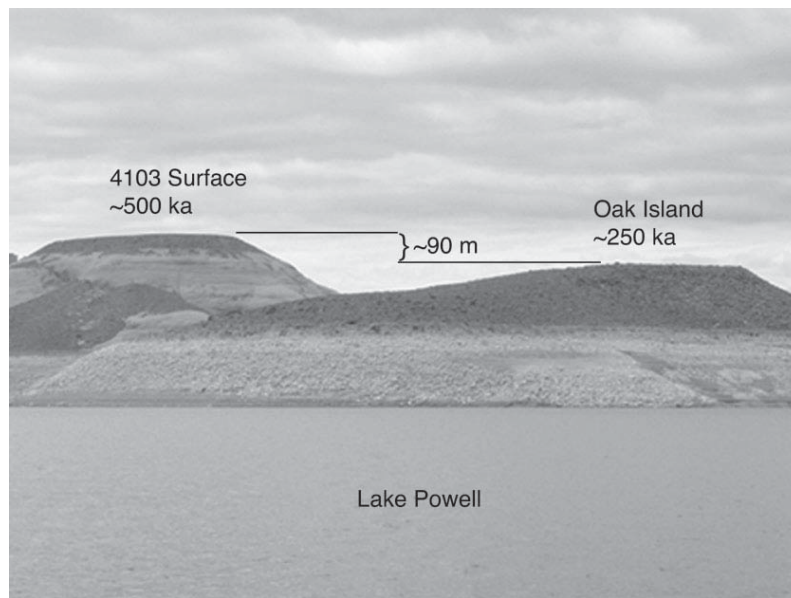
The Hanks *et al.* (2001) incision rate was the result of determining the age of the Cha family of surfaces high on the flank of Navajo Mountain, the modern remnants of a once broad apron of pediment gravels that graded smoothly to the top of Glen Canyon before it existed. Using cosmogenic nuclide abundances, soil development, and palaeomagnetic data, Hanks *et al.* (2001) estimated the age of these surface to be *c.* 500 ka. However, considerable uncertainties of up



**Figure 1.** USGS 10 m digital elevation model of the field area around Navajo Mountain. The fragments of Quaternary deposits, shown in white, are the basis of determining incision rates. Note that the area northwest of Navajo Mountain is heavily dissected, while the southeast region is relatively smooth and unaffected by stream incision.

**Table I.** Reported incision rate estimates for Colorado River and tributaries

Location	Time period (ka)	Incision rate (m ka <sup>-1</sup> )	Source cited
Colorado River; Grand Canyon, Granite Park	500–present	0.072–0.092	Pederson <i>et al.</i> (2002)
Colorado River; Eastern Grand Canyon	500–present	0.135–0.144	Pederson <i>et al.</i> (2002)
Colorado River; Grand Canyon, Granite Park	600–present	0.09–0.16	Lucchitta <i>et al.</i> (2000)
Virgin River; Zion National Park	1060–present	0.38	Willis and Biek (2001)
Colorado River; Glen Canyon, Bullfrog Basin	500–present	0.4	Davis <i>et al.</i> (2001)
Colorado River; Lees Ferry	500–present	0.31–0.48	Lucchitta <i>et al.</i> (2000)
Fremont River; Capitol Reef	190–present	0.4	Marchetti and Cerling (2001)
Colorado River; Glen Canyon, Navajo Mt	500–present	0.5	Hanks <i>et al.</i> (2001)
Colorado River; Glen Canyon, Navajo Mt	500–250	0.4	See text
Colorado River; Glen Canyon, Navajo Mt	250–present	0.7	See text
Oak Creek & Bridge Creek; Navajo Mt	100–present	0.6	See text



**Figure 2.** The 4103 and Oak Island surfaces, adjacent to the Glen Canyon, are within 1 km of each other. Age and elevation differences of these two surfaces are used to determine bedrock incision rates of the Colorado River. Glen Canyon and the Colorado River are now inundated by Lake Powell due the impoundment of the river behind Glen Canyon Dam in 1963.

to *c.* 50 per cent attend this age determination, and a considerable extrapolation was required to project these surfaces to the modern edge of Glen Canyon.

Finally, Wolkowinsky and Granger (2004) determined an average incision rate for the San Juan River near Bluff, Utah, *c.* 200 km upstream of Navajo Mountain, to be  $0.1 \text{ m ka}^{-1}$  and concluded their results 'are incompatible' with those of Hanks *et al.* (2001). Hanks and Finkel (2005), however, showed that the results of Wolkowinsky and Granger (2004) depended heavily upon their assumption of a single-stage deposition model. A two-stage deposition model, suggested by both field relations and the depth profile of the  $^{26}\text{Al}/^{10}\text{Be}$  ratios, admits both younger deposition and greater incision rates.

In this study, we investigate two surfaces underlain by debris-flow deposits interbedded with river gravels right next to the Colorado River downslope from Navajo Mountain (Figure 2). By dating these two surfaces, we determine incision rates of the main stem of the Colorado River over two time periods. Because the surfaces are adjacent to the Colorado River, we are able to eliminate the uncertainty caused by the large extrapolation required to relate this surface to the Cha surface. The first of the surfaces, named 4103 after its elevation in feet above sea level, turns out to be part of the Cha family surfaces identified and dated by Hanks *et al.* (2001), as revealed by its position and corresponding age of *c.* 500 ka. The second site, the Oak Island surface, is set into Glen Canyon *c.* 90 m below the 4103 surface but still *c.* 170 m above the pre-dam river level, with an age of *c.* 250 ka. We also study two sets of surfaces inset into local major tributaries, Oak Creek and Bridge Creek. These inset surfaces are both *c.* 100 ka in age and stand *c.* 60 m above the modern drainage levels.

## Field Setting

Bedrock lithology on the northern flank of Navajo Mountain extending down to Glen Canyon is composed mostly of two early Jurassic formations: the Navajo Sandstone overlying the Kayenta Formation (Chidsey *et al.*, 2000). The Kayenta Formation is well below the surface deposits, thus does not play a role in this work. The Navajo Sandstone is an aeolian quartz, well cemented with carbonate and silica. Minor outcrops of Dakota Formation sandstone and Entrada Formation sandstone lie at higher elevations on Navajo Mountain.

Structural control on the Rainbow Plateau is dominated by the laccolithic intrusion of Navajo Mountain that overprints the gentle and variable northwest dip of the sandstone bedrock (Chidsey *et al.*, 2000). We assume that Navajo Mountain is similar in age to the nearby Henry, La Sals and Abajo Mountains, which were also formed by

laccolith emplacement between 31.2 Ma and 23.3 Ma (Nelson *et al.*, 1992). The abrupt relief of Navajo Mountain provides a continuous source of debris flow and rock falls onto the surrounding pediment and canyon floors. About 1000 m or more of upper Cretaceous and lower Tertiary bedrock have been removed from Navajo Mountain (Hanks *et al.*, 2001).

Quaternary surface deposits fan away from Navajo Mountain (Figure 1). The un-dissected surface on the southeast side of the mountain suggests that the surfaces to the northwest graded smoothly to the Colorado River prior to incision. The dissection on the northwest side of Navajo Mountain has left remnant surfaces that are steep-sided topographic highs.

The general descriptions of the deposits underlying the Cha family of surfaces, studied by Hanks *et al.* (2001), also apply to the deposits of interest in this study. The deposits are composed of a loosely cemented, poorly sorted mix of angular to sub-rounded, boulder-to-pebble-size gravels in a pink, sand-to-silt matrix. Boulder sizes range up to 2 m, with the smaller boulders being more abundant. The surfaces of the deposits are smooth and planar with shallow swales and channels with rounded margins that terminate at cliff edges. Larger (>1 m) boulders are common within the deposits, but are rare on the surfaces, except at the edges where exposed by lateral erosion. Surface boulders are commonly eroded down to ground level giving a 'sawn off' appearance with cross-sectional areas of up to about 3 m<sup>2</sup>. Boulders that retain above-ground relief apparently represent the least erodible fraction of the deposit (Hanks *et al.*, 2001). Deposits are about 10 m thick and massive with no bedding planes or sorting. The internal structure of the deposits is characteristic of debris flows rather than fluvial processes. The gravel debris deposits conform to the dip of the underlying bedrock layers that slope uniformly and concentrically away from Navajo Peak. These deposits consist of predominantly Navajo sandstone clasts, with minor amounts of Entrada and Dakota sandstone clasts.

The Colorado River in Glen Canyon is now inundated by Lake Powell, due to the impoundment of the river by the closing of Glen Canyon Dam in 1963. The pre-dam elevation of the Colorado River adjacent to 4103 and Oak Island surfaces is 990 m above sea level.

### 4103 surface

The 4103 surface is adjacent to the Colorado River and about 260 m above the river channel. In terms of its geomorphic position, its composition and, as determined below, its age of *c.* 500 ka, 4103 surface is a downslope extension of the Cha family of surfaces. 4103 surface has closely spaced gravels resembling a desert pavement, yet few boulders (Figure 3). Most of the surface boulders are composed of Navajo sandstone; rocks from the Dakota Formation and Entrada Formation are present in lesser quantities. Buried clasts within the deposit have well developed calcium carbonate rinds and carbonate lag is abundant on the surface. Unlike the higher Cha surfaces, Colorado River



**Figure 3.** A view of 4103 surface showing the small gravel fragments and few boulders covering the surface.





**Figure 4.** Oak Island surface; view is to the southeast towards Navajo Mountain. Note the abundance of boulders ranging in height up to 1 m above ground surface.

gravel is present in the 4103 surface deposits due to its proximity of the river. The well rounded river gravels are easily distinguished from the angular debris-flow clasts and possess distinctly different lithologies.

### Oak Island surface

Set within Glen Canyon, Oak Island (now surrounded by Lake Powell) represents the lowest surface level of this study. Oak Island surface is about 90 m below 4103 surface and about 170 m above the Colorado River channel. Abundant Navajo sandstone boulders, 0.5–1.0 m in diameter, cover the surface (Figure 4). A few quartzite clasts from the Dakota Formation are also present. Rinds of calcium carbonate several millimetres thick are present on the undersides of the buried clasts, and calcium carbonate lag is present on the surface. Angular to sub-angular rocks are abundant and occasional river gravels are present on the surface.

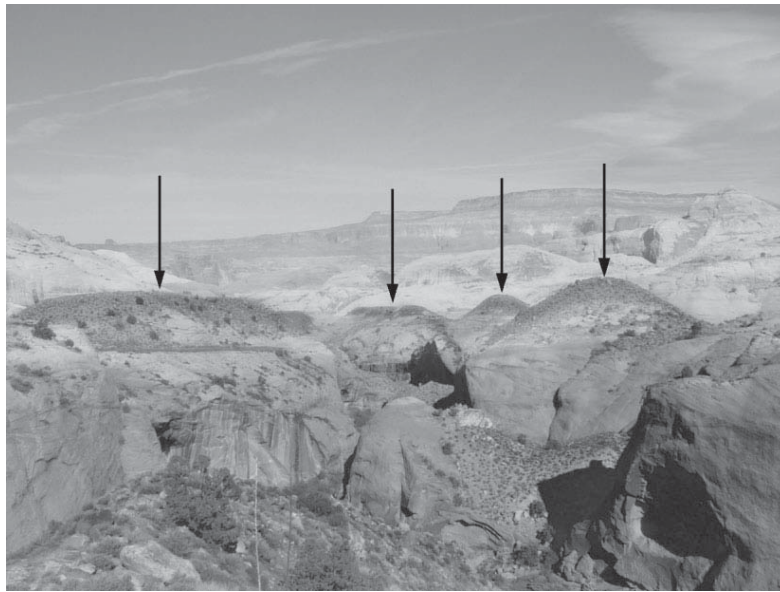
### The Bridge and Oak surfaces

The Bridge and Oak surfaces consist of dozens of well preserved remnants that lie along most of the length of Rainbow Bridge and Oak Canyon Creeks. These surfaces are inset within the surrounding canyons. Oak and Bridge surfaces are both presently about 60 m above their respective drainages. In several places, the Bridge and Oak surface fragments can be visually connected, allowing us to infer that they were once topographically integrated and sloped gently away from Navajo Mountain (Figure 5).

Light-coloured carbonate rinds *c.* 0.5 cm thick have developed on the bottom of most of the buried clasts, yet only moderate carbonate lag is present on the surface. Many of the surface boulders are deeply varnished, except for patches where erosion has breached the varnish coating. The largest boulder sampled in this study, sample HB-16, composed of Navajo sandstone, is 1.83 m high and found on the Bridge surface midway between the Colorado River and Navajo Mountain.

## Dating Methods

We use cosmogenic  $^{10}\text{Be}$  concentration and uranium-series dating of the pedogenic calcium carbonate rinds that have formed on buried rocks (Ludwig and Paces, 2002) to determine the ages of the four surfaces (4103, Oak Island, Oak



**Figure 5.** The Bridge surfaces, indicated by the arrows, are inset into the surrounding canyons. See Figure 1 for surface locations. The Oak surfaces, in adjacent Oak Creek Canyon, have similar morphology, and can be similarly visually reconstructed into a single surface. The photo was taken looking down Bridge Creek Canyon to the northwest.

and Bridge). We also estimate soil ages by the extent of pedogenic calcium carbonate development in the soils (Machette, 1985; Davis *et al.*, 1995; Lucchitta *et al.*, 2000).

### Cosmogenic dating

We determined a minimum of three independent cosmogenic exposure ages for each isolated surface fragment that we sampled. Beryllium-10 concentrations were determined in the upper 3 cm of each sample (Lal, 1988). The samples were always taken from the tops of the largest surface boulders present. These represent the least erodible fraction of the deposits left behind after more erodible boulders have been removed and therefore give the best estimate of the deposit age. We calculated exposure ages from our  $^{10}\text{Be}$  measurements by assuming a zero erosion rate. Therefore our model ages are minimum exposure ages (Lal, 1991).

Significant ground stripping is evidenced by the abundance of carbonate lag as previously described. However, as long as the surface deflation has not caused shifting of the boulders, then the exposure ages of the boulders should not be affected once the boulder tops are exposed. The boulders that we sampled have apparently remained in their original positions after deposition, as is evidenced by the trend in boulder height versus exposure age.

### Cosmogenic nuclide inheritance

In the case of boulders that are part of a debris-flow deposit, such as those investigated in this study, cosmogenic nuclide production can occur during three periods: (1) while the rock is exposed prior to being freed from its initial source (e.g. cliff face); (2) while debris collects on talus slopes at the base of the cliff; and (3) after the debris flow occurs and the material is deposited downslope.

We assume that surface to volume ratios are low enough and cliff spalling intervals are short enough that inheritance from exposure during this period is small, except in rare instances. If, in addition, the transport time and recurrence period of deposition events are short relative to the age of the deposit, then inherited cosmogenic nuclides contribute a small fraction of the total nuclide concentration and have little effect on the resulting exposure ages. We estimate an average recurrence interval of debris flows of less than  $10^4$  years, or at least one order of magnitude less than the exposure ages of the Glen Canyon terrace surfaces (Jackson, 1977; Kochel, 1987; Lips and Wiczorek, 1990; Cerling *et al.*, 1999; Webb *et al.*, 2001). Thus, we assume the contribution of  $^{10}\text{Be}$  accumulated during transport is negligible. Beryllium-10 depth profiles, from similar nearby surfaces obtained by Hanks *et al.* (2001), demonstrate that there is negligible inherited  $^{10}\text{Be}$  in the surface rocks.

Furthermore, the differencing method used to calculate incision rates only works if the surface ages approximate the time that vertical incision began. That is, exposure ages may represent the time of last deposition, yet not necessarily the onset of incision. Given the estimated recurrence interval <10 000 years of debris flows from Navajo Mountain and the shallow thickness of the deposits, it is likely that deposition continued until the remnants became isolated via incision.

### Uranium-series dating

Ingrowth of  $^{230}\text{Th}$  from the decay of  $^{234}\text{U}$  in silica-carbonate rinds that commonly form on the underside of buried clasts in arid regions can yield pedogenic ages of surface deposits (Ku *et al.*, 1979). Quantitative analysis of uranium-series dating has been used to date soils in the Nevada desert as described by Ludwig and Paces (2002). The possible delay between deposit emplacement and onset of carbonate rind accumulation makes the U-series date the minimum age of a deposit. Uranium-series dating depends on the ratio of parent and daughter isotopes, thus the rinds must maintain a closed system in which the uranium decay takes place. Although we collected several carbonate samples from 4103 and Oak Island surfaces, we processed only one sample from each surface. The processed samples were chosen from carbonate rinds that were tightly affixed to cobble and that appeared to be dense and free of sand, silt and air inclusions. The innermost, thus oldest layers of carbonate, in the samples were measured for  $^{230}\text{Th}$ ,  $^{234}\text{U}$  and  $^{238}\text{U}$  activities using thermal ionization mass spectrometry (TIMS).

## Results

Tables II and III show surface and deposit ages based on cosmogenic nuclide and U-series measurements. Both dating techniques consistently show younger ages for the lower surfaces. The cosmogenic exposure ages shown in Table II have 5–6 per cent analytical uncertainty, arising primarily from uncertainties in the accelerator mass spectrometry (AMS) measurement and in the carrier addition. Systematic analytical uncertainties in the ages include uncertainties in the  $^{10}\text{Be}$  standard, in the sea-level high-latitude production rates and in the scaling factors used to calculate production at the Glen Canyon site. It is difficult to quantify these uncertainties at the moment. In addition there are epistemic uncertainties arising from boulder history, including pre-exposure and erosion, that are even more difficult to quantify.

Observed exposure ages for a given surface can vary by >100 ka; however, there is a strong correlation between boulder size and cosmogenic nuclide concentration (Figure 6). Preferred surface-exposure ages are often taken from the larger, more resistant boulders with greater exposure (Hanks *et al.*, 2001). The oldest exposure ages calculated from  $^{10}\text{Be}$  concentrations are: 4103 –  $581 \pm 130$  ka; Oak Island –  $266 \pm 58$  ka; Bridge –  $122 \pm 27$  ka; and Oak –  $102 \pm 23$  ka.

The average uranium-series ages of the deposits underlying 4103 surface and Oak Island surface are  $340 \pm 54$  ka and  $222 \pm 85$  ka, respectively. These uranium-series dates are consistent with estimates of soil-formation ages based on pedogenic calcium carbonate development near Glen Canyon (Lucchitta *et al.*, 2000; Davis *et al.*, 1995, 2001). Pedogenic calcium carbonate development on 4103 surface is classified as Stage IV to Stage V, suggesting a soil formation age of 250 ka to >525 ka (Davis, pers. comm.; Lucchitta *et al.*, 2000). Carbonate rinds on the lower portions of buried clasts on Oak Island indicate Stage II to Stage III calcium carbonate development according to the soil classification of Machette (1985), thus an absolute age of soil formation of <100 ka to <250 ka (Davis, pers. comm.; Lucchitta *et al.*, 2000; Davis *et al.*, 2001). Oak/Bridge surface has about Stage II carbonate suggesting ages of about *c.* 100 ka or less.

A variety of uncertainties attend the ages of the four surfaces that we consider here, quite apart from the formal analytical uncertainties associated with any one technique or age determination. Even for the same surface, different techniques typically yield different ages. The different techniques have different applicable age ranges and are sensitive to different characteristics of surface history. Finally, because we are dating a boulder, but actually require the age of the surface, the same technique can yield different ages for different samples from the same surface.

All of this suggests to us that a considerable but not easily quantifiable uncertainty attends the ages we assign to the surfaces that interest us here. To reflect this uncertainty, we dismiss the third and second significant figures. Thus, we assign an age of  $500 \pm 100$  ka to the 4103 surface, denoting this *c.* 500 ka in recognition of the range in cosmogenic-abundance ages, possible saturation in the uranium-series ages, and uncertainties in the time to form Stage IV–V soils. Similarly, the available data suggest an age for the Oak Island surface of about half this much, which we take to be  $250 \pm 50$  ka, or *c.* 250 ka. Finally, and for the same reasons, we find the ages of the Oak and Bridge creek surfaces to be  $100 \pm 25$  ka, or *c.* 100 ka.

**Table II.** Cosmogenic exposure ages determined from  $^{10}\text{Be}$  concentration in quartz samples taken from surface rocks

Sample ID	Surface	Lat. (N)	Long. (W)	Altitude (m)	Boulder (m)	Lithology	$^{10}\text{Be}$ concentration (atoms/gr)	$\pm$	$^{10}\text{Be}$ exposure Age (ka)	$\pm$
HB-1	Oak Island	37-12	110-96	1159	1-10	Nav. Ss	3-15E+06	1-55E-11	266	60
HB-2	Oak Island	37-12	110-96	1159	0-00	Nav. Ss	1-20E+06	8-73E-12	95	21
HB-3	Oak Island	37-12	110-96	1159	0-00	Nav. Ss	1-21E+06	1-77E-11	96	22
HB-4	Oak Island	37-12	110-96	1159	0-61	Nav. Ss	2-09E+06	1-13E-11	177	40
HB-5	Oak Island	37-12	110-96	1159	0-76	Dak. Qtz	1-52E+06	1-10E-11	120	27
HB-6	Oak Island	37-12	110-96	1159	0-61	Nav. Ss	2-78E+06	2-34E-11	230	52
HB-7	4103	37-12	110-96	1251	0-25	Nav. Ss	6-33E+06	2-08E-11	567	127
HB-8	4103	37-12	110-96	1251	0-20	Nav. Ss	5-28E+06	2-07E-11	450	101
HB-9	4103	37-12	110-96	1251	0-33	Nav. Ss	6-44E+06	2-70E-11	581	130
HB-10	4103	37-12	110-96	1251	0-28	Nav. Ss	5-00E+06	1-37E+05	420	94
HB-19	Oak	37-08	110-91	1439	0-20	Nav. Ss	5-12E+05	6-77E-12	33	7
HB-20	Oak	37-08	110-91	1439	0-31	Nav. Ss	4-90E+05	9-16E-12	32	7
HB-21	Oak	37-08	110-91	1439	0-74	Nav. Ss	4-67E+05	5-48E-12	31	7
HB-25	Oak	37-08	110-92	1402	0-46	Nav. Ss	4-90E+05	2-72E-12	33	7
HB-26	Oak	37-08	110-92	1402	0-46	Nav. Ss	3-02E+05	5-26E-12	21	5
HB-27	Oak	37-08	110-92	1402	0-61	Nav. Ss	2-55E+05	4-39E-12	18	4
RF94-11	Oak	37-08	110-92	1402	1-00	Nav. Ss	9-81E+05	3-01E+04	64	14
RF94-12	Oak	37-08	110-92	1402	0-40	Nav. Ss	5-32E+05	2-53E+04	35	8
RF94-13	Oak	37-07	110-90	1481	1-50	Nav. Ss	1-49E+06	5-27E+04	92	21
RF94-14	Oak	37-07	110-90	1481	1-20	Nav. Ss	1-42E+06	5-43E+04	88	20
RF94-15	Oak	37-07	110-90	1481	1-30	Nav. Ss	1-63E+06	3-68E+04	101	23
HB-14	Bridge	37-06	110-92	1550	0-46	Nav. Ss	1-93E+05	4-50E-12	13	3
HB-15	Bridge	37-06	110-92	1550	0-31	Nav. Ss	1-85E+05	4-75E-12	13	3
HB-16	Bridge	37-07	110-94	1378	1-83	Nav. Ss	1-76E+06	2-19E-11	122	27
HB-17	Bridge	37-07	110-94	1378	0-61	Nav. Ss	1-47E+06	2-11E-11	99	22
HB-18	Bridge	37-07	110-94	1378	1-07	Nav. Ss	1-46E+06	1-80E-11	98	22
HB-28	Bridge	37-06	110-96	1317	0-46	Nav. Ss	3-16E+05	4-42E-12	24	5
HB-29	Bridge	37-06	110-96	1317	0-31	Nav. Ss	3-56E+05	6-33E-12	26	6
HB-30	Bridge	37-06	110-96	1347	0-31	Nav. Ss	3-93E+05	5-32E-12	28	6
HB-31	Bridge	37-06	110-96	1347	0-76	Nav. Ss	1-09E+06	1-20E-11	76	16
CGS-1	Bridge	37-06	110-92	1555	0-61	Nav. Ss	9-00E+05	3-30E+04	54	12
CGS-2	Bridge	37-06	110-92	1555	1-37	Nav. Ss	1-45E+06	3-72E+04	87	19
CGS-3	Bridge	37-06	110-92	1555	0-61	Nav. Ss	9-82E+05	2-80E+04	59	13

$^{10}\text{Be}$  production rate ( $5.1 \pm 0.3$  atoms  $\text{g}^{-1} \text{a}^{-1}$  at sea-level high latitude), scaling factors and shielding corrections are from Stone (2000).

$^{10}\text{Be}/^9\text{Be}$  ratios were determined by AMS at Lawrence Livermore National Laboratory, and the measurements normalized to LLNL  $^{10}\text{Be}$  secondary standards calibrated against an ICN  $^{10}\text{Be}$  standard prepared by K. Nishiizumi using a half life of  $1.5 \times 10^6$  years. Sample concentrations were corrected for process blanks; mean process blanks were generally low ( $^{10}\text{Be}/^9\text{Be} = 4.0 \times 10^{-15}$ ) compared to samples. Quoted uncertainties include the uncertainty in the blank-corrected AMS measurement and various epistemic uncertainties discussed in the text.

### Incision rates

Between *c.* 500 ka and *c.* 250 ka the Colorado River cut through 90 m of bedrock, yielding an incision rate of *c.*  $0.4 \text{ m ka}^{-1}$ . Similarly, from *c.* 250 ka to present, the Colorado River cut through 170 m of bedrock at a rate of *c.*  $0.7 \text{ m ka}^{-1}$ . The 170 m vertical separation between Oak Island surface and the pre-dam river level includes neither water depth nor sediment fill in the channel. Oak and Bridge surfaces each have a vertical distance of 60 m from remnant surface to modern stream channel. The exposure age of both Oak and Bridge surface is *c.* 100 ka, resulting in an incision rate of *c.*  $0.6 \text{ m ka}^{-1}$ .

### Discussion

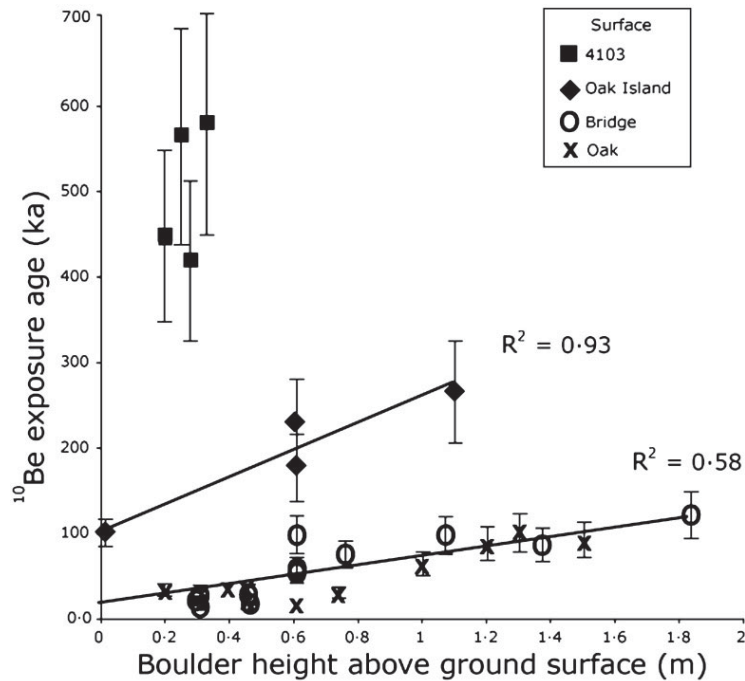
Oak Island and 4103 surfaces are composed of nearly identical lithologies and are within a few kilometres of each other, thus we assume they have similar surface lowering rates. Therefore, since we use age differences between the



**Table III.** Deposit ages based on uranium-series dating of CaCO<sub>3</sub> rinds of buried clasts. See Figure 1 for surface locations

Sample name	Sample wt. (g)	U (ppm)	Th (ppm)	Measured activity ratios				Detritus-corrected activity ratios		Detritus-corrected values <sup>a†</sup>			
				<sup>230</sup> Th/ <sup>238</sup> U (2σ)	<sup>234</sup> U/ <sup>238</sup> U (2σ)	<sup>232</sup> Th/ <sup>238</sup> U (2σ)	<sup>230</sup> Th/ <sup>232</sup> Th (2σ)	<sup>230</sup> Th/ <sup>238</sup> U (±2σ%)	<sup>234</sup> U/ <sup>238</sup> U (±2σ%)	Initial <sup>234</sup> U/ <sup>238</sup> U activity (2σ)	<sup>230</sup> Th/U age (ka) (2σ)	<sup>234</sup> U/ <sup>238</sup> U age (ka) (2σ)	
HB-OM-U2	0.012	1.46	1.56	1.067 (0.053)	1.135 (0.012)	0.3516 (0.0025)	3.03 (0.16)	1.092 (0.120)	1.186 (0.055)	0.094	1.36 (0.11)	235 (90)	208
OakHigh I-U1	0.053	1.73	0.64	1.090 (0.007)	1.110 (0.007)	0.1227 (0.0009)	8.89 (0.07)	1.100 (0.028)	1.122 (0.014)	0.085	1.30 (0.04)	321 (51)	358

\* Corrected isotope ratios based on measured <sup>232</sup>Th/<sup>238</sup>U compositions and an assumed detrital component with <sup>232</sup>Th/<sup>238</sup>U AR = 1.276 ± 0.638; <sup>234</sup>U/<sup>238</sup>U AR = 1.0 ± 0.1 and <sup>230</sup>Th/<sup>238</sup>U = 1.0 ± 0.25.  
 † Model <sup>234</sup>U/<sup>238</sup>U age based on an assumed initial <sup>234</sup>U/<sup>238</sup>U = 1.334 (average of six sub-sample analyses excluding OakHigh I-U1).



**Figure 6.** Boulder size versus cosmogenic exposure age. Nuclide concentration data are shown in Table I. A  $2\sigma$  error is shown as vertical bars on the exposure ages that include uncertainties in nuclide production rates (c. 20 per cent) and analytical uncertainty (c. 5 per cent).

two surfaces, the effect of surface lowering on incision rate estimates is reduced. Furthermore, since erosion has already removed the susceptible boulders, the remaining boulders likely have minimal erosion rates.

Figure 6 shows that exposure age is dependent on boulder size and that this trend is more pronounced on older surfaces. The latter point suggests a time-dependent evolution of boulder size distribution on a surface. If it were the case that similar-sized boulders were merely exposed above the ground surface to different extents, then exhumation would be the likely mechanism to explain the trend seen in Figure 6. However, since boulders of differing dimensions, not just height above ground surface, systematically differ in age, we interpret the mechanism for the trend to be primarily differential weathering among boulders and secondarily from sequential exhumation. The end result is that both differential weathering and exhumation cause the larger boulders to always have the highest concentration of  $^{10}\text{Be}$ , thus rationalizing the choice of exposure ages of the largest boulders as the preferred exposure age for each surface.

Potential problems with nuclide inheritance do not seem to affect our exposure age calculations because (1) the transport time of debris-flow material from source was very short relative to the age of the surface, (2) the  $^{10}\text{Be}$  depth profile of Hanks *et al.* (2001) indicates little or no inherited  $^{10}\text{Be}$ , and (3) the boulder size versus  $^{10}\text{Be}$  concentration dependence in Figure 6 is unlikely if inherited nuclides were present.

## Conclusions

The results of this study confirm and extend the earlier finding that the 250 m deep, modern slot of Glen Canyon in the vicinity of Navajo Mountain has been incised in the last c. 500 ka. Hanks *et al.* (2001) required a significant extrapolation from the Cha family of pediment remnants, high on the north flank of Navajo Mountain, to the edge of Glen Canyon, which they estimated to be c. 1240 m. The more recently discovered 4103 surface is within 10 m of this extrapolated elevation and shares the same age as the Cha family of surfaces, c. 500 ka. The Oak Island surface, set deeply into Glen Canyon, provides a more recent timeline of incision, following the depositional hiatus preserved on the island. We estimate the age of the gravels on Oak Island to be c. 250 ka.

Incision of all 250 m of the modern slot of Glen Canyon proceeded at an average rate of  $0.5 \text{ m ka}^{-1}$  over the past c. 500 ka. From the 4103 surface to the Oak Island surface, or equivalently from c. 500 ka to c. 250 ka, incision

proceeded at a slightly slower pace of  $0.4 \text{ m ka}^{-1}$ , while incision from the Oak Island surface to the former (pre-dam) river level, or equivalently from *c.* 250 ka to the present, occurred at a faster rate of  $0.7 \text{ m ka}^{-1}$ , almost twice the rate of the earlier interval.

Oak Creek and Bridge Creek, both major tributaries to the Colorado River from their sources high on Navajo Mountain, have incised 60 m in the past *c.* 100 ka, at rates of  $0.6 \text{ m ka}^{-1}$  that have basically kept pace with main stem incision.

These rates of incision of the Colorado River in Glen Canyon near Navajo Mountain significantly exceed those in both the western Grand Canyon (Lucchitta *et al.*, 2001; Pederson *et al.*, 2002) and the eastern Grand Canyon (Pederson *et al.*, 2002). These incision rates are, however, comparable to those Lucchitta *et al.* (2001) reported for Lees Ferry over a comparable period of time; Lees Ferry, remarkably, is the nexus joining the lower end of the Glen Canyon and the upper end of the Grand Canyon.

### Acknowledgements

This work was performed partially under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory, under Contract No. W-7405-Eng-48. We greatly appreciate the company and conversations with Sid and Marie Davis, Steve Lefton, Ivo Lucchitta and Diane Stanley while doing much of the fieldwork for this project in May 2002. Thanks to James Paces at the United States Geological Survey for providing the uranium-series analysis. We also thank the two anonymous reviewers who provided many insightful suggestions that significantly improved this paper from the original submission.

### References

- Cerling TE, Webb RH, Poreda RJ, Rigby AD, Melis TS. 1999. Cosmogenic He-3 ages and frequency of late Holocene debris flows from Prospect Canyon, Grand Canyon, USA. *Geomorphology* **27**(1–2): 93–111.
- Chidsey TC, Willis GC, Sprinkel DA, Anderson PB. 2000. Geology of Rainbow Bridge National Monument, Utah. In *Utah Geological Association Publication 28*, Sprinkel DA, Chidsey TC, Anderson PB (eds). 251–262.
- Davis SW, Davis ME, Lucchitta I, Caffee M, Finkel R. 1995. *Soil survey of the Palisades-Unkar area, eastern Grand Canyon*. US Bureau of Reclamation Glen Canyon Environmental Studies: Flagstaff, Arizona.
- Davis SW, Davis ME, Lucchitta I, Hanks TC, Finkel RC, Caffee M. 2001. Erosional history of the Colorado river through the Glen and Grand Canyons. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park: Arizona; 135–139.
- Hanks TC, Finkel RC. 2005. Comment (on Early Pleistocene Incision of the San Juan River, Utah, Dated with  $^{26}\text{Al}$  and  $^{10}\text{Be}$ ). *Geology*: e78 (online forum). <http://www.gsjournals.org/i0091-7613-31-6-e78.html>
- Hanks TC, Lucchitta I, Davis ME, Davis SW, Finkel RC, Lefton SA, Garvin CD. 2001. The Colorado River and the age of Glen Canyon. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park, Arizona: 129–133.
- Jackson LE. 1977. Dating and recurrence frequency of prehistoric mudflows near Big Sur, Monterey County, California. *Journal of Research of the U.S. Geological Survey* **5**(1): 17–32.
- Kochel RC. 1987. Holocene debris flows in central Virginia. In *Debris flows/avalanches; process recognition, and mitigation*. Costa JE, Wieczorek GF (eds). Geological Society of America Reviews in Engineering Geology **7**: 139–155.
- Ku TL, Bull WB, Freeman ST, Knauss KG. 1979. Th (super 230) -U (super 234) dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California. *Geological Society of America Bulletin* **90**: 1063–1073.
- Lal D. 1988. In situ produced cosmogenic isotopes in terrestrial rocks. *Annual Review of Earth and Planetary Science* **16**: 355–388.
- Lal D. 1991. Cosmic ray labeling of erosion surfaces: In situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* **104**: 424–439.
- Lips EW, Wieczorek GF. 1990. Recurrence of debris flows on an alluvial fan in central Utah. In *Hydraulics/Hydrology of Arid Lands, Proceedings of the International Symposium, Hydraulics and Irrigation Divisions*. American Society of Civil Engineers: 555–560.
- Lucchitta I, Curtis GH, Davis ME, Davis SW, Turrin B. 2000. Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil-carbonate stages in western Grand Canyon. *Quaternary Research* **53**: 23–33.
- Lucchitta I, Curtis GH, Davis ME, Davis SW, Hanks TC, Finkel RC, Turrin B. 2001. Rates of Downcutting of the Colorado River in the Grand Canyon Region. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park: Arizona; 155–157.
- Ludwig KR, Paces JB. 2002. Uranium-series dating of pedogenic silica and carbonate, Crater Flat, Nevada. *Geochimica et Cosmochimica Acta* **66**: 487–506.
- Machette MN. 1985. Calcic soils of the southwestern United States. In *Soils and Quaternary Geology of the Southwestern United States*, Weide DL (ed.). Geological Society of America Special Paper 203.

- Marchetti DW, Cerling TE. 2001. Bedrock incision rates for the Fremont River, Tributary of the Colorado River. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park: Arizona; 125–127.
- Nelson ST, Davidson JP, Sullivan KR. 1992. New age determinations of the central Colorado Plateau laccoliths, Utah: recognizing disturbed K-Ar systematics and re-evaluating tectonomagmatic relationships. *Geological Society of America Bulletin* **104**: 1547–1560.
- Pederson JLK, Sharp WD, McIntosh W. 2002. Differential incision of the Grand Canyon related to Quaternary faulting; constraints from U-series and Ar/Ar dating. *Geology* **30**: 739–742.
- Stone JO. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* **105**: 23753–23759.
- Webb RH, Griffiths PG, Melis TS. 2001. Debris flows and rapids in Grand Canyon: implications for erosion rates and evacuation of sediment from tributary canyons. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park: Arizona; 183–188.
- Willis GC, Biek RF. 2001. Quaternary incision rates of the Colorado River and major tributaries in the Colorado Plateau. Utah. In *The Colorado River Origin and Evolution: Proceedings of a Symposium Held at Grand Canyon National Monument*, Young RA, Spamer EE (eds). Grand Canyon Association Monograph 12. Grand Canyon Association, Grand Canyon National Park: Arizona; 119–123.
- Wolkowinsky AJ, Granger DE. 2004. Early Pleistocene incision of the San Juan River, Utah, dated with <sup>26</sup>Al and <sup>10</sup>Be. *Geology* **32**: 749–752.
- Woodward-Clyde Consultants 1983. *Overview of the regional geology of the Paradox Basin study region*. ONWI-92. Prepared for the Office of Nuclear Waste Isolation, Battelle Memorial Institute: Columbus, Ohio.