Dates and rates of arid region geomorphic processes

Kyle K. Nichols*, *Department of Geosciences, Skidmore College, Saratoga Springs, New York 12866, USA;* ***Paul R. Bierman****, *Department of Geology, University of Vermont, Burlington, Vermont 05405, USA;* ***W. Ross Foniri,*** *Department of Geosciences, Skidmore College, Saratoga Springs, New York 12866, USA;* ***Alan R. Gillespie,*** *Quaternary Research Center, Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195, USA;* ***Marc Caffee†,*** *Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California 94405, USA; and* ***Robert Finkel,*** *Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California 94405, USA*

ABSTRACT

Analysis of in situ–produced cosmogenic nuclides, including ^{10}Be, ^{26}Al, and ^{36}Cl, has changed how geologists understand desert surface processes. Here, we provide a series of examples from arid mountain-piedmont systems that illustrate both the power and limitations of this geochronometer. Analyses of samples collected from bare bedrock surfaces at the Alabama Hills, California, demonstrate slow but variable (1.4–20 m m.y.$^{-1}$) rates of erosion, whereas cosmogenic dating of the Blackhawk landslide debris (~6.5–31 k.y.) and the Castle Dome piedmont allows linkages between landscape-scale processes and climate change. However, data show that nuclides inherited from prior periods of exposure, as well as the effect of post-depositional surface change, limit the accuracy and precision of exposure dating in some settings. On the broad Castle Dome piedmont, detailed isotopic stratigraphies, coupled with analysis of desert soils, indicate depositional histories over the past ~70 k.y. in the absence of radiocarbon-datable organic material. Transect-based amalgamated sampling techniques allow for estimation of sediment velocity down mountain-fringing piedmonts. In drainage basins, the concentration of ^{10}Be in fluvial sediment demonstrates the efficacy of fluvial mixing even in areas where surface flow is intermittent. Considered together, these applications of the cosmogenic technique allow the delineation of sediment budgets in areas where no other technique has been useful. Such data are important for the arid Southwest, where population is increasing rapidly, as is the interaction of society and surface processes.

INTRODUCTION

Desert landscapes contain a rich record of geomorphic and geologic change (Cooke et al., 1993). Over the past century, geomorphologists and pedologists have used a variety of approaches, such as interpreting and dating sediments from dry-lake playas (Enzel, 1992; Lowenstein, 2002; Anderson and Wells, 2003), alluvial fans (Harvey and Wells, 2003; McDonald et al., 2003), and landforms offset by fault systems (Weldon et al., 2004; Matmon et al., 2005), to determine the effects of climate change on sediment generation and transport systems and to quantify process rates. Such studies allow us to understand the broad timing of sediment deposition and erosion, their drivers, and the overall rates and processes of soil development. However, at finer temporal and spatial resolution, there is significant variability in the data, which often makes it difficult to interpret because numeric age-control is frequently lacking. Furthermore, the timing of older events is often inferred solely from the behavior of the system during more recent ^{14}C-datable climatic and tectonic episodes. Quantifying rates and dates beyond the 40–50 k.y. limit of radiocarbon dating not only allows geologists to test long-standing hypotheses regarding desert process behavior during climate change (e.g., Bull, 1991), but also allows for systematic evaluation of the effects of lithology, nonglacial climate change, tectonics, and other potential drivers of landscape change.

Determining rates of surface change in the desert is no simple task. Most desert surfaces change imperceptibly over human time scales (Webb, 1996) because much geomorphic work in arid climates is accomplished during large but infrequent storm events (Schick, 1977; Cooke et al., 1993). Quantifying the effects of such storms, both spatially and temporally, requires expensive and time-consuming monitoring programs (Schick, 1977; Persico et al., 2005). Over millennia, the timing of such events is difficult to establish because dry desert climates are not conducive to the generation or preservation of plant material for radiocarbon analysis, the standard means by which late Quaternary deposits are dated and rates of surface change are often calculated (Bull, 1991). It is clear that major advances in the understanding of desert landforms and the rate at which they shed sediment require widely applicable, quantitative, and reliable chronometers. In this paper, we present new data to illustrate both the promise and limitations of cosmogenic nuclides when combined with field data as a tool for understanding arid-region geomorphic systems. Many of the approaches we present are also applicable to other climatic and tectonic settings (Bierman and Nichols, 2004).

CASE STUDIES

Fundamental to the application of cosmogenic nuclides as a monitor of desert surface processes is understanding that (1) most production of cosmogenic nuclides occurs near Earth's surface and (2) production decreases to minimal rates at depths of several meters. The measured concentration of isotopes, such as ^{10}Be, reflects the near-surface residence time, or cosmic-ray dosing, of a mineral grain. This leads to an inverse relationship between nuclide concentration and erosion rate and a direct relationship between surface age and nuclide con-

GSA Today: v. 16, no. 8, doi: 10.1130/GSAT01608.1

*E-mails: knichols@skidmore.edu; Paul.Bierman@uvm.edu
†Current address: PRIME Laboratory, Purdue University, West Lafayette, Indiana 47907, USA

centration. Here, we present a series of three case studies from sites in southern Arizona and California (Fig. 1) that highlight both the utility and limitations of using cosmogenic nuclides to study arid-region geomorphology and the landscape-scale continuum of sediment production, transport, and deposition.

Case 1—Sediment Production from Eroding Rock: The Alabama Hills, California

You have probably seen the Alabama Hills even if you've never been there. This weathered granite landscape in the shadow of the Sierra Nevada is one of Hollywood's favorites, providing backdrops for John Wayne movies, Subaru Outback ads, and the subterranean monsters of the movie *Tremors*. Despite the visual popularity of this and other bare rock landscapes, little is known about the rates of bedrock weathering, which is a problem because weathering-limited bare-rock slopes play an important role as sources of desert sediment (Bull, 1991) and runoff (Yair and Kossovsky, 2002). Without knowledge of bare-rock erosion rates, one cannot craft accurate and useful sediment budgets (Dietrich and Dunne, 1978).

The Alabama Hills, dominated by varnished tors and inselbergs that crop out of small but distinct grus-mantled pediment surfaces (Fig. 2A), are a down-faulted block of deeply weathered and jointed granite (Richardson, 1975; Chen and Tilton, 1991) that sit ~3000 m below the crest of the Sierra Nevada but well above the deeply alluviated bedrock floor of adjacent Owens Valley (Pakiser et al., 1964). The linear eastern margin of the Hills appears to be controlled by the Owens Valley fault system (Beanland and Clark, 1993), whereas to the west their margin is convoluted and buried by debris fans shed from the Sierra Nevada (Bierman et al., 1994).

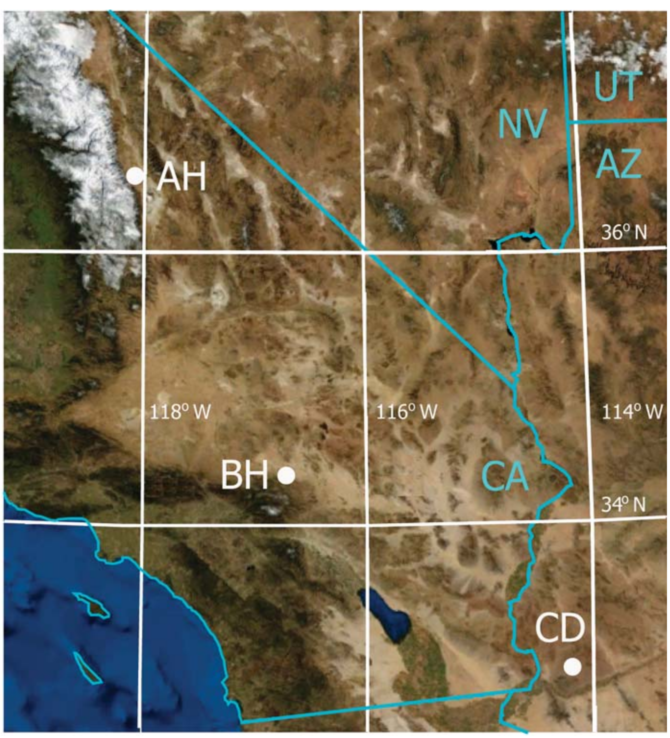

Figure 1. Location of case studies. The Alabama Hills (AH) are in Owens Valley near Lone Pine, California (CA); the Blackhawk slide (BH) is in the Mojave Desert near Apple Valley, California; and the Castle Dome piedmont (CD) is north of Yuma, Arizona (AZ). Background is a true color image of the American Southwest taken in January 2004 (courtesy of the National Aeronautics and Space Administration's Blue Marble: Next Generation database). NV—Nevada; UT—Utah.

To estimate the rate at which the Alabama Hills are eroding, we obtained 20 measurements of ^{10}Be from quartz that had been separated from samples of exposed rock. This provides a direct measure of bedrock landscape stability (Fig. 2; Data Repository Table DR1[1]). The samples were collected from three distinct geomorphic environments (Bierman, 1993) in order to test the hypothesis that heavily varnished, high-standing landforms were eroding more slowly than nonvarnished, lower geomorphic features. Five samples were collected from the top or sides of dark, high inselbergs, which stand tens of meters above low-lying, colluvium-covered valleys within the Alabama Hills. These high inselbergs are losing mass primarily via detachment of 1–3-cm-thick rock sheets (Fig. 2B). Seven samples were collected from more topographically isolated low inselbergs 5–20 m above the adjacent pediments or colluvial surfaces (Fig. 2C). Eight samples were collected from unvarnished, flat-lying bedrock pediment surfaces sloping away from the inselbergs (Fig. 2D). Unlike the inselbergs, the pediment surfaces appeared to be losing mass primarily by granular disintegration.

Field observations and isotopic data show that the inselbergs and pediments of the Alabama Hills are dynamic landforms losing mass over time and shedding sediment onto adjacent colluvial surfaces. All samples contain significant amounts of cosmogenically produced ^{10}Be, 0.45–5.4 × 10^6 atoms g^{-1}. If we interpret the data as reflecting nuclide concentration in steadily eroding surfaces, model erosion rates range from 1.4 to 20 m/m.y. and are related to the sampled geomorphic environment (Fig. 2E). The high inselbergs are the most stable, eroding at 5.4 ± 2.7 m/m.y. (n = 5); the low inselbergs are eroding at 7.2 ± 3.2 m/m.y. (n = 7); and the pediments are least stable, eroding on average at 11.1 ± 4.5 m/m.y. (n = 8). It is possible that the bare-rock pediment surfaces we sampled were exposed by the recent stripping of colluvial or alluvial cover; thus, the inferred erosion rates are maxima. In any case, the pediment surfaces we sampled experienced less cosmic-ray dosing than the inselbergs.

The isotopic data are consistent with bare-rock erosion rates for granite measured in other arid regions of North America (Nishiizumi et al., 1986; Bierman and Turner, 1995) and Namibia (Bierman and Caffee, 2001). In all of these cases, erosion rates are higher than those indicated by samples collected from Australian granite surfaces, particularly those on the semiarid Eyre Peninsula, where many samples indicate erosion rates on the order of ≤1 m/m.y. (Bierman and Caffee, 2002). It does not appear that precipitation or temperature play major roles in setting the rate of bare-rock erosion (Bierman and Caffee, 2001; Riebe et al., 2001), with the possible exception of Australian granites (Bierman and Caffee, 2002). Therefore, we

[1]Data repository item 2006166, cosmogenic isotope data for the Alabama Hills, the Castle Dome piedmont, and the Blackhawk landslide, is available on the Web at www.geosociety.org/pubs/ft2006.htm. You can also obtain a copy by writing to editing@geosociety.org.

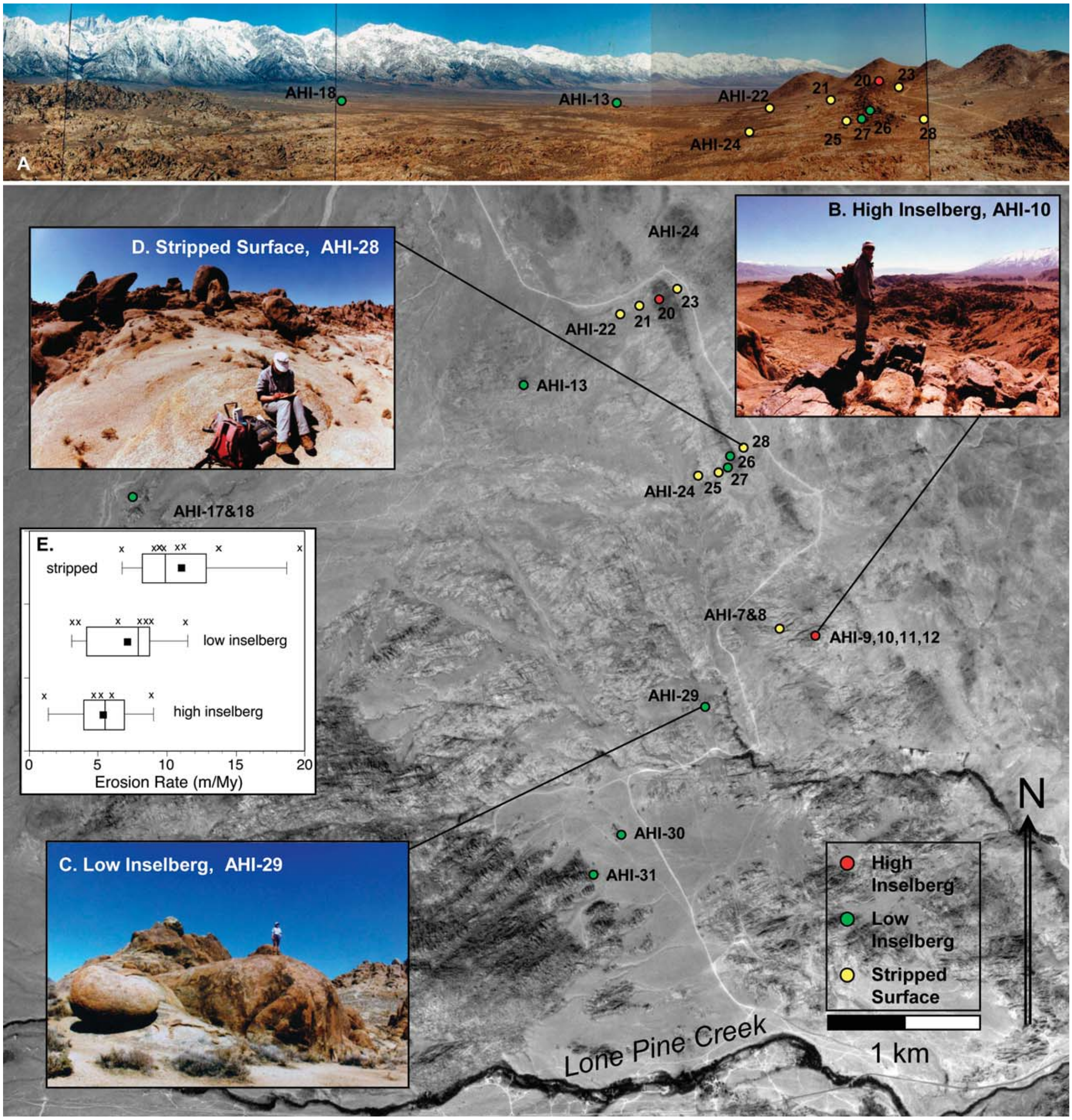

Figure 2. Alabama Hills, California, sample site map, based on scanned aerial photograph (GS-VEQR 133, 8-15-1978). Sample locations are marked by sample identification numbers and color-coded by geomorphic environment (red—high inselberg; green—low inselberg; yellow—stripped surface). Inset images show typical morphology of the three sampled geomorphic environments. (A) Panoramic view taken looking north from sample sites AHI-9–AHI-12 shows other sample sites and their topographic relationships. (B) High inselberg, sample site AHI-10. (C) Low inselberg, sample site AHI-29. (D) Stripped pediment surface, sample site AHI-28. (E) Box and whisker plot showing results of isotopic analyses; solid square—mean; vertical line—median; box ends—25th and 75th percentiles; whisker ends—10th and 90th percentiles; x—data points. Students *t*-test (two-tailed) indicates that at $\alpha < 0.1$, mean erosion rates of high and low inselbergs are indistinguishable and that both populations have lower erosion rates than stripped pediment surfaces.

suspect that the measured variation in the Alabama Hills bare-granite erosion rates may result primarily from differences in joint frequency and spacing, as suggested by Twidale (1982). The inselbergs may be blocks of less-jointed rocks that have greater topographic relief today because they are eroding more slowly, as indicated by the cosmogenic data, than their low-lying brethren. Alternatively, the valleys and peaks of the Alabama Hills may be inherited features, and the isolation of the inselbergs from erosion catalysts, such as soil moisture and wildfire (Bierman and Gillespie, 1991), may explain their stability and relatively low rates of erosion.

Case 2—Sediment Deposition on the Castle Dome Piedmont, Arizona

After sediment is shed from mountainous uplands, it is transported to and deposited on low-gradient alluvial slopes, or piedmonts. Such deposits have the potential to reveal important events in surface histories, such as the timing of fan incision

(Liu et al., 1996), the timing and rate of tectonic activity (Bierman et al., 1995; Zehfuss et al., 2001; Phillips, 2003; Matmon et al., 2005), and the rate of surface aggradation (Nichols et al., 2002, 2005b). Here, we present ^{10}Be data from a soil pit dug into a piedmont that has a well-developed and varnished pavement extending as an apron from the Castle Dome Mountains in Arizona (Fig. 3; Data Repository Table DR2 [see footnote 1]). These data demonstrate how cosmogenic nuclide data compliment traditional soil profile descriptions, providing more precise age control and quantifying piedmont process rates at time scales beyond the 40 k.y. limit of radiocarbon dating.

Soil development in piedmont sediment and the shape of nuclide depth profiles derived from soil-pit samples depend on both the deposition rate and the length of time since deposition (Phillips et al., 1998; Birkeland, 1999; Nichols et al., 2002, 2005b). For example, cummulic soils (overthickened, homogeneously weathered soil profiles) represent periods of steady, relatively slow deposition (Birkeland, 1999). Such slow deposition yields nuclide concentrations that increase with depth. Conversely, packages of sediment with no evidence of pedogenesis suggest well-mixed soils or relatively rapid sediment deposition characterized by uniform nuclide concentrations with depth. Sediment that was deposited rapidly but has been stable since deposition will exhibit both soil development that is representative of the age of the deposit as well as nuclide concentrations that decrease with depth. However, many desert surfaces have complex histories of deposition, erosion, and stability. Buried soils represent a paleo-ground surface, where the degree of soil development is representative of the length of surface stability before burial. Often, these buried soils are truncated, as evidenced by missing horizons or sharp irregular boundaries, providing evidence of some erosion prior to burial. A model of the ^{10}Be depth profile, set in the context of soil development, can constrain near-surface depositional histories.

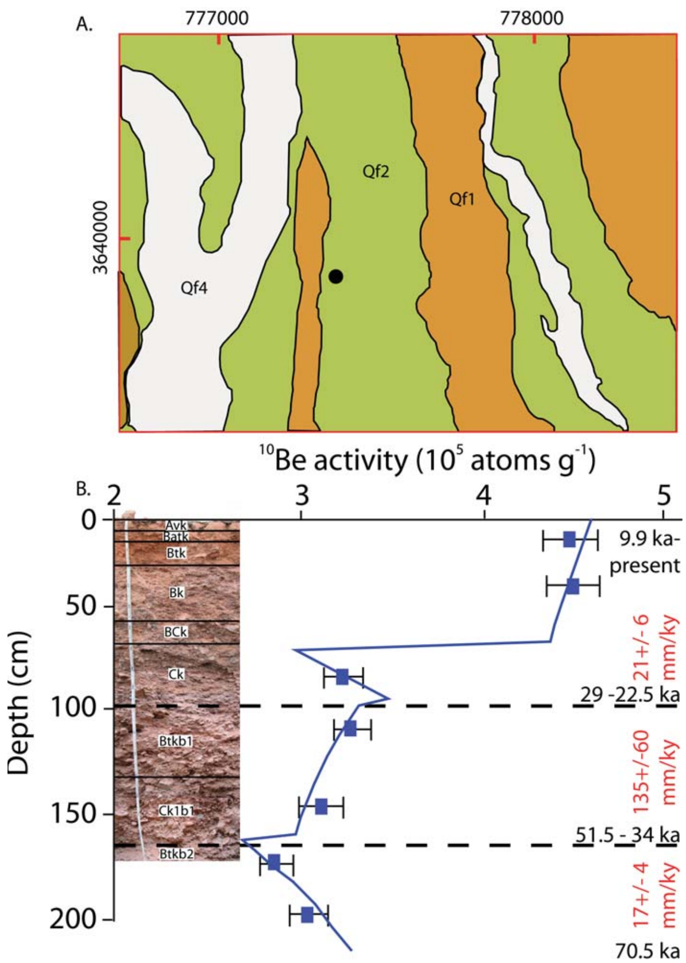

Figure 3. (A) Geomorphic map of the Castle Dome piedmont near soil pit location (black dot). Qf1 surfaces are topographically high abandoned piedmont surfaces, Qf4 surfaces represent active channels, and Qf2 surfaces are intermediate. Map modified after Lashlee et al. (1999). Map datum and red 1000-m tick marks are in zone 11N 1927 of the North American Datum. (B) Nuclide and soils data for Castle Dome piedmont soil pit. Photo mosaic of pit wall shows two buried soils (dashed lines) at 98 cm and 165 cm. Thin black lines—approximate boundaries of soil horizons; blue squares and 1σ analytical error bars—mid-point of depth samples; blue line—average model fit based on Monte Carlo simulation (root mean square error = 3.4 × 10^3 atoms g^{-1}); black numbers—time before present; aggradation rates are represented by red numbers (in k.y.). The total time represented in the soil pit is ~70.5 k.y.

The Castle Dome Mountain piedmont has multiple surfaces (Fig. 3A; Lashlee et al., 1999). The lowest surface (Qf4) corresponds to the active ephemeral channels; the highest surface (Qf1) has the best-developed and most darkly varnished pavements, an indicator of landscape stability. Soils data, from a pit dug into the Qf2 surface, suggest that the surface is between 12 and 70 ka based on a correlation to the soil development of the nearby Whipple Mountain piedmont (Lashlee et al., 1999). Two buried soils at depths of 98 cm and 165 cm in the pit each suggest a period of stability and shallow erosion before the next episode of deposition (Fig. 3B). The data, however, do not show significant changes in nuclide concentration in sediment above and below these depositional unconformities. Rather, the nuclide data are uniform from the surface to 50 cm and then step to lower but uniform nuclide concentrations from 50 to 165 cm. The bottom of the soil pit shows increasing nuclide concentrations from 165 to 200 cm.

An interpretative model constrains both the ages and the rates of piedmont processes (Nichols et al., 2005b). We use a numerical solution, optimized by Monte Carlo simulation of normally distributed nuclide concentrations for each sample, to estimate the mean and standard deviation of each period of stability, as recognized by buried soils (Nichols et al., 2005b). We also date each period of deposition and calculate average aggradation rates. Starting at the bottom of the soil pit, sediment was deposited at a rate of 17 ± 4 mm/k.y. for ~19 k.y. from 70.5 to 51.5 ka. At ca. 51.5 ka, the surface was stable for ~17.5 ± 3.5 k.y., producing the Btkb2 soil horizon from 165 to 200 cm depth. At ca. 34 ka, deposition at a rate of 135 ± 60 mm/k.y. began, likely caused by erosion and incorporation of sediment up-gradient of the soil pit location. Such reworking, common in piedmont soils of the Desert Southwest, would also cause the higher nuclide inheritance values required for the model fit. At ca. 29 ka, the surface was stable for at least 6.7 ± 2.8 k.y., depending on the assumed amount of soil erosion, forming the Btkb1 and Ck1b1 soils at 98 to 165 cm. Slow aggradation, at a rate of 21 ± 6 mm/k.y., occurred from ca. 22.5 ka to ca. 9.9 ka. At ca. 9.9 ka, rapid deposition of 70 cm of sediment with high ^{10}Be activity suggests derivation from a near-surface source. Over the past 9.9 ± 2.6 k.y., the surface has aggraded 8 cm from dust accumulation.

Our numerical model constrains the ages and rates of piedmont processes that are within the 12–70 ka soils-based age estimated by Lashlee et al. (1999). The model suggests three periods of stability (present to ca. 9.9 ka, 22.5–29 ka, and 34–51.5 ka) separated by periods of slow aggradation (135 and 17 mm/k.y.), and instantaneous deposition of the top 70 cm of sediment. Deposition from ca. 70 ka to ca. 50 ka agrees with many dated depositional events in the Southwest (Gosse et al., 2004; Anders et al., 2005; Nichols et al., 2005b). The pulse of sediment at the Pleistocene–Holocene transition is consistent with other depositional events identified elsewhere and with geomorphic models (Bull, 1991; McDonald et al., 2003). The periods of deposition and stability between ca. 10 ka and 50 ka vary from being in phase with some data to being out of phase with other data (Anders et al., 2005). Such asynchrony may result from lags induced by changing basin processes or from differing propagation rates of base-level change. In any case, cosmogenic nuclide depth profile data, teamed with soil development analysis, offer an improved understanding of piedmont surface processes, soil ages, and piedmont history. The use of nuclide depth profiles allows for quantification of past surface processes and histories, supplementing the information available from boulders cropping out at the surface.

Case 3—Dating Desert Landslides: The Blackhawk, California

Sometime in the past, a thundering avalanche of rock peeled off Blackhawk Mountain above the Mojave Desert and came crashing down to the valley bottom, leaving lobes of pulverized rock studded with boulders (Shreve, 1968, 1987; Stout, 1977). The Blackhawk slide is not alone; large slides have affected other parts of the Mojave Desert (Bishop, 1997). The exact timing and cause of these events is unknown. Some suggest an increase in precipitation is to blame (Stout, 1977); however, seismic shaking can trigger large landslides (Philip and Ritz, 1999). Accurate and precise dating is needed to better understand the timing, and thus perhaps the triggers, such as dated large earthquakes, of these megaslides.

Until recently, the only age control for the Blackhawk landslide was radiocarbon dating of freshwater gastropod and pelecypod shells found in the sediments of a small, ephemeral pond on the landslide's surface: 17,400 ± 550 ^{14}C yr B.P. (Stout, 1975, 1977). This age is problematic for two reasons. The pond is younger than the slide; thus, the age is a stratigraphic minimum. However, since the pond developed on carbonate rocks that may have added ^{14}C-free carbon to the pond water, the date may be too old. With such ambiguity in the ^{14}C dating, the Blackhawk would seem to be an excellent site for applying cosmogenic nuclides as a dating tool; therefore, Stone et al. (1995) collected and analyzed samples of limestone for ^{36}Cl, and we collected samples from gneissic and sandstone boulders and analyzed them for ^{10}Be and ^{26}Al. Stone et al. (1995) concluded that the ^{36}Cl data were ambiguous and difficult to interpret, with apparent ages between 12 and 44 ka. Our results are similarly equivocal and point out limitations in cosmogenic-nuclide dating.

We sampled five boulders to date the Blackhawk landslide (Fig. 4A): a 1.5-m-high quartz-rich gneissic boulder (BH-3) located on the left levee side slope facing the debris zone (Fig.

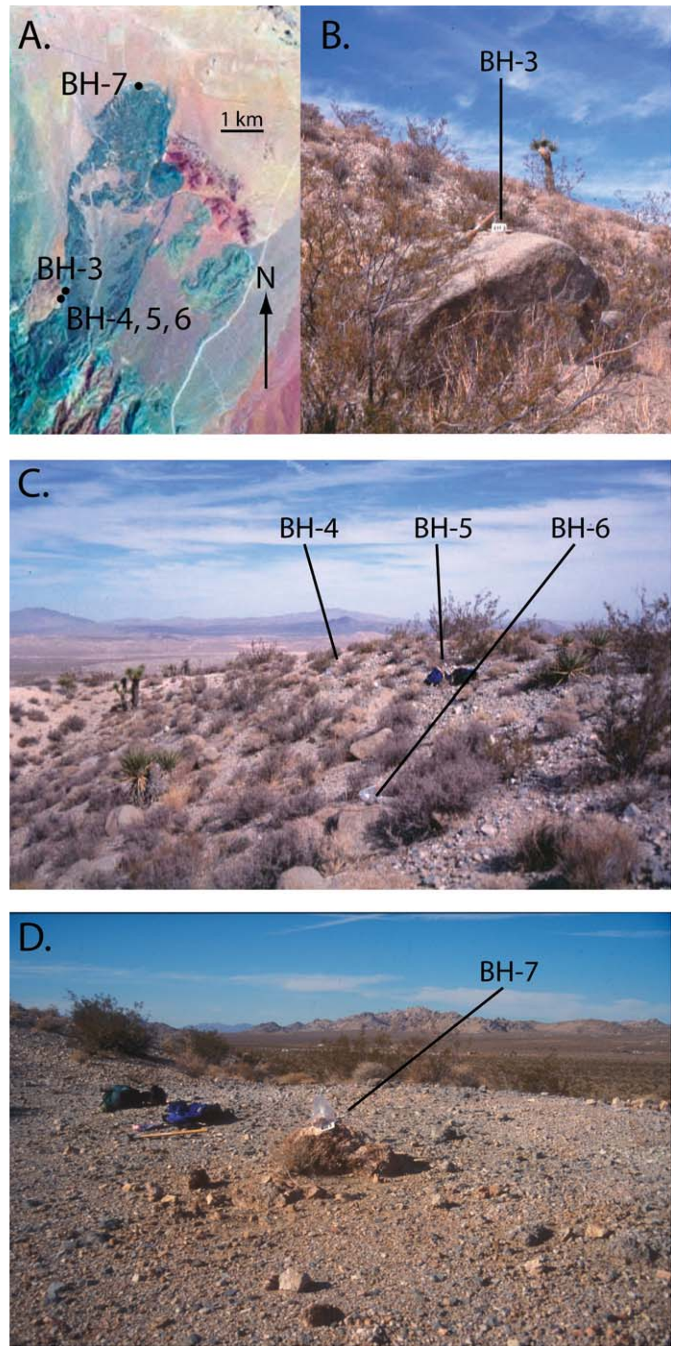

Figure 4. Location map and photographs of Blackhawk landslide boulders sampled for ^{10}Be and ^{26}Al analysis. (A) Landsat 7 image (bands 7, 4, 2) of the Blackhawk landslide debris (dark gray) with sample locations. (B) Granitic boulder BH-3, located on the side of the levee. There is little evidence of sediment erosion or deposition; thus, the slope is a surface of transport. (C) Three granitic boulders (BH-4, BH-5, and BH-6) are near the levee crest, suggesting little chance of burial after initial exposure. (D) Varnished sandstone boulder (BH-7) located at the toe of the landslide debris.

4B); three gneissic boulders (~1 m high, BH-4, BH-5, BH-6) near the left levee crest (Fig. 4C); and one varnished sandstone boulder (BH-7) near the top of the levee crest at the toe of the landslide (Fig. 4D). We set out to determine the age of the slide by assuming that the boulders were unearthed by the landslide and deposited on the surface of the debris, and that the boulders and the slide debris have not eroded since the landslide event. At least one of these assumptions, however, is invalid.

The amount of ^{10}Be and ^{26}Al varies from sample to sample. Because the concentrations of ^{10}Be and ^{26}Al are well correlated (Data Repository Table DR3 [see footnote 1]), we quote two-isotope, average ages. The three boulders near the levee crest have low amounts of ^{10}Be and ^{26}Al and suggest a young age (6.4–7.7 ka; $n = 3$), whereas the boulder at the toe of the landslide and the side slope boulder contain higher concentrations of nuclides, which suggest older ages (24.1 ± 3.7 ka and 30.9 ± 5.1 ka, respectively; Table DR3).

These data suggest that cosmogenic-nuclide dating is not straightforward for the Blackhawk landslide and that the sampled boulders have not had the same exposure history. The lightly dosed levee boulders could initially have been buried in the levee and later exhumed, a scenario that would result in an age underestimate. Conversely, the boulder at the toe of the landslide and the side-slope boulder could have had previous cosmic-ray exposure, resulting in nuclide inheritance and an age overestimate (Briner and Swanson, 1998). If we assume that the nuclide concentration in levee-crest boulders represents a two-stage history (initial burial followed by exhumation and exposure), we can model a range of landslide ages. By extrapolating the levee slopes to a peak, a maximum of 9.5 m of levee crest erosion could have occurred, based on measured nuclide concentrations. If we use erosion rates of moraines from the eastern side of the Sierra Nevada (Hallet and Putkonen, 1994)—even though such rates may not represent the erosion rates of the Blackhawk landslide debris very well—and model the depth of boulder burial between the surface and 9.5 m, we can model deposition ages between 6.4 and 31 ka. Regardless of the landslide debris erosion rates, the nuclide data do not constrain the age of the landslide any more precisely than to the late Pleistocene. The resulting age ambiguity precludes investigation into possible landslide timing and causes of failure.

The Blackhawk slide highlights two problems inherent to dating landforms: nuclide inheritance and landform erosion or modification after deposition. Boulders exposed near Earth's surface before being transported to a new location carry nuclides from prior periods of cosmic-ray exposure. Thus, a boulder's model age represents total exposure time, not the age of the sampled landform. Such inherited nuclides have proven to complicate the interpretation of cosmogenic data from moraine boulders (Putkonen, 2003), lake-shoreline clasts (Trull et al., 1991; Matmon et al., 2003), striated bedrock (Colgan et al., 2002), and alluvial fan clasts and boulders (e.g., Liu et al., 1996; Zehfuss et al., 2001; Matmon et al., 2005). If one is fortunate enough to avoid, or account for, nuclide inheritance, then exhumation of boulders through landform erosion and/or the loss of mass from boulder surfaces complicates the interpretation of boulder ages (Bierman and Gillespie, 1991; Hallet and Putkonen, 1994; Zimmerman et al., 1994; Putkonen, 2003). Therefore, predepositional exposure and post-depositional surface modification are fundamental limits on the accuracy of cosmogenically determined landform ages.

OTHER RECENT APPLICATIONS

The power of cosmogenic nuclides as a tool for understanding desert systems is just beginning to be realized. In addition to dating fan surfaces (Liu et al., 1996; Phillips et al., 1998), quantifying erosion rates (Bierman and Caffee, 2001, 2002), and determining burial ages (Granger and Smith, 2000), cosmogenic nuclides can be used as sediment tracers (Clapp et al., 2001, 2002; Matmon et al., 2006), allowing the construction of sediment budgets (Nichols et al., 2005a). Such budgets can be robust quantitative descriptors of desert systems, addressing rates of change, forming a framework for rational landscape management, and providing the means to test long-standing conceptual models of landscape behavior in arid regions (Bierman and Nichols, 2004).

Recently, the rich history contained in the sediments of long piedmonts has been deciphered using ^{10}Be (Bierman et al., 1995; Liu et al., 1996; Zehfuss et al., 2001; Phillips, 2003; Matmon et al., 2005). Sediment amalgamation techniques provide cost- and time-effective means to address the spatial variability in ^{10}Be concentration and thus describe the behavior of the piedmont sediment transport system as a whole (Nichols et al., 2002, 2005b). Cosmogenic data allow calculation of long-term average sediment velocities and fluxes on low-gradient piedmonts. The average sediment grain on a piedmont moves a few decimeters to meters per year, depending on the geomorphic setting (Nichols et al., 2005a). These data provide an important land-management tool, essentially a natural benchmark against which to measure human-induced rates of change as development sweeps across the Desert Southwest.

One way to address the role of tectonics, lithology, and climate change on the rate and distribution of geomorphic process is to measure erosion over space and through time. Bierman et al. (2005) quantified the spatial variability of subbasin erosion rates and constrained the average erosion rate of the 14,225 km^2 Rio Puerco basin to ~100 m/m.y. ^{10}Be concentration, and thus erosion rates, are more variable in smaller headwater basins (98% standard deviation [s.d.]; $n = 16$, $\mu = 392$ km^2) than in larger downstream basins (53% s.d.; $n = 21$, $\mu = 5440$ km^2), because stream flows homogenize sediment with different cosmic-ray exposure histories and erosion histories. As predicted by numerous geomorphologic studies (e.g., Bull, 1991), Bierman et al. (2005) found that erosion rates are best correlated to vegetation, precipitation, and rock erodibility.

Erosion rates over time can also be measured. Using a flight of well-preserved fluvial terraces, Schaller et al. (2004) measured paleo-erosion rates of the humid Meuse River catchment. By dating the terraces and back-calculating the nuclide inventory during deposition, they were able to determine paleo-erosion rates. Similarly, Bierman et al. (2005) measured ^{10}Be in a 6-m radiocarbon-dated section of Rio Puerco sediment deposited over >1000 yr; the similarity of ^{10}Be concentration among the 15 samples indicated that average cosmic-ray dosing, and thus the basin-scale erosion rate, did not change substantially over the millennial time scale on this arid-region river.

These are only a few examples of how cosmogenic nuclides have advanced our understanding of desert systems and of how using cosmogenic nuclide dating in conjunction with methods, such as thermochronology and luminescence dating, will enable geomorphologists to more thoroughly decipher the detailed history of desert landscape change (House et al., 2001; Lancaster and Tchakerian, 2003). These new data provide quantitative estimates of rates and dates, an important requirement for testing the validity of long-standing models of desert processes/response, such as those linking aggradation and incision with climate and tectonics (Bull, 1991).

ACKNOWLEDGMENTS

Discussions with B. Harrison, Y. Enzel, M. Eppes, E. McDonald, M. Pavich, S. Wells, K. Whipple, D. Clark, L. Persico, A. Matmon, and L. McFadden helped shape our thinking about desert systems. D. Elmore, C. Massey, and L. Persico assisted with sampling and analysis. Edits by M. Eppes, A. Matmon, G. Ross, and B. Harrison improved earlier versions of the manuscript. Funding for analyses and writing provided by the Army Research Office and U.S. Department of Defense grants DAAD19-03-1-0205 and DAAD199910143, National Science Foundation grant EAR-9396261, the J. Hoover Mackin Award, and the Jonathan O. Davis Award.

REFERENCES CITED

Anders, M., Pederson, J., Rittenour, T.M., Sharp, W.D., Gosse, J.C., Karlstrom, K.E., Crossey, L.J., Goble, R.J., Stockli, L., and Yang, G., 2005, Pleistocene geomorphology and geochronology of eastern Grand Canyon: Linkages of landscape components during climate changes: Quaternary Science Reviews, v. 24, p. 2428–2448, doi: 10.1016/j.quascirev.2005.03.015.

Anderson, D.A., and Wells, S.G., 2003, Latest Pleistocene lake highstands in Death Valley, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts: Geological Society of America Special Paper 368, p. 115–128.

Beanland, S., and Clark, M., 1994, The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake: U.S. Geological Survey Bulletin, 29 p.

Bierman, P.R., 1993, Cosmogenic isotopes and the evolution of granitic landforms [Ph.D. thesis]: Seattle, University of Washington, 289 p.

Bierman, P.R., and Caffee, M.W., 2001, Slow rates of rock surface erosion and sediment production across the Namib Desert and escarpment, southern Africa: American Journal of Science, v. 301, p. 326–358.

Bierman, P., and Caffee, M., 2002, Cosmogenic exposure and erosion history of ancient Australian bedrock landforms: Geological Society of America Bulletin, v. 114, p. 787–803, doi: 10.1130/0016-7606(2002)114<0787:CEAEHO>2.0.CO;2.

Bierman, P.R., and Gillespie, A.R., 1991, Range fires: A significant factor in exposure-age determination and geomorphic surface evolution: Geology, v. 19, p. 641–644, doi: 10.1130/0091-7613(1991)019<0641:RFASFI>2.3.CO;2.

Bierman, P.R., and Nichols, K.K., 2004, Rock to sediment—Slope to sea with ^{10}Be—Rates of landscape change: Annual Review of Earth and Planetary Sciences, v. 32, p. 215–255, doi: 10.1146/annurev.earth.32.101802.120539.

Bierman, P., and Turner, J., 1995, ^{10}Be and ^{26}Al evidence for exceptionally low rates of Australian bedrock erosion and the likely existence of pre-Pleistocene landscapes: Quaternary Research, v. 44, p. 378–382, doi: 10.1006/qres.1995.1082.

Bierman, P.R., Gillespie, A., and Caffee, M., 1995, Cosmogenic age-estimates for earthquake recurrence intervals and debris-flow fan deposition, Owens Valley, California: Science, v. 270, p. 447–450.

Bierman, P.R., Reuter, J.M., Pavich, M., Gellis, A.C., Caffee, M.W., and Larsen, J., 2005, Using cosmogenic nuclides to contrast rates of erosion and sediment yield in a semi-arid, arroyo dominated landscape, Rio Puerco Basin, New Mexico: Earth Surface Processes and Landforms, v. 30, p. 935–953, doi: 10.1002/esp.1255.

Birkeland, P.W., 1999, Soils and geomorphology: New York, Oxford University Press, 430 p.

Bishop, K.M., 1997, Miocene rock-avalanche deposits, Halloran/Silurian Hills area, southeastern California: Environmental & Engineering Geoscience, v. 3, p. 501–512.

Briner, J.P., and Swanson, T.W., 1998, Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet: Geology, v. 26, p. 3–6, doi: 10.1130/0091-7613(1998)026<0003:UICCTC>2.3.CO;2.

Bull, W.B., 1991, Geomorphic responses to climate change: New York, Oxford University Press, 326 p.

Chen, J.H., and Tilton, G.R., 1991, Applications of lead and strontium isotopic relationships to the petrogenesis of granitoid rocks, central Sierra Nevada batholith, California: Geological Society of America Bulletin, v. 103, p. 439–447, doi: 10.1130/0016-7606(1991)103<0439:AOLASI>2.3.CO;2.

Clapp, E.M., Bierman, P.R., Nichols, K.K., Pavich, M., and Caffee, M., 2001, Rates of sediment supply to arroyos from upland erosion determined using in situ-produced cosmogenic ^{10}Be and ^{26}Al: Quaternary Research, v. 55, p. 235–245, doi: 10.1006/qres.2000.2211.

Clapp, E.M., Bierman, P.R., and Caffee, M., 2002, Using ^{10}Be and ^{26}Al to determine sediment generation rates and identify sediment source areas in an arid region drainage: Geomorphology, v. 45, p. 89–104, doi: 10.1016/S0169-555X(01)00191-X.

Colgan, P.M., Bierman, P.R., Mickelson, D.M., and Caffee, M., 2002, Variation in glacial erosion near the southern margin of the Laurentide ice sheet, south-central Wisconsin, USA: Implications for cosmogenic dating of glacial terrains: Geological Society of America Bulletin, v. 114, p. 1581–1591, doi: 10.1130/0016-7606(2002)114<1581:VIGENT>2.0.CO;2.

Cooke, R.U., Warren, A., and Goudie, A., 1993, Desert Geomorphology: London, UCL Press, 526 p.

Dietrich, W.E., and Dunne, T., 1978, Sediment budget for a small catchment in mountainous terrain: Zeitschrift für Geomorphologie, v. 29, p. 191–206.

Enzel, Y., 1992, Flood frequency and the formation of late Holocene playa lakes, California: The Holocene, v. 2, p. 11–18.

Gosse, J., McDonald, E., Pederson, J., Stockli, D., Lee, J., Stockli, L., and Yang, G., 2004, Oxygen isotope stage 4 sediment dominates the U.S. Southwest alluvial record: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 307.

Granger, D.E., and Smith, A.L., 2000, Dating buried sediments using radioactive decay and muonogenic production of ^{26}Al and ^{10}Be: Nuclear Instruments & Methods in Physics Research, Section B, Beam Interactions with Materials and Atoms, v. 172, p. 822–826, doi: 10.1016/S0168-583X(00)00087-2.

Hallet, B., and Putkonen, J., 1994, Surface dating of dynamic landforms: Young boulders on aging moraines: Science, v. 265, p. 937–940.

Harvey, A.M., and Wells, S.G., 2003, Late Quaternary variations in alluvial fan sedimentologic and geomorphic processes, Soda Lake basin, eastern Mojave Desert, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts: Geological Society of America Special Paper 368, p. 207–230.

House, M.A., Wernicke, B.P., and Farley, K.A., 2001, Paleo-geomorphology of the Sierra Nevada, California, from (U-Th)/He ages in apatite: American Journal of Science, v. 301, p. 77–102.

Lancaster, N., and Tchakerian, V.P., 2003, Late Quaternary eolian dynamics, Mojave Desert, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts: Geological Society of America Special Paper 368, p. 231–249.

Lashlee, D., Briuer, F., Murphy, W., and McDonald, E.V., 1999, Geospatial distribution of cultural resources in the combat systems maneuver area, U.S. Army Yuma Proving Ground: Yuma, Arizona, U.S. Army Yuma Proving Ground, p. 86.

Liu, B., Phillips, F.M., Pohl, M.M., and Sharma, P., 1996, An alluvial surface chronology based on cosmogenic ^{36}Cl dating, Ajo Mountains (Organ Pipe Cactus National Monument), southern Arizona: Quaternary Research, v. 45, p. 30–37, doi: 10.1006/qres.1996.0003.

Lowenstein, T.K., 2002, Pleistocene Lakes and Paleoclimates (0 to 200 Ka) in Death Valley, California: Smithsonian Contributions to the Earth Sciences, v. 33, p. 109–120.

Matmon, A., Crouvi, O., Enzel, Y., Bierman, P.R., Larsen, J., Porat, N., Amit, R., and Caffee, M., 2003, Complex exposure histories of chert clasts in the late Pleistocene shorelines of Lake Lisan, southern Israel: Earth Surface Processes and Landforms, v. 28, p. 493–506, doi: 10.1002/esp.454.

Matmon, A., Schwartz, D.P., Finkel, R., Clemmens, S., and Hanks, T., 2005, Dating offset fans along the Mojave section of the San Andreas fault using cosmogenic ^{26}Al and ^{10}Be: Geological Society of America Bulletin, v. 117, p. 795–807, doi: 10.1130/B25590.1.

Matmon, A., Nichols, K., and Finkel, R., 2006, Isotopic insights into smoothening of abandoned fan surfaces, Southern California: Quaternary Research, doi:10.1016/j.yqres.2006.02.010 (in press).

McDonald, E.V., McFadden, L.D., and Wells, S.G., 2003, Regional response of alluvial fans to the Pleistocene-Holocene climatic transition, Mojave Desert, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts: Geological Society of America Special Paper 368, p. 189–205.

Nichols, K.K., Bierman, P.R., Hooke, R.L., Clapp, E.M., and Caffee, M., 2002, Quantifying sediment transport on desert piedmonts using ^{10}Be and ^{26}Al: Geomorphology, v. 45, p. 105–125, doi: 10.1016/S0169-555X(01)00192-1.

Nichols, K.K., Bierman, P.R., Caffee, M., Finkel, R., and Larsen, J., 2005a, Cosmogenically enabled sediment budgeting: Geology, v. 33, p. 133–136, doi: 10.1130/G21006.1.

Nichols, K.K., Bierman, P.R., Eppes, M.C., Caffee, M., Finkel, R., and Larsen, J., 2005b, Deciphering the late Pleistocene and Holocene history of the complex Chemehuevi Mountain piedmont using ^{10}Be and ^{26}Al: American Journal of Science, v. 305, p. 345–368.

Nishiizumi, K., Lal, D., Klein, J., Middleton, R., and Arnold, J.R., 1986, Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates: Nature, v. 319, p. 134–136, doi: 10.1038/319134a0.

Pakiser, L.C., Kane, M.F., and Jackson, W.H., 1964, Structural geology and volcanism of Owens Valley region, California—A geophysical study: U.S. Geological Survey Professional Paper 438, 68 p.

Persico, L.P., Nichols, K.K., and Bierman, P.R., 2005, Tracking painted pebbles: Short-term rates of sediment movement on four Mojave Desert piedmont surfaces: Water Resources Research, v. 41.

Philip, H., and Ritz, J.F., 1999, Gigantic paleo-landslide associated with the active faulting along the Bogd Fault (Gobi-Altay, Mongolia): Geology, v. 27, p. 211–214, doi: 10.1130/0091-7613(1999)027<0211:GPAWAF>2.3.CO;2.

Phillips, F.M., 2003, Dating rupture events on alluvial fault scarps using cosmogenic nuclides and scarp morphology: Earth and Planetary Science Letters, v. 215, p. 203–218, doi: 10.1016/S0012-821X(03)00419-9.

Phillips, W.M., McDonald, E.V., Reneau, S.L., and Poths, J., 1998, Dating soils and alluvium with cosmogenic ^{21}Ne depth profiles: case studies from the Pajarito Plateau, New Mexico, USA: Earth and Planetary Science Letters, v. 160, p. 209–223, doi: 10.1016/S0012-821X(98)00076-4.

Putkonen, J., 2003, Accuracy of cosmogenic ages for moraines: Quaternary Research, v. 59, p. 255–261, doi: 10.1016/S0033-5894(03)00006-1.

Richardson, L.K., 1975, Geology of the Alabama Hills, California [M.S. thesis]: Reno, University of Nevada, 146 p.

Riebe, C.S., Kirchner, J.W., Granger, D.E., and Finkel, R.C., 2001, Minimal climatic control on erosion rates in the Sierra Nevada, California: Geology, v. 29, p. 447–450, doi: 10.1130/0091-7613(2001)029<0447:MCCOER>2.0.CO;2.

Schaller, M., von Blanckenburg, F., Hovius, N., Veldkamp, A., van den Berg, M.W., and Kubik, P.W., 2004, Paleoerosion rates from cosmogenic ^{10}Be in a 1.3 Ma terrace sequence: Response of the River Meuse to changes in climate and rock uplift: Journal of Geology, v. 112, p. 127–144, doi: 10.1086/381654.

Schick, A.P., 1977, A tentative sediment budget for an extremely arid watershed in the southern Negev, *in* Doehring, D.O., ed., Eighth Annual Geomorphology Symposium: Geomorphology in arid regions: Binghamton, State University of New York, v. 8, p. 139–164.

Shreve, R.L., 1968, The Blackhawk landslide: Geological Society of America Special Paper 108, 47 p.

Shreve, R.L., 1987, Blackhawk landslide, southwestern San Bernardino County, California, *in* Hill, M.L., ed., Cordilleran Section of the Geological Society of America, Centennial Field Guide: Boulder, Colorado, Geological Society of America, v. 1, p. 109–114.

Stone, J.O., Evans, J.M., Fifield, L.K., Allan, G.L., and Cresswell, R.G., 1995, Cosmogenic isotope dating of landslide hazards, 209th American Chemical Society National Meeting: Anaheim, California, American Chemical Society, p. NUCL 023.

Stout, M.L., 1975, Age of the Blackhawk landslide, southern California: Geological Society of America Abstracts with Programs, v. 7, no. 3, p. 378–379.

Stout, M.L., 1977, Radiocarbon dating of landslides in southern California: California Geology, v. 30, p. 99–105.

Trull, T.W., Kurz, M.D., and Jenkins, W.J., 1991, Diffusion of cosmogenic ^{3}He in olivine and quartz: Implications for surface exposure dating: Earth and Planetary Science Letters, v. 103, p. 241–256, doi: 10.1016/0012-821X(91)90164-D.

Twidale, C.R., 1982, Granite landforms: Amsterdam, Elsevier Sciences Publishing, 395 p.

Webb, R.H., 1996, Grand Canyon, a century of change: Tucson, University of Arizona Press, 290 p.

Weldon, R.J., Scharer, K.M., Fumal, T.E., and Biasi, G., 2004, Wrightwood and the earthquake cycle: What a long recurrence record tells us about how faults work: GSA Today, v. 14, no. 9, p. 4–10, doi: 10.1130/1052-5173(2004)014<4:WATECW>2.0.CO;2.

Yair, A., and Kossovsky, A., 2002, Climate and surface properties; hydrological response of small arid and semi-arid watersheds: Geomorphology, v. 42, p. 43–57, doi: 10.1016/S0169-555X(01)00072-1.

Zehfuss, P.H., Bierman, P.R., Gillespie, A.R., Burke, R.M., and Caffee, M.W., 2001, Slip rates on the Fish Springs fault, Owens Valley, California deduced from cosmogenic ^{10}Be and ^{26}Al and relative weathering of fan surfaces: Geological Society of America Bulletin, v. 113, p. 241–255, doi: 10.1130/0016-7606(2001)113<0241:SROTFS>2.0.CO;2.

Zimmerman, S.G., Evenson, E.B., Gosse, J.C., and Erskine, C.P., 1994, Extensive boulder erosion resulting from a range fire on the type-Pinedale moraines, Fremont Lake, Wyoming: Quaternary Research, v. 42, p. 255–265, doi: 10.1006/qres.1994.1076.

Manuscript received 25 January 2006;
accepted 26 May 2006 ✩