

ROCK TO SEDIMENT—SLOPE TO SEA WITH ^{10}Be —RATES OF LANDSCAPE CHANGE

Paul Robert Bierman

*Department of Geology and School of Natural Resources, University of Vermont,
Burlington, Vermont 05405, email: pbierman@zoo.uvm.edu*

Kyle Keedy Nichols

*Department of Geology, Skidmore College, Saratoga Springs, New York 12866,
email: knichols@skidmore.edu*

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■ **Abstract** Measurements of cosmogenic nuclides, predominately ^{10}Be , allow new insights into the ways in which and the rates at which sediment is generated, transported, and deposited over timescales ranging from 10^3 to 10^6 years. Samples from rock exposures are used to estimate erosion rates at points on the landscape, whereas samples of fluvial sediment provide estimates of basin-scale rates of denudation integrated over <1 to $>10^4$ km². Nuclide data show that hilltop, bare rock outcrops erode more slowly than basins as a whole, suggesting the potential for relief to increase over time as well-drained outcrops grow higher. More elaborate experiments and interpretive models provide insight into the distribution of hillslope processes, including the bedrock-to-soil conversion rate, which appears to increase under shallow soil cover and then decrease under deeper soils. Changes in average nuclide activity down slopes can be used to estimate grain speed over millennia, suggesting, for example, that sediment on desert piedmonts moves, on average, decimeters to meters per year. In other cases, changes in nuclide activity down river networks or along shorelines can be interpreted with mixing models to indicate sediment sources. Sediment deposition rates in otherwise undateable deposits can now be estimated by analyzing samples collected from depth profiles. Over the past decade, the analysis and interpretation of cosmogenic nuclides has given geomorphologists an unprecedented opportunity to measure rates and infer the distribution of geomorphic processes across Earth's varied landscapes. Long-standing models of landscape change can now be tested quantitatively.

INTRODUCTION

Earth's surface is a dynamic place where rocks weather and sediment is produced. Once released from bedrock, sediment begins an episodic, down-gradient journey that can take hours or millions of years. Driven by the force of gravity, rock and soil pour from mountain peaks, from desert hillslopes, and from tropical highlands (Figure 1). Some sediment is trapped temporarily on the continents, for example,

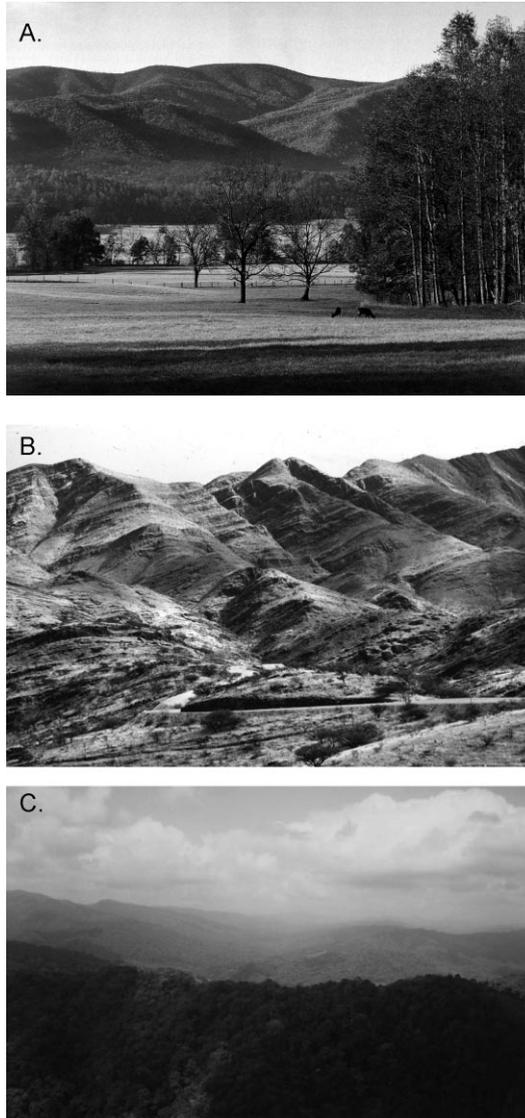


Figure 1 Landscapes sampled for cosmogenic nuclide analysis of sediment generation rates. (A) Great Smoky Mountains (as reported in Matmon et al. 2003a,c). (B) Great Namibian Escarpment near Gamsburg (as reported in Bierman & Caffee 2001). (C) Heavily forested tropical hillslopes in Panama.

baking in desert playas and other internally drained basins, but eventually most finds its way to the abyssal plains and trenches of the deep ocean.

For decades, and at a wide range of spatial and temporal scales, geologists have measured the rate at which sediment is generated and transported over Earth's surface, using a grab bag of techniques, beholden to many different assumptions (Judson 1968, Saunders & Young 1983). Such knowledge, although uncertain and fragmentary, is fundamental to understanding Earth as a dynamic system. Knowing local and global rates of sediment generation and transport has important implications for environmental management at all scales (Hooke 1994), from the sediment budget of an urban stream (Wolman 1967) to the ability of weathering rock to influence atmospheric CO₂ levels (Raymo & Ruddiman 1988).

This review considers what one relatively new technique, the analysis of cosmogenic nuclides in general, and ¹⁰Be specifically, can tell us about the rates at which sediment is generated on landscapes, transported down slope, carried by rivers, stored intermittently, and finally deposited in the ocean. Routinely measured for over a decade, cosmogenic nuclides have broadened our understanding of many different landscapes and provided rates and dates where there were none before (Greensfelder 2002). In the pages that follow, we weave together a selected series of cosmogenic nuclide studies in order to illustrate, in a landscape-scale context, what this method has done to illuminate the complex web of processes changing Earth's surface over time and space (Figure 2).

This paper is not a comprehensive review of the rapidly expanding body of cosmogenic literature; rather, we have selected a limited number of papers directly

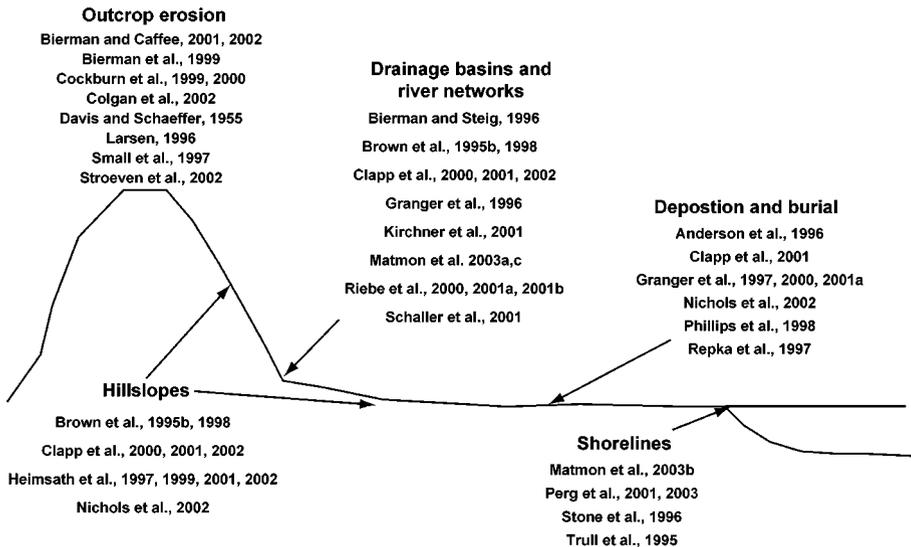


Figure 2 Schematic diagram shows location of cosmogenic nuclide studies, discussed in this review, which as a group trace sediment along a geomorphic continuum.

relevant to understanding the rate and distribution of processes that generate, transport, and deposit sediment. More inclusive review papers include Bierman et al. (2001a, 2003), Gosse & Phillips (2001), Kurz & Brooke (1994), and Zreda & Phillips (2000). We focus on ^{10}Be because this isotope has been used more than any other in geomorphic process studies.

SETTING THE CONTEXT

Most early attempts at quantifying present-day mass flux over Earth's surface relied on physical measurements of sediment concentration convolved with stream flow data (Figure 3). For example, in 1964, Judson & Ritter used contemporary suspended sediment loads to infer the erosion rate of North America and specific river basins draining the continent, an effort updated and expanded by Summerfield & Hulton (1994) and Milliman & Syvitski (1992) and augmented today by the measurement of ^{10}Be in river sediments. Trimble (1977) pointed out the impact of modern land use practices on contemporary sediment yields and alluvial storage, demonstrating the importance of time and spatial scale in determining how much sediment moved and how much was stored (Figure 4). In many cases, measurement of ^{10}Be can avoid the pitfalls of human impact pointed out by Trimble because the nuclide's concentration represents landscape history over integrated at least millennia (Bierman & Steig 1996, Brown et al. 1995b).

Using a different approach, others have worked back in time using sediment volumes deposited in basins along with a variety of dating constraints to estimate



Figure 3 Early estimates of sediment flux from drainage basins relied on sampling suspended sediment over a range of flows and integrating results over time, a technique that provided sediment yield data for which extrapolation back in time was uncertain. Photograph circa 1960 of suspended sediment sampling from the H.J. Andrews Experimental Forest (Photo AAB-057 used with permission of H.J. Andrews Experimental Forest).

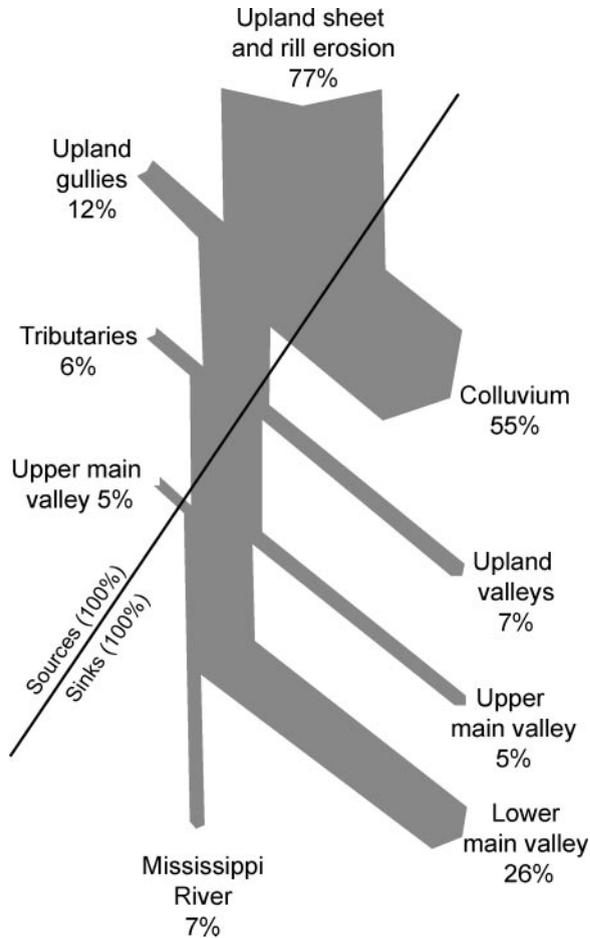


Figure 4 Sediment budget of a Mississippi River tributary, Coon Creek, based on data from 1938 to 1975. Diagram shows the percentage of sediment generated from different sources from within the basin and the percentage of sediment deposited in different sinks. Figure modified from Trimble (1983). The values were based on cross-sectional surveys, stratigraphic analysis, and historical records.

mass loss from the land over time. Some considered continents and ocean basins, thereby estimating the erosion rate of North America since rifting began 175 million years ago (Mathews 1975, Menard 1961), although doing so requires bold assumptions concerning the location of long-vanished drainage divides. Others, such as Schick & Lekach (1993), worked at more human time and spatial scales using a small dam (Figure 5) to capture, for 30 years, all sediment leaving a 0.6-km² basin in the Negev Desert. From these sediment yield data, Schick & Lekach



Figure 5 View upstream from the dam at Nahal Yael that trapped all sediment coming from the drainage basin until it was overtopped in the flood of 1997. Flat, alluviated surface in the foreground is sediment from the basin trapped by the dam.

inferred rates of basin erosion and thus sediment generation, presuming steady state, an assumption later tested by Clapp et al. (2000) using cosmogenic nuclides.

Workers have long attempted to understand the generation, movement, and storage of sediment along the hillslope-river continuum. For example, Dietrich & Dunne (1978) developed a sediment budget for the Rock Creek basin in the Oregon Coast Range based both on field mapping and physical sediment flux measurements. This budget explicitly considers fluxes of mass into and out of the system as well as the volume of sediment in storage, an approach revisited by Nichols (2002) with measurements of ^{10}Be in desert piedmont sediment. Using a stochastic model, Kelsey et al. (1987) estimated the residence time of sediment in different geomorphic elements along Redwood Creek in northern California. They, as well as Dietrich & Dunne (1978), concluded that most sediment delivered to the channel from hillslopes moved quickly ($<10^3$ years) through the river system, spending relatively little time in near-channel storage before making its way to the ocean. This finding supports the use of cosmogenic nuclides, measured in alluvial sediment, as a monitor of basin-scale erosion rates because it implies that most cosmic ray dosing occurs on hillslopes where sediment is generated and not during river transport.

Over the past few decades, geologists have expanded the variety of tools used to infer erosion rates beyond measuring suspended sediment load in streams in order to infer sediment generation rates. A variety of new erosion rate monitors have been developed and exploited, most prominently the analysis and modeling of in situ cosmogenic nuclides (Bierman et al. 2003, Gosse & Phillips 2001, Lal & Peters 1967), fission tracks (Brown et al. 1994), and U/He concentrations in apatite and zircon (Ehlers & Farley 2003, Reiners 2002). The latter two systems allow one to infer the rate at which rock moves through geotherms on its way to Earth's surface

and thus calculate long-term (million year) rates of rock unroofing (c.f., Brown et al. 1994, 2000). In the absence of tectonic removal of mass by faulting, such unroofing rates reflect long-term, time-integrated erosion of Earth's surface and represent a powerful tool for understanding the evolution of the planet over millions to tens of millions of years (Brown et al. 1994, Ehlers & Farley 2003). Combining these geochemical tools, imaging of erosion rates over time is now possible (Cockburn et al. 2000, Matmon et al. 2003a, Nott & Roberts 1996, Vance et al. 2003).

HOW COSMOGENIC NUCLIDES ARE USED TO QUANTIFY RATES OF EARTH SURFACE CHANGE

Cosmogenic nuclides are produced in the atmosphere and the solid Earth by the interaction of cosmic rays, primarily neutrons, with a variety of target atoms (Lal & Peters 1967). Since this review's concern is the production and transport of sediment, we consider only those nuclides produced in rock and soil. Because neutrons, which cause most nuclide production, are rapidly attenuated with depth (Figure 6), cosmogenic nuclides are most typically employed as monitors of near-surface processes, those occurring within several meters of Earth's surface. Thus, nuclide measurements integrate over a duration that scales with the rate at which a meter or two of rock or soil is eroded. For rapidly eroding landscapes, such as the Himalayas, integration times may be less than a millennium (Vance et al. 2003). For very stable landscapes, such as hyperarid Namibia or Antarctica, nuclide activities may integrate erosion over 10^5 to 10^6 years (Bierman & Caffee 2001, Nishiizumi et al. 1991).

Measuring nuclide concentration is now relatively straightforward, although time consuming. Sample processing typically involves separation of a mineral phase (usually quartz), purification of the element of interest (usually Be), and isotopic measurement by accelerator mass spectrometry (Bierman et al. 2003, Gosse & Phillips 2001). Data for most samples are precise at the several percent level, usually less than the natural geologic variance between samples. Other nuclides (^{36}Cl , ^3He) allow the method to be used for rocks not bearing quartz.

The heroic phase of sample measurement (Davis & Schaeffer 1955, Elmore & Phillips 1987) is past (Granger 2002); thus, geoscientists can now concentrate on getting the geology and nuclide interpretation right. Such interpretation is key because the laboratory work returns nothing more than an activity, an isotopic abundance per unit weight of material. Interpreting this activity is a classic inverse problem. One knows the final result but needs to ferret out the path that led the sample to its current activity level. Such sleuthing is typically handled by analytical or numerical models designed to represent (and inevitably simplify) the field situation from which the samples were collected (c.f., Lal 1991).

Indeed, interpreting the isotopic data is now the most significant challenge. In the early years of cosmogenic nuclide science, a single straightforward model was employed to interpret most data (Lal 1988). Such a model continues to work

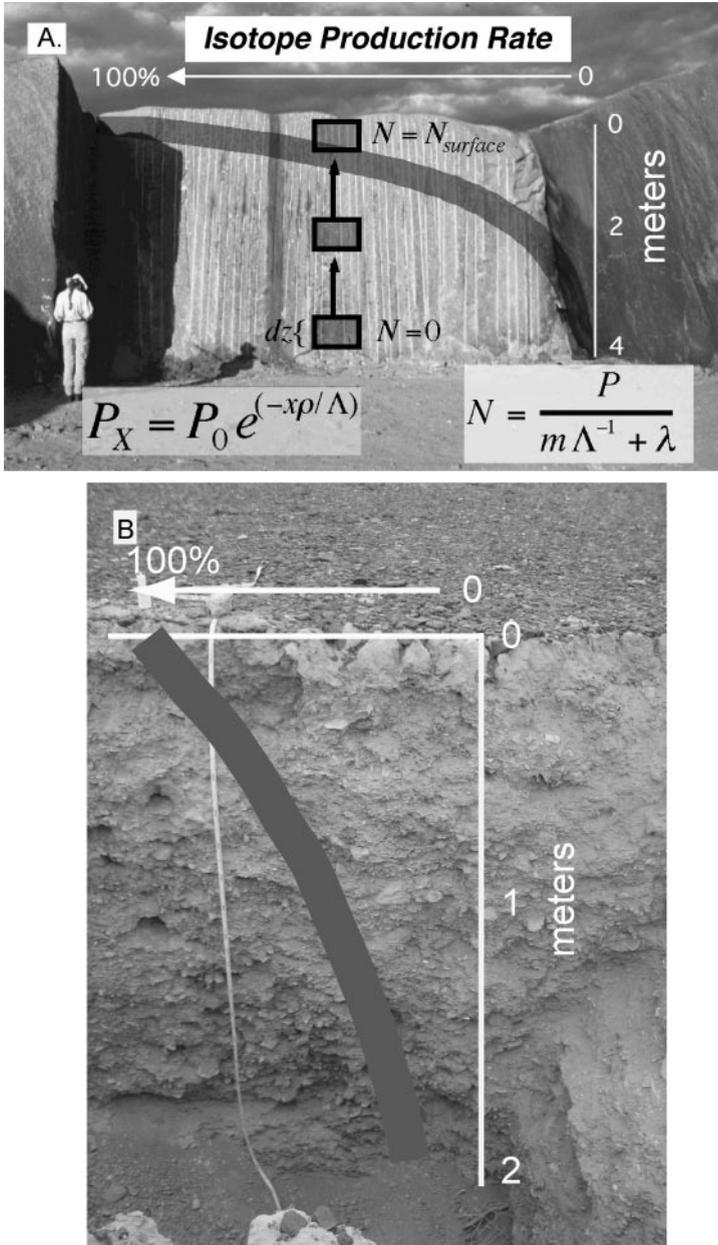


Figure 6 Cosmic ray neutrons, the primary producers of most cosmogenic nuclides including ^{10}Be , are attenuated rapidly below Earth's surface as a function of the mass penetrated. (A) Attenuation in rock ($\rho = 2.7 \text{ g cm}^{-3}$). (B) Attenuation in soil ($\rho = 1.5 \text{ g cm}^{-3}$).

well for simple geologic scenarios, including steady erosion of bedrock outcrops (Nishiizumi et al. 1986), the rapid exposure of well-preserved boulders on a glacial moraine (Briner et al. 2003), or the dating of recent lava flows (Zreda et al. 1993). The model considers the nuclide activity (N) of outcropping rock and has two variables, exposure time (t) and erosion rate (ε), as well as a number of constants, including a nuclide production rate (P), an attenuation length for neutrons (Λ), nuclide half life (λ), and rock or soil density (ρ). The background level (B) of the nuclide generated by processes other than cosmic-ray interaction is unimportant for ^{10}Be and ^{26}Al (Sharma & Middleton 1989) but may be significant for ^{21}Ne and ^{36}Cl (Bierman et al. 1995, Niedermann et al. 1993).

$$N = \frac{P}{(\rho\varepsilon\Lambda^{-1} + \lambda)}(1 - e^{-(\rho\varepsilon\Lambda^{-1} + \lambda)t}) + B \quad (1)$$

Interpretive models have changed over the past decade. Models now consider sediment generation on a basin scale (Bierman & Steig 1996, Brown et al. 1995b, Granger et al. 1996) as well as sediment transport (Bierman & Steig 1996, Nichols et al. 2002, Perg et al. 2003). Production during sediment accumulation has been considered (Clapp et al. 2001, Lal & Arnold 1985). The dating of sedimentary deposits has been accomplished with other models that consider isotope decay (Granger & Muzikar 2001) as well as the nuclide activity inherited by sediment once it leaves the hillslopes and enters river systems (Anderson et al. 1996, Repka et al. 1997). Others have modeled the effect of water and ice shielding outcrops as glaciers come and go and the sea level rises and falls (Bierman et al. 1999, Stone et al. 1996). Today, most geomorphic process studies develop or modify interpretive models needed to translate nuclide activities into geomorphically interesting and useful rates and dates.

Finally, extensive work has shown that the constants are not so constant. Production rates vary over time (Clapp & Bierman 1996, Masarik et al. 2001). Recent work (Dunai 2000) has challenged accepted correction schemes (Lal 1991) for elevation as a function of altitude and latitude. Muons have been shown to produce relatively small concentrations of nuclides both near the surface and at depth (Brown et al. 1995a). For most geomorphic process studies, where rates are unknown a priori and where even 20% to 30% uncertainties represent a major advance, the uncertainty introduced by these varying constants is unimportant. For dating studies (not considered in this review) such uncertainties are of much greater concern as one attempts to link cosmogenic dates to those generated by other means in order to decipher leads and lags of the climate system (Clark et al. 1995).

FOLLOWING SEDIMENT DOWNSTREAM

To illustrate how ^{10}Be data have influenced thinking about various landscapes and the flux of sediment across Earth's surface, we follow sediment grains from source to sink through the works of various authors (Figure 2). We begin on the

hillslopes, considering the generation of sediment from both bare rock outcrops and soil-mantled slopes. Once the sediment enters streams, it can be transported (and sampled to determine basin-scale sediment generation rates) or stored in terraces (which can be dated and/or used to imply paleo rates of sediment generation). Finally, the sediment encounters base level. Perhaps it is stored temporarily on beaches or perhaps it moves offshore to a final resting place deep under the ocean.

Outcrop Erosion

Nearly 50 years ago, Davis & Schaeffer (1955) first applied cosmogenic nuclides to geomorphology by measuring the ^{36}Cl content of a rock outcrop in Colorado in order to estimate how long the rock had been exposed. After purifying 20 g of Cl and decay counting, they detected ^{36}Cl and predicted the utility of cosmogenic nuclides as a geomorphic tool. After a 30-year hiatus, the development of accelerator mass spectrometry (Elmore & Phillips 1987) allowed a new generation of workers to take up where Davis & Schaeffer left off and quickly measure large numbers of milligram-size samples from a variety of outcrops around the world, beginning with a few samples from the Mojave Desert (Nishiizumi et al. 1986) and continuing to much larger studies (e.g., Bierman & Caffee 2002, 2001) containing dozens of samples from Africa and Australia (Figure 7).

Analysis of cosmogenic nuclides in outcrop samples can be used to estimate rates of rock erosion and sediment generation at temporal and spatial scales where no other techniques provide useful data. Although short-term, small-scale rock erosion rates have been estimated by measuring the weathering of tombstones (Judson 1968, Matthias 1967) and long-term, large-scale erosion rates can be inferred from U/He or fission track measurements (Brown et al. 1994, Reiners 2002), at the outcrop scale only cosmogenic nuclides currently allow geomorphologists to infer directly the rate at which now-eroded rock was shed. In this sense, cosmogenic nuclides give information about what is absent, exactly the inverse of how geologists typically work by measuring the accumulation of material in stratigraphic sections. Sampling of outcrops in different settings allows comparison of bedrock lowering rates between different lithologies, climates, and landscape positions, thus providing quantitative constraints on the rate of sediment generation from bare rock surfaces (Figure 8A). For example, bare rock in humid regions of Australia appears to be eroding more quickly than bare rock in arid regions of Australia (Figure 8B).

Exposed rock erodes at significantly different rates in different localities. Cosmogenic data (^{10}Be , ^{21}Ne , and ^{26}Al) indicate that some unglaciated sandstone bedrock surfaces in Antarctica have eroded only centimeters to decimeters over the past several million years, an extraordinary stability matched nowhere else in the world (Brown et al. 1991, Ivy-Ochs et al. 1995, Nishiizumi et al. 1991). Rates of weathering almost as low have been measured in granitic samples from arid south central Australia (30 cm/million years) (Bierman & Caffee 2002) in gneissic and quartz samples from the hyperarid Namibian Desert (40 to 90 cm/million years)

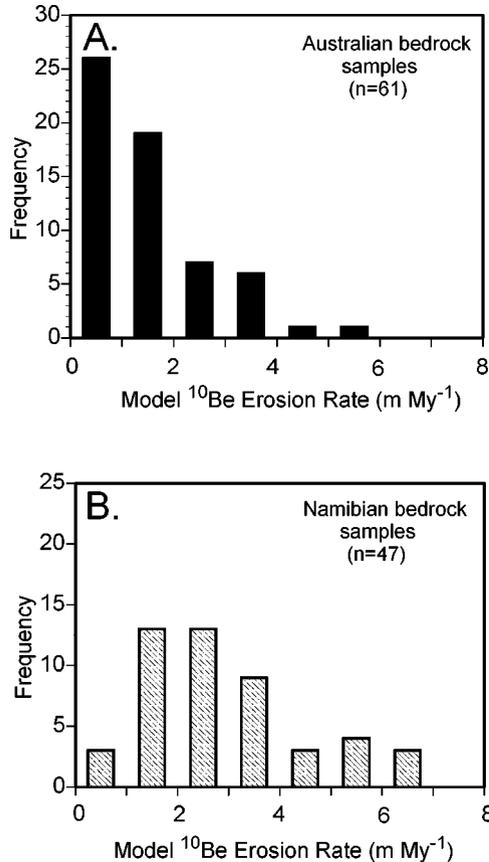


Figure 7 Histograms of outcrop erosion rates. (A) Granites from the Eyre Peninsula of south-central Australia (from Bierman & Caffee 2002, used by permission of the Geological Society of America). (B) Gneissic rocks, quartz veins, and sandstone from Namibia (from Bierman et al. 2003, used by permission from the Mineralogical Society of America).

(Bierman & Caffee 2001, Cockburn et al. 1999), and in alluvial fan samples from the hyperarid Atacama desert (Nishiizumi et al. 1998). Yet, samples of crystalline rocks cropping out in similarly dry areas ($\text{MAP} \leq 130 \text{ mm}$) in the Mojave, Great Basin, and Negev deserts (Clapp et al. 2002, 2000, Nishiizumi et al. 1986) suggest erosion rates several to many times higher; rates that are similar to those measured in samples of gneiss, sandstone, and quartz outcropping along the ridge crest of the Great Smoky Mountains of Tennessee where annual rainfall totals exceed 1.5 m (Matmon et al. 2003c). Thus, it appears that a paucity of water likely accounts only in part for the extreme stability of polar, Namibian, Australian, and Atacama rocks.

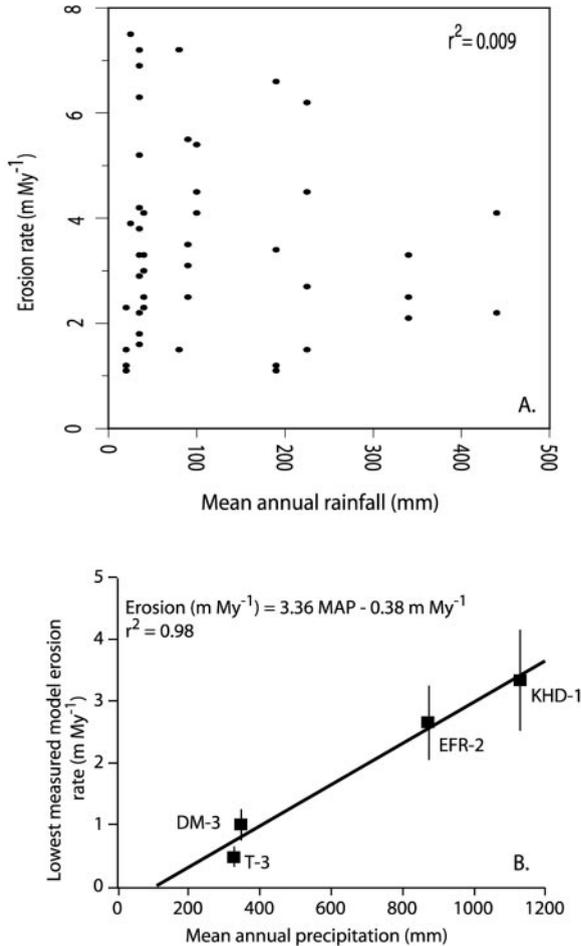


Figure 8 Relation between model erosion rates (¹⁰Be-based) and mean annual precipitation. (A) The erosion rates of quartz-rich outcrops in Namibia (gneiss, sandstone, quartzite, granite) have no relation to mean annual precipitation (modified from Bierman & Caffee 2001). (B) Minimum model erosion rate of granitic outcrops in Australia rise with increasing mean annual precipitation (from Bierman & Caffee 2002, used by permission of the Geological Society of America).

Rock strength, in particular the spacing of joints and fractures, is likely an important control on the weathering rate of exposed rock (Twidale 1982) as are changes in base level occasioned by tectonics or trunk stream incision (Riebe et al. 2000). Indeed, ¹⁰Be measurements by Riebe et al. (2000, 2001b) in sediment of numerous drainage basins in the California Sierra Nevada indicates that basin-scale erosion rates are much less sensitive to climate (Figure 9) than to changes

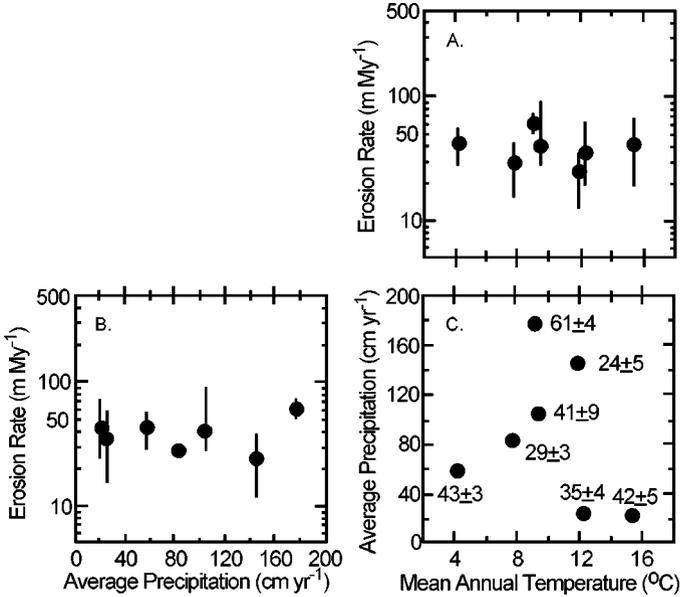


Figure 9 Climate has no discernible control on basin-scale erosion rates in the Sierra Nevada. (A) Erosion rate has no relation to mean annual temperature. (B) Erosion rate has no relation to mean annual precipitation. (C) Erosion rates plotted as a function of each site's mean annual temperature and precipitation. Figure modified from Riebe et al. (2001b) and used by permission from the Geological Society of America.

in local base level. Thus, it seems likely that the very high nuclide activities (and consequently the low model erosion rates) measured in some outcrops result from the combination of base-level stability, arid microclimate, and the lack of jointing.

Samples from adjacent and otherwise similar-looking outcrops may have similar or significantly different nuclide activities (Bierman & Caffee 2002, 2001; Cockburn et al. 1999; Small et al. 1997). Such differences are likely related to violation of assumptions inherent to the interpretive model, that is, steady and uniform erosion of rock at a scale smaller than the attenuation length of neutrons producing the nuclide of interest. Many outcrops shed mass in centimeter-to meter-thick sheets, episodically exposing less-dosed rock below (Figure 10). In such a situation, the actual erosion rate of the outcrop as a whole lies between the low estimates generated from samples on sheets about to fail and the high estimates generated from surfaces from which sheets have just peeled off; the mean of measurements from numerous outcrops provides a reasonable estimate for a geomorphic surface (Small et al. 1997). A lower-than-expected ratio of ²⁶Al to ¹⁰Be can also be used as an indicator that a site sampled today was once covered by a significant thickness of now-vanished rock (Bierman et al. 1999, Cockburn et al. 1999, Lal 1991); however, lowered ratios can also result from incomplete

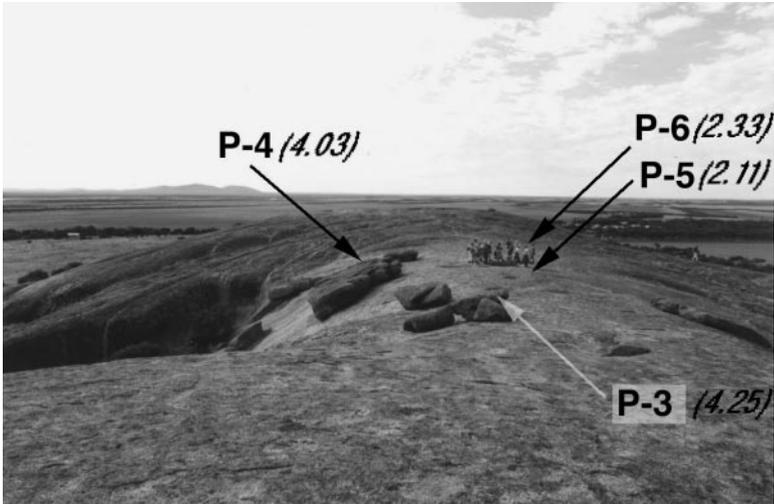


Figure 10 Top surface of Pildappa Rock, a granitic inselberg on the Eyre Peninsula of south central Australia. Samples from tops of detached sheets have nuclide activities ($\times 10^6$ atoms/g, shown in parentheses) about two times higher than activities in adjacent rock surfaces (figure modified from Bierman & Caffee 2002).

recovery of Al during sample processing, an artifact that typically manifests itself in similar ^{10}Be but dissimilar ^{26}Al activities between adjacent samples (Bierman & Caffee 2002).

Sampling of previously glaciated outcrops usually reveals the age at which ice last left the area and rock was exposed, unless erosion has removed several meters of rock since deglaciation in which case an erosion model for interpreting nuclide activity could be appropriate. However, erosion of rock surfaces by glacial ice may be ineffective in some areas (Bierman et al. 1999, Colgan et al. 2002, Stroeven et al. 2002), leaving rock surfaces with a significant inheritance of nuclides from prior interglacial periods of exposure if less than a meter or two of rock were removed (Figure 11). This inheritance is likely the result of overriding by nonerosive, cold-based ice frozen to its bed. Thus, the magnitude of inheritance is dependent both on rock strength and the vertical and lateral distribution of thermal conditions below the now-vanished glacier (Colgan et al. 2002). In cases where nuclide activity clearly exceeds that predicted by deglaciation age data, ^{10}Be and/or ^{26}Al activity can be interpreted as a maximum limiting, time-integrated erosion rate. Such rate estimates include ~ 1.6 m million years $^{-1}$ for gneiss under the Fennoscandian Ice Sheet (Stroeven et al. 2002), 0.9 m million years $^{-1}$ for quartzite under the margin of the Laurentide Ice Sheet (Colgan et al. 2002), and 0.5 m million years $^{-1}$ for gneiss overrun by ice on the highlands of Baffin Island (Bierman et al. 1999).

In contrast, warm-based ice or glacial fluvial activity is sufficiently effective at eroding rock that few, if any, nuclides remain in newly exposed outcrops when

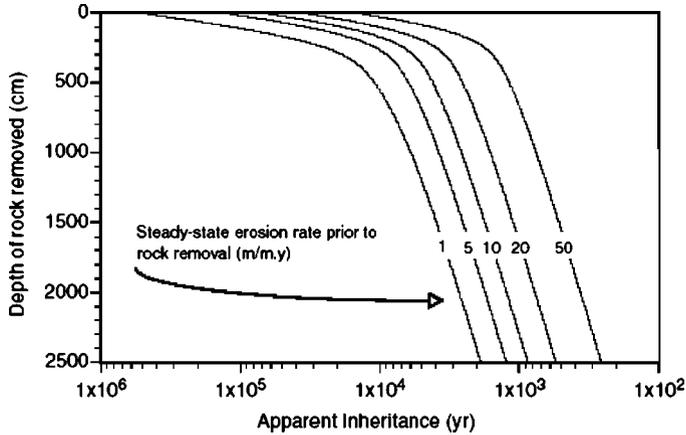


Figure 11 Apparent inheritance (in ^{10}Be years) resulting from instantaneous glacial erosion of rock from a landscape that was in erosional steady state. Each line represents a different erosion rate (in m million years $^{-1}$). Increase in line slope reflects change from predominately neutron to predominately muon production at a depth of ~ 3 m. Calculations were made for lat 43.5°N and 250 m above sea level. From Colgan et al. (2002), used by permission of the Geological Society of America.

the ice melts away. Measuring ^{10}Be in glaciated rock surfaces of known age in New Jersey, Larsen (1996) showed that Latest Pleistocene glacial ice removed enough rock to carry away most if not all nuclides produced prior to glaciation and subsequent re-exposure. Stroeven et al. (2002) reported a similar result from a meltwater channel in Fennoscandia. Using exposures in a Baffin Island fiord bottom, Davis et al. (1999) demonstrated that in most landscape positions, even a short-lived neoglacal advance was sufficient to remove most nuclides formed during prior periods of cosmic-ray exposure. Using the few samples that did contain excess nuclides, they calculated rates of glacial erosion that ranged from 0.1 to ≥ 0.16 mm year $^{-1}$, rates consistent with those calculated by others using the same approach (Briner & Swanson 1998, Colgan et al. 2002). Cosmogenic nuclide data are not yet sufficiently numerous to settle the arguments about the relative efficacy of glacial versus nonglacial erosion put forth by Harbor & Warburton (1993).

Hillslopes

Hillslopes are dynamic, complex geomorphic environments where sediment is both generated by the breakdown of rock and transported by a variety of gravity-driven processes. Studies using ^{10}Be , in combination with geomorphically based interpretive models, have begun to quantify rates of bedrock-to-soil conversion as well as the flux of sediment down slope, both long-standing geomorphic questions. Below, we consider a series of papers that trace sediment as it is produced by bedrock weathering and then remobilized, transported, and deposited on

soil-mantled hillslopes ranging from steep mountain basins to gently dipping desert piedmonts.

SEDIMENT GENERATION ON HILLSLOPES The rate and distribution of hillslope processes appear to depend on many variables, including climate (Langbein & Schumm 1958), gradient (Montgomery & Brandon 2002), vegetation (Rey 2003), and animal activity (Gabet et al. 2003); thus, it is not surprising that hillslopes in different environments have distinctive characteristics. In areas where rates of sediment production exceed transport capacity, soil mantles hillslopes. Conversely, in areas where rates of sediment transport exceed rates of regolith production, bare rock slopes dominate. Both types of slopes are amenable to analysis with cosmogenic nuclides.

Since the late 1800s, geomorphologists have assumed that the rate at which soil is generated by the weathering and erosion of bedrock declines with increasing soil thickness (Gilbert 1877); however, because soil production occurs so slowly, this assumption remained untested until recently. In 1997, using ^{10}Be produced in rock underlying the soil mantle, Heimsath et al. quantified soil generation rates under the grassed and forested slopes of the Tennessee Valley in Marin, California. They determined that soil production and thus subsoil bedrock erosion there were indeed fastest under a thin soil cover and that the rate of soil production decreased under increasingly thick soil mantles (Heimsath et al. 1997, 1999). Applying this same approach to the metasedimentary rocks of the Oregon Coast Range (Heimsath et al. 2001) and the granites of southeastern Australia (Heimsath et al. 2000) yielded similar results (Figure 12). In each case, soil production rates were greatest under shallow soil cover and were less under deep soil cover and on bare rock surfaces.

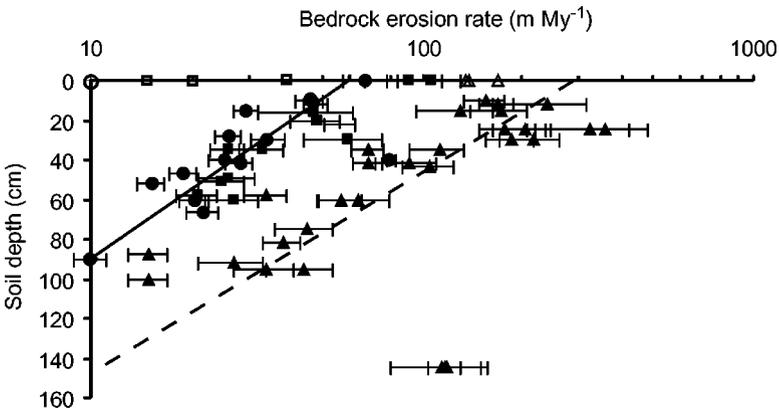


Figure 12 Compilation of soil production rates versus soil depth showing that bedrock erosion rates decrease as soil cover depth increases. Exposed outcrop samples are shown as open symbols and soil production rates are shown as filled symbols for southeastern Australia (*circles*); for Tennessee Valley, California (*squares*); and for Sullivan Creek, Oregon (*triangles*). Modified from Heimsath et al. (1997, 2000, 2001).

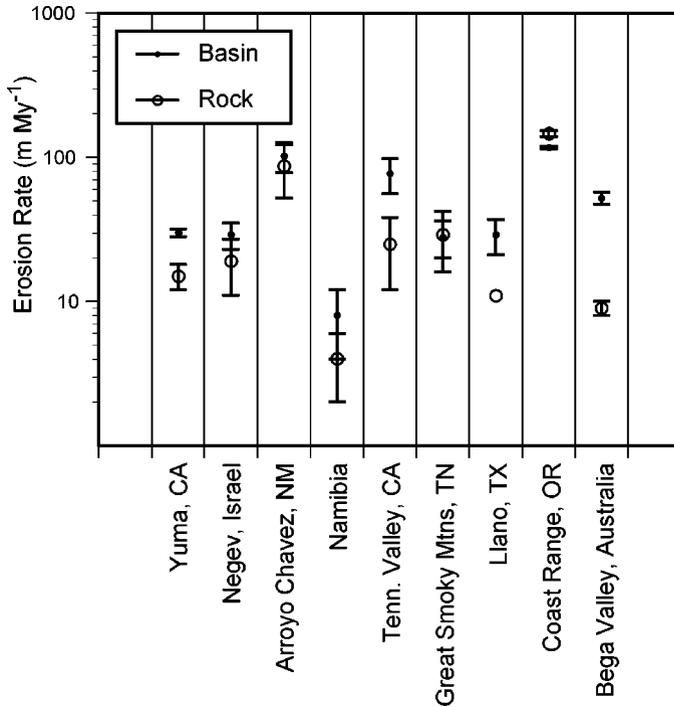


Figure 13 Comparison of cosmogenically determined erosion rates on outcrops (rock) and in sediments (basin) from same locales. Bar indicates standard deviation of erosion rates. Outcrop samples shown with open circles.

Numerous cosmogenic data now support the common-sense conclusion that bare-rock outcrops are by their nature erosion-resistant features (Bierman 1994); they stand proud of the landscape around them allowing water to drain and preventing the accumulation of soil (Twidale 1982). In all places where both outcrop and soil samples have been analyzed, soil has lower activities of ^{10}Be (Figure 12), implying that sediment generation rates are higher under soil cover than on bare rock surfaces. Other studies find or infer that sediment generation is much slower on outcropping bedrock than in drainage basins as a whole, where at least some, and often most, slopes are soil-mantled (Figure 13).

In arid regions, bedrock exposures more stable than the drainage basin in which they crop out have been noted at Arroyo Chavez, New Mexico (Clapp et al. 2001); Yuma Wash, Arizona (Clapp et al. 2002); in the Negev Desert, Israel (Clapp et al. 2000); in northeastern California (Granger et al. 2001b); and in Namibia (Bierman & Caffee 2001). In more humid regions, rock cropping out in the Llano Uplift, Texas (Bierman 1993, Bierman et al. 2001a); the Tennessee Valley, California (Heimsath et al. 1997); and the Bega Valley, Australia (Heimsath et al. 2000)

erodes more slowly than nearby drainage basins as a whole. Although the number of sites where both rock outcrops and fluvial sediment have been analyzed is small, it is striking that the Coast Range, Oregon (Heimsath et al. 2001), and the Great Smoky Mountains (Matmon et al. 2003a), landscapes that some believe to approach steady state (Matmon et al. 2003a, Reneau & Dietrich 1991), are two places so far where bedrock and sediment erosion rates agree well.

Considering these observations along with the Heimsath et al. analysis of ^{10}Be in soil-mantled bedrock samples (Figure 12), it appears that much bedrock-to-soil conversion occurs under shallow soil cover, perhaps no more than a meter thick. At Heimsath's sites, deeper soils reduce subsoil rock weathering rates below those measured on bare rock outcrops. However, in an alpine environment, Small et al. (1999) measured nuclide activity in regolith and in bedrock buried by regolith. They found that nearly a meter of regolith increased bedrock erosion by a factor of two over rates measured on exposed outcrops (Small et al. 1997). Granger et al. (2001b) used ^{10}Be measurements on bedrock, residual boulders, and catchment sediments to suggest the importance of hillslope armoring in slowing rates of regolith erosion. Clearly, additional studies in different environments are needed to clarify the effect of regolith and soil cover on rock weathering rates, but in most environments it appears that shallow soil and regolith cover increase rates of bedrock weathering.

SEDIMENT TRANSPORT ON HILLSLOPES Sediment is transported down hillslopes by a variety of processes, which at the right spatial and temporal scale are amenable to investigation with cosmogenic nuclides. Slow, diffuse movement of sediment down hillslopes, termed creep, plays an important role in sediment movement in areas with sufficient precipitation and steep slopes. Some creep is catalyzed by distributed biologic activity, including tree throw and burrowing animals (worms, gophers, and rodents); other creep is driven by freeze-thaw cycles, soil deformation, and soil expansion/contraction from wetting/drying. Sediment is also transported down slope by diffuse overland flow and flow concentrated in rills and channels. Lastly, sediment is transported episodically down hillslopes by both shallow and deep-seated landslides.

Creep is an episodic and nonuniform process over short-temporal and small spatial scales. However, over longer and larger scales, creep can be modeled as a uniform process, thus allowing Heimsath et al. (2002) to use ^{10}Be , in concert with single-grain optical dating, to quantify the creep-driven sediment rates and fluxes down a hillslope in the Bega Valley, southeastern Australia. They determined that creep rates were on the order of meters to a few tens of meters per thousand years and that the process involves repeated movement of grains from depth to the surface before reburial presumably by tree throw and burrowing wombats.

In contrast to vegetated, steep hillslopes are the lightly vegetated, low-gradient, alluvial piedmonts that extend from desert uplands. On such piedmonts, creep is not significant; rather, sediment moves mostly during episodic flows in ephemeral channels. On the Iron Mountain piedmont in the Mojave Desert, small

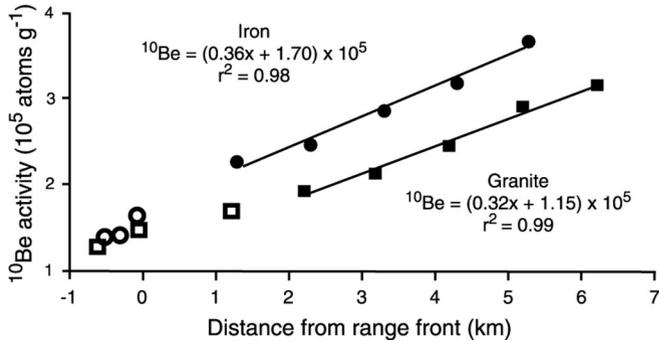


Figure 14 Increase in normalized ^{10}Be as a function of distance down Iron Mountain (*circles*) and Granite Mountain (*squares*) piedmonts in the Mojave Desert (Nichols et al. 2002). Open symbols represent ^{10}Be activity of sediment issuing from source basins, closed symbols represent amalgamated sediment sampled at 1-km intervals from mountain front. Modified from Nichols et al. (2002).

(meter-wide), shallow (10–20 cm) channels migrate freely across the many kilometers-wide piedmont and transport sand and granule-sized sediment over 6 km from mountain source basins to a lowland dry lake (Nichols et al. 2002). Amalgamating sediment collected from 21 locations along 4-km-long transects spaced at 1-km intervals from the mountain front, Nichols et al. (2002) found a regular increase in ^{10}Be activity as sediment moved down piedmont (Figure 14). Using a nuclide and mass balance model, they determined that sediment moves, on average, decimeters to a meter per year. Separate samples collected from the channel beds and from interfluves had indistinguishable ^{10}Be activities, suggesting that the ephemeral channels migrate across and rework the entire piedmont in less than 1000 years. Pebble tracing (Persico et al. 2002) indicates that sediment moves episodically and that particles may move many meters in single events.

Mass wasting, including debris flows and landslides, moves sediment rapidly down slope, scouring steep, proximal channels and depositing material on lower gradient parts of the landscape (Dietrich & Dunne 1978). With the exception of attempts to date large landslides (Ballantyne et al. 1998, Nichols et al. 2000) and the use of otherwise well-dated slides to calculate integrated nuclide production rates (Kubik et al. 1998), cosmogenic nuclides have not been used to understand landslide processes directly. Brown et al. (1995b, 1998) did attribute grain-size-specific differences in nuclide activity in Puerto Rico rivers to landslide delivery of large, lightly dosed clasts directly to stream channels. They suggested that finer material was brought to the channel by more continuous, near-surface creep processes and are thus more highly dosed than coarse, landslide-derived clasts.

Landslide activity in a drainage basin can affect nuclide activity in fluvial sediment. Although shallow slides usually remobilize already-dosed material,

deep-seated mass movements tap a reservoir of sediment and rock from meters below the surface that contains little, if any, ^{10}Be . Because large, deep landslides are an episodic process, the rate of which varies over time, pulses of relatively low-activity, landslide-derived sediment should move down channel in waves (Benda 1990, Sutherland et al. 2002). Thus, on human timescales, nuclide activity in fluvial sediment from landslide-prone terrains probably varies over time.

In steep human-disturbed terrains, where erosion is often accelerated, analysis of ^{10}Be can place useful constraints on presettlement sediment generation rates and the depth of postsettlement erosion. For example, Brown et al. (1998) measured ^{10}Be in a variety of grain sizes to quantify human influence on the rate and style of sediment generation in the agriculturally impacted Cayaguás River basin, Puerto Rico. Data, modeling, and comparison to the unimpacted Icacos River basin suggest that accelerated erosion, triggered by land use changes, caused the ^{10}Be -based model to overestimate sediment generation rates in the impacted basin by only a factor of two (Figure 15), supporting prior assertions that ^{10}Be activity in sediment is relatively insensitive to present-day land use (Bierman & Steig 1996, Brown et al. 1995b, Granger et al. 1996).

In the Cayaguás River basin, the ^{10}Be estimate of sediment generation remains an order of magnitude lower than the present-day sediment yield, allowing definitive quantification of disturbance-related impact. Nuclide activity in fine-grain material from the impacted basin is half that of similar-sized sediment from the unimpacted basin. Considering the depth-production relationship for ^{10}Be in soils,

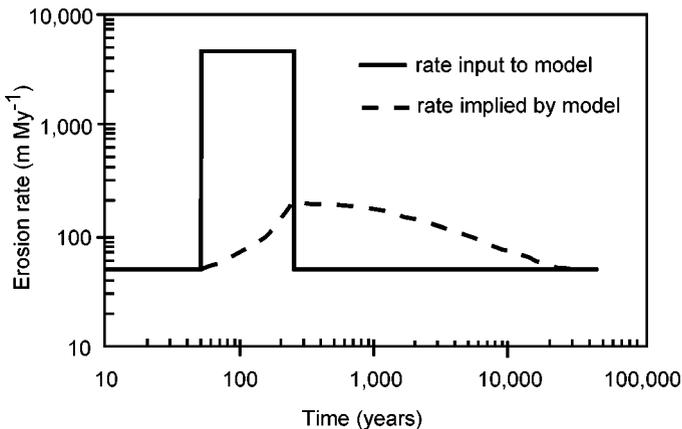


Figure 15 Long-term average erosion rates based on measured concentration of ^{10}Be in sediment are not sensitive to short-term episodes of accelerated erosion. For example, a 1000-fold increase in erosion rate (*solid line*) lasting for 200 years results in only a 4-fold apparent increase in erosion rate as inferred from ^{10}Be concentration (*dashed line*). Figure modified from Brown et al. (1998) and used by permission.

this finding suggests that human impact has triggered the loss of ~50 cm of soil that includes highly dosed, fine-grain material. Coarse grain material from both basins has similar ^{10}Be activity, suggesting it is similarly derived from deep landslides.

SEDIMENT DEPOSITION ON AND BELOW HILLSLOPES The movement of sediment down slope is often punctuated by varying lengths of time during which grains are immobile and, depending on the depth of burial, are dosed to varying degrees by cosmic radiation. Some sediment may be effectively removed from the transport regime if it is buried below the active depth of sediment transport (Lekach & Schick 1995); buried deeply enough, the sediment is also shielded from most cosmic-ray dosing (Granger & Smith 2000) and nuclide activities diminish by radioactive decay. After a change in climate or tectonic regime, such buried sediment may again be reintroduced into the transport system, a common occurrence in arroyos of the American southwest (Bierman et al. 2001b) or in areas where drainage captures have occurred (Matmon et al. 1999).

Until recently, sediment deposition rates were qualitatively determined using soil development indices or by dating incorporated organic or volcanic material, a rare occurrence in many environments. However, measuring ^{10}Be in soil and sediment depth profiles and interpreting these data using simplifying models of cosmic-ray dosing over time and depth provides unique insights into sediment deposition dynamics and rates on and below hillslopes. Using such tools, one can estimate rates of sediment deposition and the duration of depositional hiatuses for many deposits containing quartz-bearing sediment. Such an approach was first suggested by Lal & Arnold (1985). The theoretical framework was established by Phillips et al. (1998) and relevant data were collected and interpreted by Clapp et al. (2001) and Nichols et al. (2002). A similar approach, used to date river terrace sediment (Anderson et al. 1996), is considered in the next section of this review.

Modeling to describe nuclide activities resulting from sediment deposition considers nuclide production as a function of depth and requires that the ^{10}Be activity in deposited sediment is similar over time, an assumption confirmed for the Pajarito Plateau, New Mexico (Phillips et al. 1998). After deposition, the sediment is continuously exposed to cosmic rays and thus additional ^{10}Be is produced, albeit at decreasing rates with depth, as newly deposited material shields material deposited earlier. Finally, at a depth of many meters, radioactive decay outpaces production and nuclide activity begins to decrease. Granger and coworkers (Granger et al. 1997, 2001a; Granger & Muzikar 2001; Granger & Smith 2000; Partridge et al. 2003) have exploited this phenomenon to generate burial ages from deeply buried sediment. Burial ages have been used to quantify river incision rates, river capture events, cave histories, and the age of hominid fossils. Extrapolation of measured ^{10}Be and ^{26}Al activity in deeply buried sediment allows estimation of nuclide concentration at deposition, a proxy for basin-scale erosion rates in the past, geomorphic data not attainable in any other fashion (Granger et al. 1997).

^{10}Be production after deposition results in distinctive depth profiles (Figure 16). Depending on the rate of deposition, the curve will either be steep (rapid deposition,

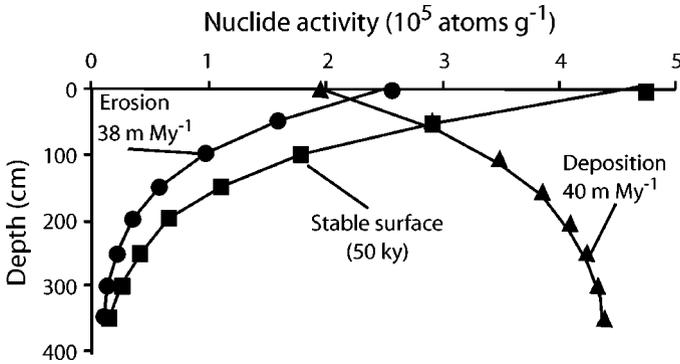


Figure 16 Calculated ^{10}Be activity depth profiles for a stable surface after 50,000 years of exposure (*squares*), an erosional surface (*circles*), and a depositional surface (*triangles*). Stable and eroding surfaces have ^{10}Be activities that decrease with depth, whereas depositional surfaces have ^{10}Be activities that increase with depth. Figure from Nichols et al. (2002) and used with permission from Elsevier.

little time for additional production during burial) or shallow (slow deposition, ample time for additional production as sediment at depth is buried). The first relevant field data are presented in Clapp et al. (2001) from a $\sim 3.5\text{-m}$ -thick alluvial fill in Arroyo Chavez, New Mexico. These data suggest a steady filling of the basin at $280\text{ mm kiloyear}^{-1}$, a rate consistent with a change to increased sediment yield at the Pleistocene/Holocene climate transition $\sim 13,000$ years ago (Bull 1991, Bull & Schick 1979, Clapp et al. 2001) (Figure 17).

Two soil pits on the Iron Mountain piedmont in the Mojave Desert also have increasing ^{10}Be activities with depth (Figure 17) (Nichols et al. 2002). Here, the top 30 cm of soil had uniform and lower ^{10}Be activities than material below. This step in activity represents a 10 kiloyear hiatus in sediment deposition as sediment in transport moves over the stationary, more deeply buried, but still continually dosed sediment. The uniform nuclide activity in the uppermost 30 cm indicates that the material is well mixed, in this case by the activity of shallow, migrating channels. ^{10}Be activity in sediment on the Iron Mountain piedmont increases more rapidly with depth than ^{10}Be activity in sediment from Arroyo Chavez; thus, interpreted long-term deposition rates are much slower at Iron Mountain, 18 and 40 m million years $^{-1}$, than at Arroyo Chavez (Figure 17).

The approach of Anderson et al. (1996) and Repka et al. (1997), developed for dating river terraces, is closely related to the examples given above. Indeed, it is the special case where sediment is deposited rapidly and then deposition ceases allowing ^{10}Be to build in steadily through the deposit with a deposition rate of zero. By taking samples from different depths in a stable alluvial profile, one can both estimate the age of the profile and estimate the nuclide activity inherited at deposition. The inherited component reflects the rate at which the drainage basin

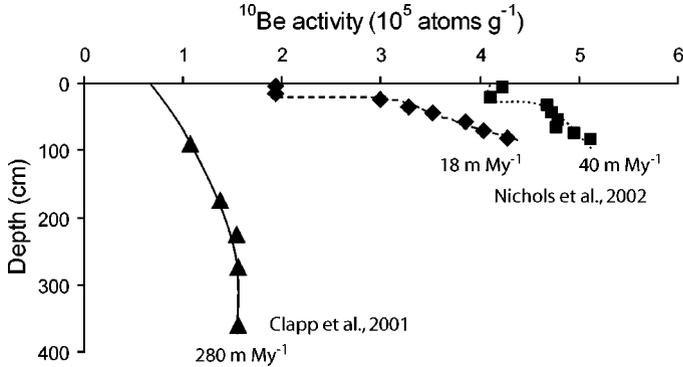


Figure 17 Increasing ^{10}Be activity at depth for aggrading surfaces. Triangles represent rapidly depositing basin fill (280 m million years⁻¹) of Arroyo Chavez, New Mexico (data from Clapp et al. 2001). Diamonds (18 m million years⁻¹) and squares (40 m million years⁻¹) represent slowly aggrading desert piedmont surface at the Iron Mountains, Mojave Desert, California (data from Nichols et al. 2002).

is eroding and thus carries additional, geomorphically useful information. Other applications of this approach have followed, including Phillips et al. (1998) and Schildgen et al. (2002), both of which consider partial shielding by overlying colluvium deposited at a later time.

^{10}Be In River Sediments

Rivers are integrators, carrying sediment derived from the outcrops, soil-mantled hillslopes, and incised bedrock channels of headwater basins. Early on, Lal & Arnold (1985) suggested how in situ-produced ^{10}Be could become a useful tool for tracing and dating both exposed and buried sediment. Work in the nearly two decades since has elaborated upon their ideas.

BASINS SCALE RATES OF SEDIMENT GENERATION In the early 1990s, several groups simultaneously began measuring ^{10}Be in quartz extracted from river sediments and thinking about how to interpret these data in terms of geomorphic process rates (Bierman & Steig 1996, Brown et al. 1995b, Granger et al. 1996). The initial goal of all three groups was the same, demonstrating that nuclide activity in river-borne quartz could be used to quantify the rate at which sediment was generated on a basin scale. That goal has been accomplished (Bierman et al. 2001a, Clapp et al. 2002, Matmon et al. 2003a, Schaller et al. 2001, Vance et al. 2003). Measurements of ^{10}Be in sediment are now commonly used to estimate basin-scale rates of erosion equivalent to rates of sediment generation presuming that loss by dissolution is inconsequential, although this can be accounted for with a few measurements of flow and solute concentrations in rivers. If the basin is in

steady state, (i.e., there is no long-term deposition and thus no change in sediment storage) and if sufficient time is considered to include extreme events, then sediment generation rates and sediment yields should be in balance.

Inferring rates of sediment generation from nuclide activities measured in fluvial sediment requires an interpretive model. The model (Brown et al. 1995b, Bierman & Steig 1996, Granger et al. 1996) is derived similarly to that used for interpreting nuclide activities at the outcrop scale (Lal 1991) and results in a similar analytical solution. Both models presume an isotopic equilibrium in which nuclide inventories have reached a steady state within the basin (for sediments) or within the underlying column of rock (for outcrops). Such an equilibrium is likely never strictly achieved in many basins, but changes in sediment generation rates over time (perhaps driven by climatic and/or tectonic forcing) are well buffered by the soil mantle where grains may reside for millennia before entering a stream or river (Bierman & Steig 1996, Brown et al. 1998). The exception here is glaciation because glacial ice shields the landscape from cosmic rays. Fluvial sediment from glaciated landscapes has not been sampled so far, although some samples reported by Duncan et al. (2001), Schaller et al. (2001), and Vance et al. (2003) are from partly glaciated basins. Selective dissolution of minerals and resultant quartz enrichment appear not to be significant issues in most environments (Riebe et al. 2001a).

Quartz is exposed at various elevations in watersheds. Because nuclide production rates vary with elevation, quantifying basin hypsometry and the distribution of quartz in the basin is required to accurately interpret ^{10}Be concentrations. Because the production-elevation function is nonlinear, basins with elevation ranges exceeding several hundred meters require calculation of an effective production rate derived from convolution of basin hypsometry and the production-elevation function (Bierman & Steig 1996). For basins with less relief, knowing the spatially weighted average elevation suffices (Hewawasam et al. 2003).

Nuclide activity has been measured in sediment collected from drainage basins of widely varying area. Early work focused on small basins. For example, Granger et al. (1996) sampled sediment from arid-region ephemeral drainages ($<1\text{ km}^2$) feeding small, Nevada alluvial fans, the volume of which could be calculated and the age of which was known, thereby allowing calculation of time-integrated sediment accumulation rates. Sediment generation rates, calculated using ^{10}Be activity in fluvial sediments, matched geologic rates of sediment accumulation, an observation used by Granger et al. to argue that ^{10}Be in sediment is an accurate erosion-rate monitor.

Cosmogenic nuclide-based estimates for basin-scale erosion rates have been used to test for relationships between landscape-scale characteristics and erosion rates. Granger et al. (1996) used nuclide data from nine basins to suggest that steeper basins eroded more quickly than less steep basins (Figure 18A), a finding repeated (albeit with less robust correlation) at a much larger scale (1 to 346 km^2) by Matmon et al. (2003c) in the Great Smoky Mountains (Figure 18B). Schaller et al. (2001) obtained a similar relation in Europe (Figure 18C), as did Vance et al.

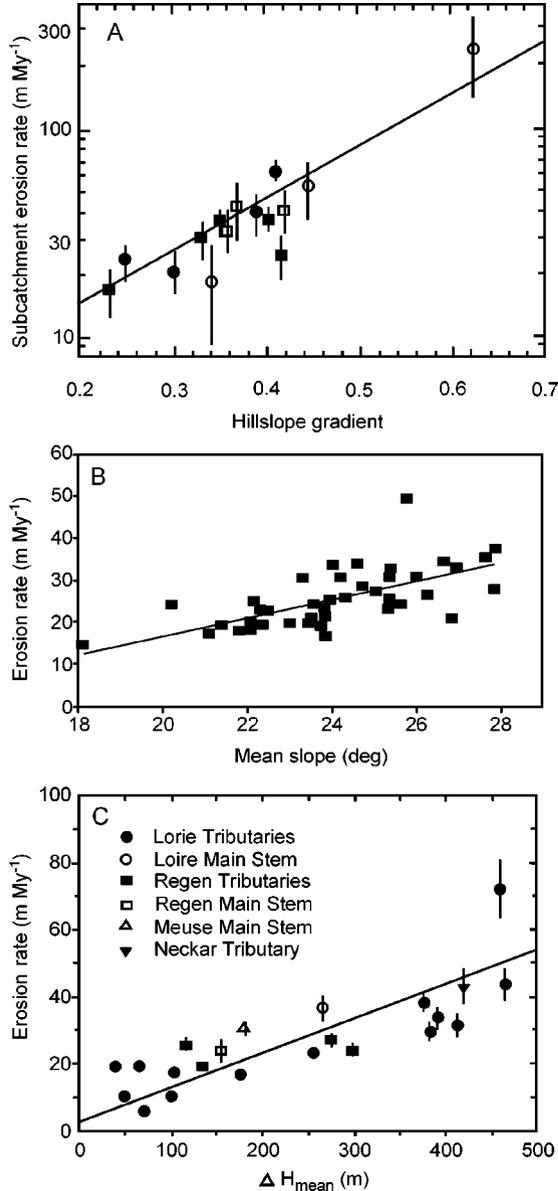


Figure 18 Graphs showing the relationship between slope or relief and basin-wide erosion. (A) Data from Fort Sage Mountains, California (figure modified from Granger et al. 1996). Solid symbols are results from samples ($n = 9$), open symbols are calculated from differences between sampled catchments. (B) Data from the Great Smoky Mountains in North Carolina and Tennessee, USA (figure modified from Matmon et al. 2003c). (C) Data from Western Europe (figure modified from Schaller et al. 2001).

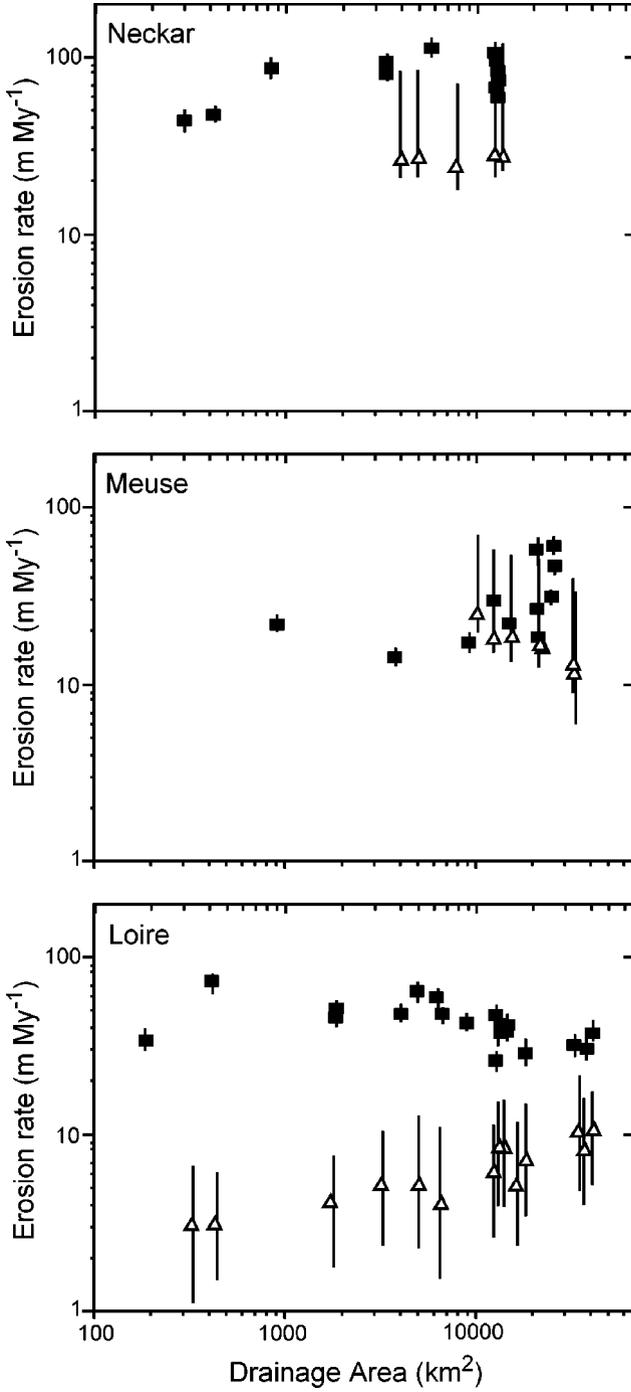
(2003) in the Himalayas, by comparing a measure of basin relief with erosion rates calculated from ^{10}Be activity in river sediment.

Riebe et al. (2000) performed a similar experiment using unglaciated basins in the Sierra Nevada, but generated very different results. They found that slope was positively correlated with erosion rates only in basins where local base level had recently dropped either by faulting or incision. In basins where base level was steady or changing only slowly, slope had no consistent relation to erosion rate. Both Riebe et al. (2000) and Matmon et al. (2003c) conclude that cosmogenic nuclide data support Hack's assertion that landscapes in dynamic equilibrium are adjusted to rock strength such that slope, rather than erosion rate, varies with rock strength. Riebe et al. (2001b) found that climate (precipitation and temperature) had at most a weak control on erosion rates (Figure 9) and that rates of chemical weathering scaled directly with rates of physical weathering (Riebe et al. 2001c).

A number of studies have now compared cosmogenic estimates of sediment generation with contemporary sediment yield as measured primarily using suspended sediment data. The most extensive data set (Figure 19) is that of Schaller et al. (2001). The timescale for most sediment yield data is years to decades, whereas nuclide activity integrates cosmic-ray exposure and thus erosion rates over thousands to hundreds of thousands of years. Some studies find that nuclide-based sediment generation rates exceed modern sediment yields in tectonically active mountain ranges, including Idaho (Kirchner et al. 2001) and the Oregon Coast Range (Bierman et al. 2001a), as well as in more quiescent and more densely populated regions, such as Europe (Schaller et al. 2001). These results have been interpreted to suggest that large sediment transport events (perhaps resulting from periods of more severe climate) are missed by the short gauge record (Kirchner et al. 2001). Schaller et al. suggest that perhaps cosmogenically inferred erosion rates are elevated in Europe because they still reflect the influence of Pleistocene glaciers in the sampled catchments.

Conversely, other studies find that sediment yields exceed cosmogenically estimated sediment generation rates, implying that stored sediment is being mined from the landscape. Clapp et al. (2000) came to this conclusion by comparing ^{10}Be measurements with the 30-year sediment yield of an arid, Israeli drainage basin gauged by accumulation behind a dam that trapped all sediment. Brown et al. (1995b) determined that sediment was currently delivered nearly twice as fast as it was being generated in a Puerto Rican drainage where annual rainfall exceeds 4 m. In the Rio Puerco, New Mexico, sediment yields are about twice the sediment generation rates (Bierman et al. 2001b). It is possible that human impact increased

Figure 19 Comparison of cosmogenic nuclide derived erosion rates (*squares*) versus suspended sediment-derived erosion rates (*open triangles*) for the Neckar, Meuse, and Loire Rivers. For these European rivers, cosmogenic nuclide-derived erosion rates exceed suspended sediment-derived erosion rates (figure modified from Schaller et al. 2001).



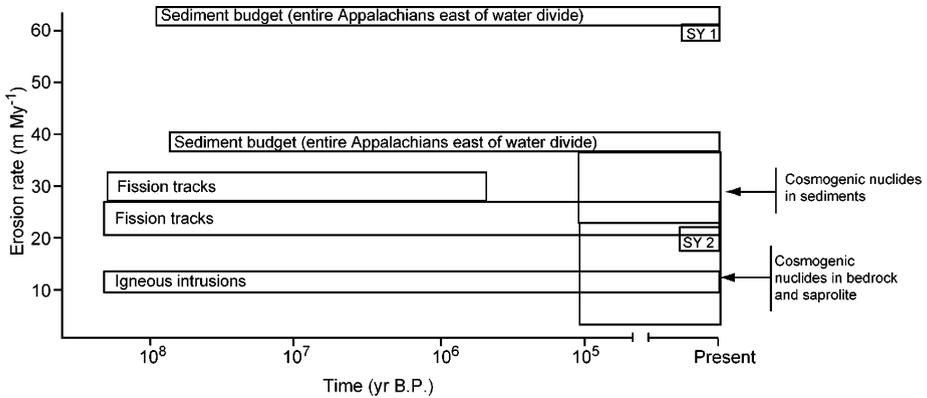


Figure 20 Graph showing similar rates of denudation in Appalachian Mountains during Mesozoic and Cenozoic from Matmon et al. (2003a). SY1 is sediment yield from Tuckasegee River and SY2 is sediment yield from Little River. Rates measured using different techniques (see original publication for details). Used by permission of the Geological Society of America.

sediment yield (Costa 1975, Hewawasam et al. 2003, Trimble 1977) or that present-day erosion arroyo results in a sediment yield that currently outstrips sediment supply.

Some cosmogenic nuclide studies suggest steady landscape behavior in terms of sediment production and export over widely varying timescales. In environments as different as the Great Basin (Granger et al. 1996) and the Great Smoky Mountains (Matmon et al. 2003a), rates of sediment yield over varying timescales match cosmogenically inferred rates of sediment generation integrated over many millennia. Other studies contrast cosmogenic data and chronometers of unroofing applicable over even longer timescales. For example, Matmon et al. (2003a) showed that erosion rates in the Great Smoky Mountains appear similar when integrated over time frames of just a few years to over 100 million years (Figure 20). Similarly, Cockburn et al. (2000) compared fission-track-inferred denudation rates to those measured with cosmogenic nuclides and concluded that the Namibian margin has been eroding steadily for tens of millions of years, a finding supported by additional ¹⁰Be measurements on Namibian rock and sediments (Bierman & Caffee 2001) (Figure 21). Vance et al. (2003) indicate that cosmogenic-nuclide-based erosion rates match rates estimated by fission tracks in the Himalayas but exceed those estimated by geochronometers integrating over longer time frames; thus, they concluded that erosion rates in the Himalayas have increased to their present values during the past several million years.

SIZE MATTERS SOMETIMES Measuring ¹⁰Be activity in fluvial sediment is typically straightforward, especially if the sediment is quartz-rich. In some environments, grain size matters; in others, it does not. Several studies in arid regions have shown no dependence of nuclide activity on grain size (Clapp et al. 2000, 2001,

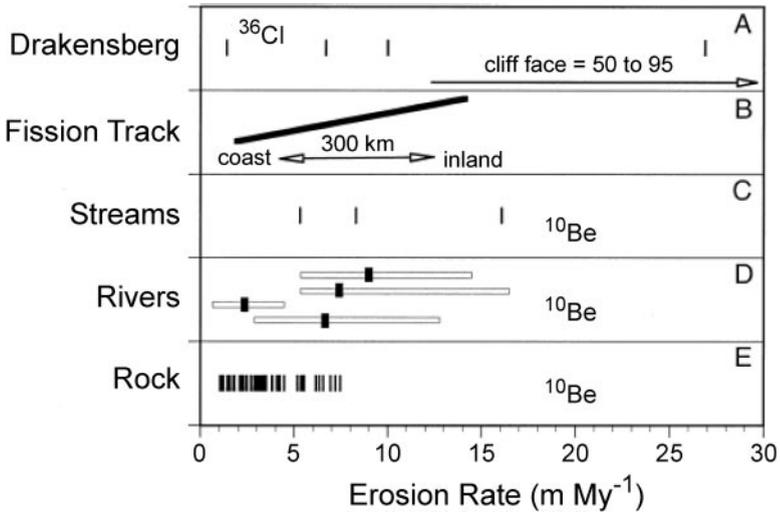


Figure 21 Summary diagram of erosion rates in southern Africa determined over different time frames using different methods. (A) ^{36}Cl measurements on Drakensberg Escarpment, South Africa. (B) Thermal modeling of fission track measurements, central Namibia. (C) Basin-scale model erosion rates determined from ^{10}Be abundance in stream sediments from small ($<10 \text{ km}^2$) basins. (D) Basin-scale model erosion rates determined from ^{10}Be abundance in river sediments (large basins). (E) Bare bedrock ^{10}Be model erosion rates. From Bierman & Caffee (2001) and used by permission of American Journal of Science.

2002; Granger et al. 1996), a finding consistent with other research suggesting that the flashy, short-lived, but high-intensity floods typical of dry environments move many grain sizes similarly. Conversely, work in humid regions (Brown et al. 1995b, 1998; Matmon et al. 2003c) shows significant grain size effects, with larger grains having lower ^{10}Be activity than sand-size material. Such a discrepancy may be due to sourcing of material from different depths below Earth's surface (e.g., the coarse fraction is land-slide derived) (Brown et al. 1995b, 1998) or the sourcing of material from different elevations [e.g., clasts originate near the channel and fine grains originate throughout the landscape (Matmon et al. 2003c)].

USE OF ^{10}Be FOR FINGERPRINTING FLUVIAL SEDIMENT SOURCES The use of ^{10}Be for sediment fingerprinting remains largely unexplored. Only a few studies have used nuclide activity to infer different sediment sources. As mentioned above, Brown et al. (1995b, 1998) use grain-size specific nuclide activities to suggest that landslides are responsible for delivering large clasts to the channel for fluvial transport. Clapp et al. (2001) measured nuclide activity in various landscape elements at Arroyo Chavez in New Mexico and concluded, based on nuclide activity, that sediment leaving the basin was largely derived from incision of the valley fill. In the

Yuma Wash basin, Clapp et al. (2002) used samples from drainages incising either bedrock highlands (high ^{10}Be activity) or the alluvial valley fill (low ^{10}Be activity) to define a combined ^{10}Be and sediment mixing model, which they used to interpret the source of sediment being transported down the main stem channel. Based on a downstream decrease in ^{10}Be activity in main stem sediments, they concluded that where Yuma Wash entered the Colorado River, nearly 50% of the sediment the wash transported was derived from reworking low-activity pre-Pleistocene valley fill.

^{10}Be in Shoreline Sediment

Unlike the significant body of literature that utilizes ^{10}Be for deciphering the rates and patterns of terrestrial surface processes, the application of cosmogenic nuclides to coastal and ocean processes is limited. Perhaps this paucity of ^{10}Be measurements on shorelines and ocean sediments reflects uncertainty in the exposure and burial history of sediments and clasts during transport from source areas. In this section, we review the use of ^{10}Be for dating shorelines and marine terraces and the use of ^{10}Be in tracing sediment movement along coastlines.

SHORELINE DATING USING CLASTS The ability to date paleo shorelines or beach terraces is important for understanding past climates and estimating rates of tectonic uplift. There have been several attempts to date such landforms using ^{10}Be . In arid locales with closed basins, paleo shorelines and terraces represent pluvial lake high stands or shorelines prior to uplift. Trull et al. (1995) used ^{10}Be and ^3He in an attempt to date quartzite and quartz-rich felsic cobbles and boulders on now-dry beach terraces of Pleistocene Lake Manly, Death Valley, California. Calculated ^3He ages were significantly lower than ^{10}Be ages of the beach clasts because of diffusive loss of ^3He . However, the ^{10}Be ages were overestimates of shoreline age because the clasts were at or near the surface during transport to the lake or were previously exposed and reworked along the lake shore. Clearly, measured ^{10}Be activity integrated clast history during transport and shoreline exposure.

Similarly, chert clasts from Pleistocene shorelines of Lake Lisan, Israel, have complex exposure histories; thus, model ^{10}Be ages are of little help in dating Lake Lisan's high stand (Matmon et al. 2003b). Model exposure ages assuming a single period of exposure suggest that clasts on beach ridges have been exposed between 35 and 354 kiloyears. These ages are far greater than the age implied by the soil development on the ridges and by optically stimulated luminescence dating of fine sands from the same and more proximal beach ridges (~20 and ~36 kiloyears). A model that accounts for both exposure and burial of clasts (using $^{26}\text{Al}/^{10}\text{Be}$ ratios) during transport to the beach suggests that clasts have a history between 0.4 million years and 4.3 million years. It appears that beach clasts in arid environments have significant histories of transport and burial prior to reaching the shorelines on which they sit.

SHORELINE DATING USING BEDROCK In contrast to dating clasts transported to depositional shorelines, Stone et al. (1996) used ^{36}Cl to date the exposure of

bedrock knobs on an erosional marine terrace in Scotland. Because the knobs are “in place,” there was no need to consider transport history. Assuming that the marine bedrock terrace was eroded into bedrock deeply scoured during the last glacial maximum, sampled sites had a low initial ^{10}Be activity and the current activity of the knobs represents the time since they were exposed at the surface. Considering shielding by sea water during emergence, Stone et al. (1996) conclude that the marine terrace was cut during the Younger Dryas Stadial (~10 to 12 kiloyears) just after deglaciation. Such dating suggests that large bedrock platforms can be eroded quickly under climate regimes different than today.

SHORELINE DATING AND UPLIFT RATE CALCULATION USING DEPTH PROFILES Perg et al. (2001) collected depth profiles of regressive beach sands deposited on a flight of five marine terraces north of Santa Cruz, California. They measured the activity of ^{10}Be in the sand fraction and used these data to estimate the age at which each terrace was abandoned. They detected a significant zone of bioturbation at the top of each profile, extending 80 to 150 cm below the surface. Because the exponential decrease of ^{10}Be production is well known as a function of depth, the profiles allowed them to estimate ^{10}Be inheritance of each terrace, a value needed for age modeling. The age of each terrace appears to correlate with a sea-level high stand based on the marine oxygen isotope record, allowing the authors to calculate a steady local uplift rate of 1.1 mm year^{-1} , a rate two to three times higher than other estimates of uplift for the area. Perg et al. demonstrate the utility of the depth profile method to date shorelines in the absence of other datable material, if the assumptions of rapid sediment deposition and a similar ^{10}Be inheritance within each profile are correct.

SEDIMENT MOVEMENT ALONG COASTLINES The complex transport and burial histories of coastline sediment make it difficult to use ^{10}Be to quantify coastal processes. However, Perg et al. (2003) used ^{10}Be activity to trace sediment along a littoral cell near Santa Cruz, California. By identifying sediment sources (backwearing cliffs and coastal basins) with significantly different ^{10}Be activities, Perg et al. were able to develop a mixing model to determine the relative sediment contributions of each source (c.f., Clapp et al. 2002). Backwearing sea cliffs provided a relatively constant input of sediment with high ^{10}Be activities. Streams draining rapidly eroding coastal basins were point sources injecting sediment with low ^{10}Be activity. Such a mixing model allowed construction of a sediment budget, which illustrated that coastal basins supply between 50% and 75% of the sediment circulating in the littoral cell.

DISCUSSION

Over the past decade, the analysis and interpretation of cosmogenic nuclides has given geomorphologists an unprecedented opportunity to measure rates and to infer the distribution of geomorphic processes across Earth's varied landscapes. Samples

have been collected and analyzed from outcrops and rivers, from polar deserts, and from the humid tropics to develop new analytical approaches; to address problems of local, regional, and global significance; and to test more general geomorphic hypotheses.

Can Cosmogenic Nuclides Help Us Decipher the Influence of Tectonics, Climate, and Lithology on Erosion Rates?

After a decade of sampling and measurement, there is growing but still incomplete knowledge of the rate at which bare bedrock erodes as a function of lithology, climate, and tectonic setting. Most ^{10}Be measurements have been made in either sandstone or coarse crystalline rocks, including granite and gneiss. Little attention has been paid to other quartz-bearing lithologies, including fine-grain sediments, schist, quartzite, or rhyolite; there are only a handful of cosmogenic erosion rate measurements (quantification of ^3He , ^{21}Ne , ^{36}Cl activity) in rocks not containing quartz. Extremely slow rates of bedrock erosion, in the range of centimeters to decimeters per million years, have been measured in Earth's most extreme arid environments (Antarctica, Namibia, Peru's Atacama Desert) and in samples from some of Earth's most tectonically stable areas (south central Australia). More rapid rates of erosion, meters to tens of meters per million years, appear to characterize more humid (e.g., the southern Appalachians) and more tectonically active regions, even if they are deserts (e.g., the Mojave and Negev). Continued sampling and cosmogenic analysis of different lithologies cropping out in a variety of climatic and tectonic settings are needed to clarify the apparent relationship between bare bedrock erosion rates and lithology, climate, and tectonic setting. Such measurements are key to informing models of landscape evolution and development.

Measurement of ^{10}Be in river sediments has characterized the erosion rate of drainage basins, and thus landscapes, on a much larger spatial scale than outcrop samples, albeit with the loss of site-specific detail that outcrop-by-outcrop sampling and analysis provide. Several studies have demonstrated the efficacy of fluvial mixing in basins ranging from $\leq 1 \text{ km}^2$ to 10^4 km^2 (Figure 22) and have placed contemporary sediment yields in a long-term geologic context, a prerequisite for responsible land management. Analysis of cosmogenically determined sediment generation rates in the context of digital elevation data allows statistical analysis of relationships between erosion and such landscape-scale variables as mean slope, basin area, various measures of relief, and lithology (Matmon et al. 2003c, Schaller et al. 2001, Vance et al. 2003). This is a fruitful area of research with rapidly expanding geographic coverage as various research groups examine sediments from much of the planet, the Appalachians, Africa, and central Europe.

Cosmogenic analysis of both bedrock and sediment samples suggests strong tectonic control on erosion rates convolved with more subtle, uncertain, and variable climatic effects. It appears that tectonic effects are promulgated as base level changes, which serve to accelerate drainage basin-scale erosion rates (Riebe et al. 2000). Current or past tectonic activity also seems to increase bare rock erosion rates, although it is uncertain whether this is the result of base-level fall or

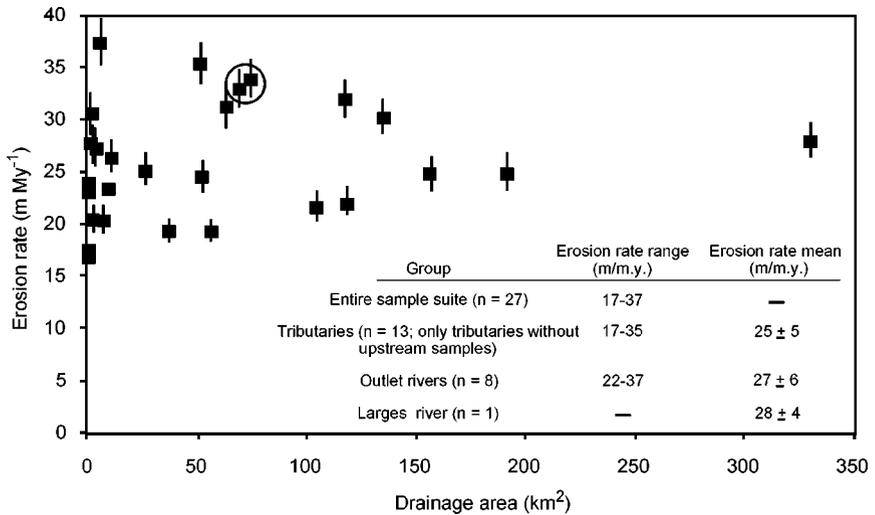


Figure 22 Variability in modeled ^{10}Be erosion rates decreases with increasing basin area verifying the assumption that sediment is well mixed by fluvial activity as it moves downstream. Data from the Great Smoky Mountains. Circled samples are laboratory replicates. Figure from Matmon et al. (2003a) and used by permission of the Geological Society of America.

tectonically induced faults and joints weakening rocks and thus accelerating erosion (c.f., differing cosmogenic erosion rate estimates for granites exposed in similarly arid parts of Australia, Israel, and the Mojave).

The effect of climate on both bare rock and basin-scale erosion rates is much less certain, although hyperarid regions appear to be eroding more slowly than the humid tropics. Riebe et al. (2001b) show convincingly that climate (over a moderate range of temperature and precipitation) has little effect on basin-scale rates of erosion in a series of lithologically similar granitic basins. In contrast, the data of Bierman & Caffee (2002) suggest that mean annual precipitation and the erosion rate of bedrock surfaces in different parts of Australia are significantly related (Figure 8B). Insufficient cosmogenic data exist to define clearly the influence of lithology on erosion rates and the sensitivity of different lithologies to climate and tectonics. More work is required to separate tectonic, climatic, and lithologic controls on erosion rates at a variety of spatial and temporal scales.

Use of Cosmogenic Nuclide Measurements for Testing Geomorphic Models

Cosmogenic methods and applications have now matured sufficiently that the potential exists to test long-standing qualitative models of landscape evolution quantitatively. For example, both Riebe et al. (2000) and Matmon et al. (2003a,c) have used analysis of cosmogenic nuclides in river sands to test Hack's (1960)

model of dynamic equilibrium. Matmon et al., working in the Great Smoky Mountains of the southern Appalachians, found no relationship between lithology and erosion rate when contrasting basins with differing amounts of sandstone and siltstone. Riebe et al. (2000) found that slope and erosion rate were uncorrelated in Sierra Nevada granitic basins with steady base levels. Both results support Hack's assertion that in some landscapes, slopes adjust to lithology (rock strength) such that erosion rates approach spatial uniformity. On a smaller scale, Small et al. (1999) used ^{10}Be measured in rock and regolith to test and verify Gilbert's model for steady-state hillslope behavior.

Understanding Geomorphic Processes Using Cosmogenic Nuclide Analysis

Nuclide measurements have allowed workers to address fundamental issues, including the timing and rate of relief generation. Such approaches rely upon contrasting erosion rates measured or inferred for upland versus lowland surfaces. At smaller scales, Bierman & Caffee (2002) contrasted the cosmogenically determined erosion rate of saprolite at the base of Stone Mountain to the erosion rate measured on samples of granite exposed at the summit. The differential rate of lowering, 15 to 20 m/million years, allowed them to suggest that Stone Mountain (240 m tall) had been a positive element on the landscape for 12 to 16 million years. A similar approach suggests that large Australian inselbergs may have stood proud of the plains for 20 to 90 million years (Bierman & Caffee 2002), that a 2.5-m-high tor in southeast Australia is <150 kiloyears old (Heimsath et al. 2000), and that tors on Wind River Mountain summit surfaces in Wyoming have existed for 2 to 3 million years (Small et al. 1999). On a much larger scale, Small & Anderson (1998) used the same rationale to suggest that relief production in the Laramide Mountains began about 3 million years ago and that relief increases about 100 m/million years.

Cosmogenic nuclides are poised to become a powerful tool for developing sediment budgets. In 1978, Dietrich & Dunne laid out the sediment budget approach to understanding drainage basin dynamics, challenging the community to gather the data necessary to balance such budgets and to constrain rates of sediment generation and transport on geologic timescales. Analysis of cosmogenic nuclides can approach many of the issues raised 25 years ago by these authors. Initial attempts at such work include the geomorphic element approach to sampling and analysis pioneered by Brown et al. (1995b, 1998) for humid sites and by Clapp et al. (2000, 2001, 2002) in arid regions. More complete cosmogenically based sediment budgets for different landscapes will surely follow (e.g., Nichols 2002).

One of the most intriguing applications of cosmogenic nuclide analyses is their use alongside other geochronometers capable of deciphering rates of Earth surface change over different timescales. For example, measurement of suspended sediment load quantifies contemporary sediment yield, whereas interpretive models can be used to infer longer-term denudation rates from the distribution of both

fission track and U/He ages over Earth's surface and at depth. Add cosmogenic nuclides to the mix and one now has the ability to measure rates of surface change integrated over 10^3 to 10^6 years depending on the erosion rate of the landscape considered. This window of time falls between hard rock chronometers and methods used to assess contemporary or late Holocene sediment yield. Such an approach has begun to bear fruit for testing hypotheses, suggesting steady landscape denudation over millions of years (Bierman & Caffee 2001, Cockburn et al. 2000, Matmon et al. 2003a) and the acceleration of erosion owing to tectonic, climatic, or human-induced forcing (Hewawasam et al. 2003, Nott & Roberts 1996, Schaller et al. 2001, Vance et al. 2003).

CONCLUSION

Cosmogenic nuclide analyses of sediments, soil, and outcrops are broadening our understanding of landscapes and the rate at which they change over a variety of time and length scales. A decade of nuclide data suggests the importance of tectonics in controlling erosion rates and thus the tempo of sediment generation. Effects of climate and lithology on rates of erosion remain less certain. In the right setting, cosmogenic nuclides can be used to trace sediment to its source. Combined with other techniques, including fission track, U/He, and suspended sediment analysis, cosmogenic nuclides serve as an important bridge linking contemporary rates of sediment yield to long-term rates of rock uplift. Interpreted with a variety of models, cosmogenic nuclide measurements are being used with increasing frequency to test long-standing geomorphic ideas at a variety of spatial scales. Now routinely measured, cosmogenic nuclides should see increasing application to more practical issues, including the development of long-term sediment budgets and the evaluation of human impact in geomorphic environments throughout the world.

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