ARTICLES

Spatially Averaged Long-Term Erosion Rates Measured from In Situ-Produced Cosmogenic Nuclides in Alluvial Sediment[1]

Darryl E. Granger, James W. Kirchner, and Robert Finkel[2]
Department of Geology and Geophysics, University of California, Berkeley, CA 94720-4767

ABSTRACT

Spatially averaged erosion rates of small catchments can be accurately inferred from the concentrations of cosmogenic nuclides in stream sediment. Here we test this technique at two catchments by comparing erosion rates inferred from cosmogenic nuclides with rates of alluvial fan deposition over the past 16,000 years. These two independent estimates agree within one standard error, demonstrating that cosmogenic nuclide signatures of stream sediment can be used to measure spatially averaged long-term erosion rates. Using this technique, we show that long-term erosion rates are an exponential function of average hillslope gradient at these sites.

Introduction

Measurements of long-term erosion rates are critical for understanding landform evolution, soil production rates, erosional effects of land use (Meyer and Turner 1992), and long-term removal of atmospheric CO_2 by silicate weathering (Berner et al. 1983; Raymo et al. 1988). However, there have been no accurate, widely applicable methods for measuring landscape erosion rates over millennial timescales. Traditional methods for estimating catchment erosion rates rely on either measuring the present-day flux of sediment in streams, or measuring the volume of debris that has accumulated in deposits of known age. Accurately measuring alluvial sediment flux is difficult, because a significant fraction of the total sediment discharge from a basin may occur during rare flood events (Meade 1988). Accurately estimating long-term sediment discharge therefore requires many years of sediment flux measurements. Furthermore, modern sediment flux measurements may be affected by storage or remobilization of sediment upstream, and thus cannot be directly interpreted as long-term erosion rates (Trimble 1977).

Denudation rates can also be estimated by measuring the rate at which erosional debris has accumulated in a sedimentary deposit (e.g., Judson 1968; Dietrich et al. 1982; Reneau et al. 1989). To be useful for this purpose, sedimentary deposits must capture most or all of the sediment eroded from the region of interest, and must include datable stratigraphic markers (such as loess, volcanic ash, or ^{14}C-datable charcoal). Long-term denudation rates can also be estimated by measuring the volume of incision into an original form of known age, such as a volcano (Ruxton and McDougall 1967; Seidl et al. 1994) or a marine terrace (Pillans 1988). However, datable sedimentary deposits and reconstructable forms are rare, so these methods for estimating erosion rates are not widely applicable.

Cosmogenic nuclides have recently provided a new method for inferring erosion rates by revealing how long mineral grains have been exposed to cosmic rays near the landscape surface. Cosmogenic nuclides record long-term erosion rates without requiring datable deposits or surfaces, and thus provide a widely applicable technique for measuring erosion rates (Nishiizumi et al. 1993; Bierman 1994; Cerling and Craig 1994).

In situ cosmogenic nuclides are produced by secondary cosmic radiation bombarding atomic nuclei in minerals near the earth's surface (Lal and Peters 1967). Because the cosmic ray flux decreases exponentially with depth below the surface, the accumulated cosmogenic nuclide concentration in a mineral grain records the speed with which that grain has been unearthed; slower erosion rates im-

[1] Manuscript received May 31, 1995; accepted December 13, 1995.

[2] Earth Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94551-9900 USA.

[The Journal of Geology, 1996, volume 104, p. 249–257] © 1996 by The University of Chicago. All rights reserved. 0022-1376/96/10403-0003$01.00]

ply longer exposure times near the surface, and thus higher concentrations. It has been shown (Lal 1991) that the cosmogenic nuclide concentration N at a steadily eroding outcrop surface is inversely proportional to the outcrop's erosion rate E,

$$N = \frac{P_o \Lambda}{E} \quad (1)$$

where P_o is the nuclide production rate at the surface and Λ is the absorption mean free path (the $1/e$ attenuation length for production rate; $\Lambda \approx 60$ cm in rock). The nuclide concentration N averages the erosion rate over a time scale of order Λ/E, the time required to erode a layer of thickness Λ from the surface. Equation (1) assumes that the radioactive meanlife, τ, of the nuclide is much longer than Λ/E; for the radionuclides considered here, ^{26}Al ($\tau = 1.0$ m.y.) and ^{10}Be ($\tau = 2.2$ m.y.), equation (1) is accurate to <6% for $E > 1$ cm ka^{-1}. Because cosmogenic nuclide concentrations are insensitive to recent changes in erosion rates, they are particularly useful for estimating long-term "background" rates of erosion, as a benchmark for evaluating the erosional effects of land use.

Cosmogenic Nuclides in Regolith and Alluvium

Cosmogenic nuclides have been widely used for determining exposure ages and/or erosion rates of outcrops (Nishiizumi et al. 1993; Bierman 1994; Cerling and Craig 1994), but these cannot be translated directly into landscape erosion rates, since outcrops "crop out" precisely because their erosion history differs from that of the surrounding terrain. Lal and Arnold (1985) reasoned that cosmogenic nuclide concentrations in sediment should correspond to erosion rates of the parent rocks. Several authors have recently elaborated this proposal by developing schemes for inferring catchment-averaged erosion rates from alluvial sediment (Bierman 1992; Brown et al. 1993; Granger and Kirchner 1994; Bierman and Steig 1995; Brown et al. 1995).

Inferring erosion rates from cosmogenic nuclide concentrations in sediment is potentially more complicated than interpreting nuclide concentrations in outcrops. Minerals in sediment can accumulate cosmogenic nuclides not just during exhumation, but also during storage and transport in regolith and alluvium. There are three major factors which could confound erosion rates inferred from cosmogenic nuclides in stream sediment; we briefly consider each of these in turn.

1. Regolith Mixing, and Shielding of Underlying Bedrock. Landscapes are usually mantled by regolith, which shields the underlying bedrock from cosmic radiation while at the same time subjecting individual sediment grains to differing cosmic ray exposure histories as they are mixed by bioturbation, soil creep, and freeze/thaw processes. What is the expected cosmogenic nuclide concentration in mobile regolith? We consider two extreme possibilities—that the regolith is not vertically mixed, and that it is vertically well-mixed—and show that they yield the same result. If the regolith is not vertically mixed, then the exhumation of individual grains proceeds just as with bedrock and yields concentrations at the surface given by equation (1). If, on the other hand, the regolith is vertically well-mixed, then the average concentration in the regolith $N_{regolith}$ will be the concentration inherited from the bedrock below ($N_{bedrock}$) plus the depth-averaged nuclide production rate in the regolith ($P_{regolith}$) times the average residence time in the regolith ($t_{regolith}$). If the regolith has thickness x, its average cosmogenic nuclide concentration is:

$$\begin{aligned} N_{regolith} &= N_{bedrock} + P_{regolith} t_{regolith} \\ &= \left[P_o (e^{-x/\Lambda}) \frac{\Lambda}{E}\right] \\ &\quad + \left[P_o (1 - e^{-x/\Lambda}) \frac{\Lambda}{x}\right] \left[\frac{x}{E}\right] = \frac{P_o \Lambda}{E} \end{aligned} \quad (2)$$

In other words, regardless of the regolith thickness x, the average cosmogenic nuclide concentration in well-mixed regolith is the same as given by the equation (1) for eroding bedrock surfaces.

2. Mixing of Sediment from Areas with Different Erosion Rates. Streams mix sediment from different source areas, which may have very different erosion rates. Which erosion rate will this mixed sediment reflect? If these different areas contribute sediment in proportion to their erosion rates (as they must, over the long term), then we can easily extend equation (1) to show that the average nuclide concentration in stream sediment, $\overline{N}$, reflects the areally averaged erosion rate $\overline{E}$, even where stream sediment is mixed from an assortment of subcatchment areas A_i with differing erosion rates E_i and thus (by equation 1) differing nuclide concentrations N_i:

$$\overline{N} = \frac{\Sigma N_i E_i A_i}{\Sigma E_i A_i} = \frac{\Sigma P_o \Lambda A_i}{\Sigma E_i A_i} = \frac{P_o \Lambda}{\overline{E}} \quad (3)$$

Equation (3) shows that cosmogenic nuclide concentrations in mixed sediment can be interpreted using equation (1) as if they were outcrop samples, and that doing so yields the areally averaged erosion rate above the sampling location. However, equation (3) only holds if each of the subcatchments contributes sediment in proportion to its long-term erosion rate. If one subcatchment contributes a greater fraction (for example, because of recent anthropogenic disturbance), then the inferred catchment-average erosion rate will be biased towards the long-term rates from that subcatchment.

3. Storage and Remobilization of Sediment. Alluvial sediment can be stored and remobilized during its transport out of a catchment. During storage and transport, sediment can accumulate additional cosmogenic nuclides, or it can be shielded from cosmic ray exposure (if it is stored at depth in alluvial deposits). However, the net effect on cosmogenic nuclide concentrations will be small as long as the mean residence time of sediment in storage and transport is much shorter than the erosional timescale Λ/E. This will be true where the total volume of stored alluvial sediment is small compared to the volume of sediment produced by eroding the catchment by an amount Λ.

This condition is met in small upland and mountainous catchments, where the volume of alluvium that is stored at any time is typically small compared to Λ times the catchment surface area (in the catchments analyzed below, it is less than 15% of that volume). However, in large lowland river systems this may not be the case. Furthermore, in large river systems that are rapidly downcutting, and thus excavating alluvial deposits emplaced long ago, the cosmogenic nuclide concentrations in river sediment may primarily reflect the erosion rates when those deposits were emplaced (and radioactive decay during storage). Cosmogenic nuclide methods must therefore be applied cautiously in river systems with large volumes of stored alluvium.

Verification of Isotopically Determined Erosion Rates

To test the accuracy of the cosmogenic nuclide technique, we compared erosion rates derived from cosmogenic nuclide concentrations in alluvial sediment at two small catchments in the Fort Sage Mountains, a granodiorite fault block in northeast California (figure 1) with independent long-term estimates, derived from the volumes of alluvial fans built by these catchments. These catchments discharge their sediments onto a basin flooded by Lake Lahontan during the last glacial maximum. ^{14}C dating of lake carbonates indicates that Lake Lahontan retreated from the fans' depositional area at 16.1 ± 0.4 ka. Lake retreat began at the top of the fans' depositional area (1310 m) at 16.4 ± 0.2 ka and passed the bottom (1240 m) at 15.7 ± 0.1 ka (Benson 1993); ^{14}C ages were calibrated to calendar ages using Bard et al. (1993). Lake Lahontan's retreat left a smooth surface of well-sorted beach sands along the shore margins below our catchments. Streams discharging from the catchments have deposited their sediment load as alluvial fans overlying the Lahontan beach sands (figure 1). The fans' volumes accurately record the long-term erosion rates in the catchments that formed them because most of the sediment is too coarse to blow away by wind and there is no evidence of significant chemical denudation (there is little clay, and micas and feldspars are largely unaltered).

We measured the fans' volumes by surveying their surface topography and measuring their thickness at 19 widely distributed core locations, where we drilled through the fans into the underlying lake deposits, distinguishing the poorly sorted fan sediment from the well-sorted lake sands by both visual and hydrometer grain size analyses. We also surveyed the sediment contributing areas. These measurements indicate that over the last 16,000 years, catchment A has eroded at an average rate of 5.8 ± 1.4 cm ka^{-1} (mean ± standard error), while catchment B has eroded at 3.0 ± 0.5 cm ka^{-1} (table 1). These measurements provide an unambiguous standard for comparison with erosion rates recorded by cosmogenic nuclide concentrations in modern-day stream sediment.

We sampled stream sand that was recently discharged from the mouths of the two catchments and measured concentrations of ^{26}Al and ^{10}Be in 0.25–2 mm quartz grains from these samples (table 2). We excluded finer grains to reduce the possibility of contamination by windblown sediment from outside the catchments. Equation (3) predicts that each sample should record the average erosion rate of the upstream sediment contributing area. The cosmogenic nuclide concentrations in sediment from the catchment mouths may therefore be directly compared with the catchment erosion rates estimated from fan accumulation rates.

From samples A-4(a), A-4(b), A-4(c), and A-4(d), we calculate that catchment A has eroded at a rate of $\bar{E} = P_0\Lambda/\bar{N} = 6.0 \pm 1.4$ cm ka^{-1}, averaged over approximately the last $\Lambda/E \approx 10$ ka, while samples

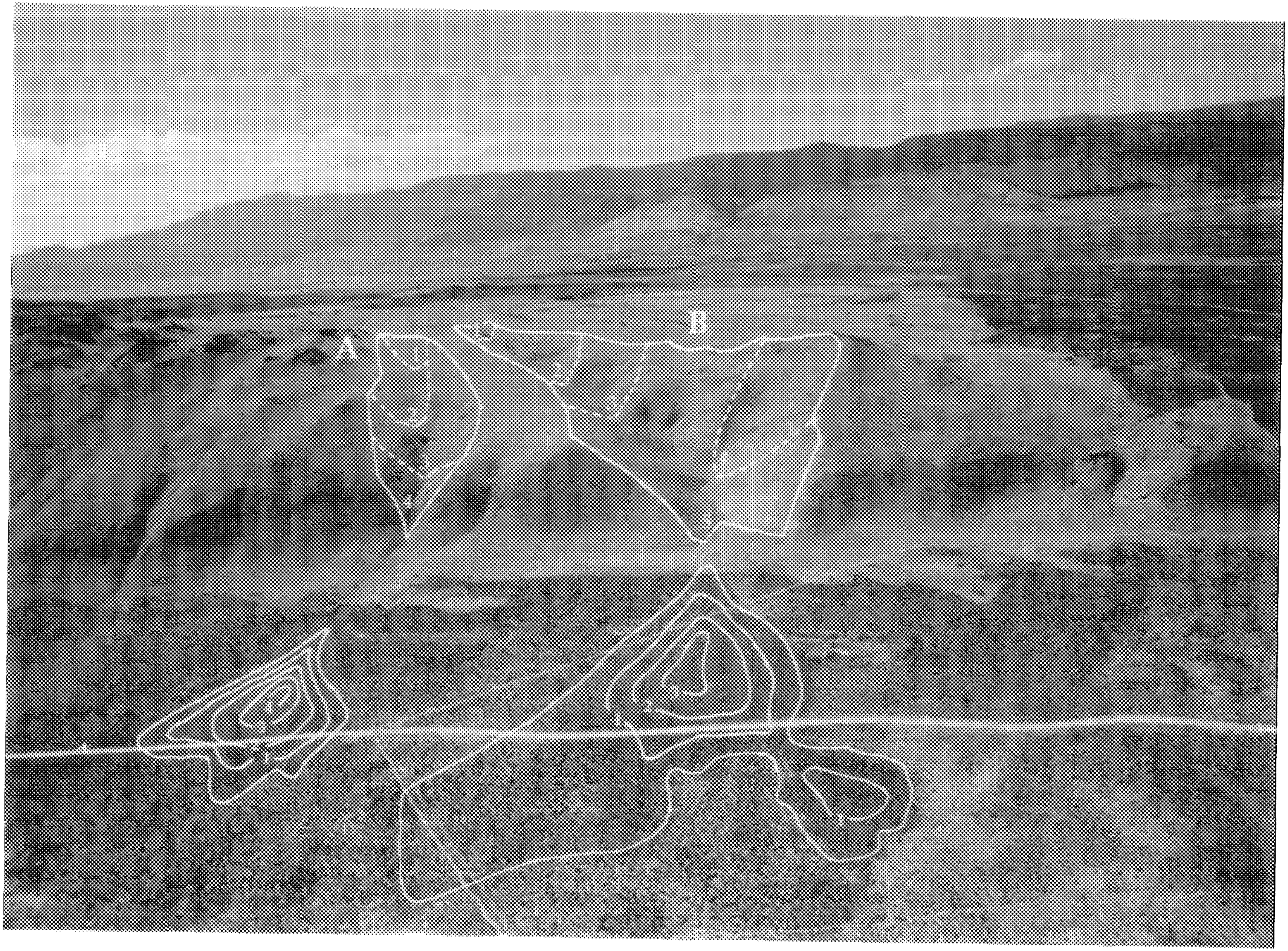
A
B

Table 1. Erosion Rates Estimated from Fan Accumulation

	Catchment A	Catchment B
Fan Volume (10^3 m^3)	188 ± 34	301 ± 52
Sediment Contributing Area (10^3 m^2)	132 ± 20	408 ± 12
Erosion rate from fan accumulation (cm ka^{-1})[a]	5.8 ± 1.4	3.0 ± .5
Erosion rate from isotopes (cm ka^{-1})	6.0 ± 1.4	3.6 ± .9

[a] Erosion rates (means ± standard errors) calculated from fan volumes accumulated since Lake Lahontan retreat (16.0 ± 0.4 ka), corrected for bulk density change from bedrock (2.6 g cm^{-3}) to fan (1.7 g cm^{-3}). Agreement (within 1.2 standard errors) with erosion rates inferred from cosmogenic nuclide measurements (table 2) verifies accuracy of isotope technique.

B-5(a), B-5(b), B-5(c), and B-5(d) indicate that catchment B has eroded at 3.6 ± 0.9 cm ka^{-1}, averaged over the last ≈17 ka (table 2). These erosion rate estimates are quantitatively consistent (within 1.2 standard errors, or 1 cm ka^{-1}) with estimates independently derived from fan accumulation since the retreat of Lake Lahontan. Furthermore, the two different erosion rate estimates are averaged over roughly the same timescale (for the cosmogenic nuclides, $\Lambda/E \approx 10$ ka at catchment A and $\Lambda/E \approx 17$ ka at catchment B, and for fan accumulation, approximately 16 ka). Erosion rates probably fluctuated as climate changed during this time period. Since cosmogenic nuclides record an average erosion rate exponentially weighted towards the present, while fan accumulation averages erosion rates linearly over time, we do not expect erosion rates inferred from cosmogenic nuclides to exactly match fan accumulation. However, the generally good agreement between the two methods demonstrates quantitatively that this geochemical technique accurately measures catchment-scale, long-term erosion rates under field conditions.

Dependence of Erosion Rates on Hillslope Gradient

Hillslope gradient has been recognized as a critical factor regulating erosion rate ever since G. K. Gilbert (1877) proposed that "erosion is most rapid where the slope is steepest." Gilbert postulated that bedrock weathers most quickly under a thin soil mantle; steep hillslopes favor rapid sediment transport, so their soil mantle is thin and their erosion rates are correspondingly high. Modern landform evolution simulation models (e.g., Kirkby 1971; Ahnert 1976; Willgoose et al. 1991) also depend critically on the assumed relationships between hillslope gradient, sediment transport rate, and erosion rate. However, there is very little empirical data showing what this relationship actually is. Here, using the cosmogenic nuclide technique verified above, we measure how erosion rates depend on hillslope gradients in our study catchments.

To assess the relationship between hillslope gradient and erosion rates, we divided our study catchments into nine subcatchments whose average hillslope gradients span a range from 0.2 (at the head of the two catchments) to 0.6 (downstream, near the fault scarp). In most other respects, these subcatchments are quite similar; they are underlain by the same bedrock, mantled with the same regolith, covered with the same sparse vegetation, and subject to the same climate. We measured average sideslope gradients for each subcatchment from direct surveying. We sampled sand from the streams where they crossed the subcatchment boundaries and measured the concentrations of ^{26}Al and ^{10}Be in quartz grains from each sample (table 2). The cosmogenic nuclide concentration at each sampling point records the average erosion rate over the entire contributing area. We calculated the erosion rate for the area between any two sampling points (termed the "subcatchment erosion rate" in table 2) by correcting for the sediment flux from upstream. For example, if sampling point 2 lies below sampling point 1, we can calculate the average erosion rate for the subcatchment between the two points, E_{2-1}, as follows:

$$E_{2-1} = \frac{E_2 A_2 - E_1 A_1}{A_2 - A_1} \quad (4)$$

Figure 1. Oblique aerial photograph of study site, showing sediment contributing area and alluvial fan boundaries for catchments A and B (fan thickness contours in meters). Subcatchment boundaries are shown as dashed lines. Cosmogenic nuclide concentrations were measured in sand sampled from streams at catchment mouths and at subcatchment boundaries.

Table 2. Erosion Rates Calculated from Cosmogenic Nuclide Concentrations

Sample ID[a]	Grain size (mm)	Nuclide Concentration[b] (10^6 atoms g^{-1})	Erosion Rate[c] (cm ka^{-1})	Average Erosion Rate[d] (cm ka^{-1})	Subcatchment Erosion Rate[e] (cm ka^{-1})	Subcatchment Area (10^3 m^2)	Subcatchment hillslope gradient
A-1	.5–1.0	2.16 ± .16 (Al) .34 ± .02 (Be)	2.4 ± .6	...	2.4 ± .6	21 ± 3	.25
A-2	.5–1.0	2.28 ± .18 (Al) .43 ± .02 (Be)	2.0 ± .5	...	1.7 ± .7	27 ± 4	.34
A-3	.5–1.0	1.43 ± .86 (Al) .19 ± .01 (Be)	3.9 ± 1.1	...	5.3 ± 1.6	69 ± 10	.45
A-4(a)	.25–0.5	.94 ± .10 (Al) .14 ± .01 (Be)	5.7 ± 1.3	6.0 ± 1.4	22.2 ± 8.4	15 ± 2	.63
A-4(b)	.5–1.0	.67 ± .15 (Al) .12 ± .01 (Be)	7.1 ± 1.7	(A-4 average weighted	...	...	...
A-4(c)	.5–1.0	.58 ± .05 (Al)	9.0 ± 2.0	by grain size distribution)	...	...	...
A-4(d)	1.0–2.0	.78 ± .07 (Al) .15 ± .01 (Be)	5.9 ± 1.3	...	...	...	...
B-1	.5–1.0	.48 ± .02 (Be)	1.7 ± .4	...	1.7 ± .4	14 ± 1	.23
B-2(a)	.5–1.0	1.60 ± .09 (Al) .30 ± .01 (Be)	2.9 ± .7	3.0 ± .7	3.3 ± .9	54 ± 2	.36
B-2(b)	1.0–2.0	1.60 ± .10 (Al) .30 ± .02 (Be)	2.9 ± .6	(B-2 average weighted	...	...	...
B-2(c)	2.0–4.0	1.42 ± .10 (Al) .37 ± .05 (Be)	3.4 ± .9	by grain size distribution)	...	...	...
B-3	.5–1.0	1.41 ± .09 (Al) .24 ± .02 (Be)	3.6 ± .9	...	4.3 ± 1.5	61 ± 2	.37
B-4	.5–1.0	2.19 ± .14 (Al) .31 ± .03 (Be)	2.4 ± .7	...	2.4 ± .7	49 ± 1	.42
B-5(a)	.25–.5	1.54 ± .11 (Al) .29 ± .01 (Be)	3.0 ± .7	3.6 ± .9	3.8 ± 1.3	230 ± 6	.42
B-5(b)	.5–1.0	1.24 ± .08 (Al) .19 ± .02 (Be)	4.2 ± .9	(B-5 average weighted	...	...	...
B-5(c)	.5–1.0	1.21 ± .08 (Al) .21 ± .02 (Be)	4.2 ± .9	by grain size distribution)	...	...	...
B-5(d)	1.0–2	1.01 ± .05 (Al) .18 ± .01 (Be)	4.9 ± 1.0	...	...	...	...

[a] Each sample was collected from modern stream sand at subcatchment boundaries indicated in figure 1. Quartz grains were chemically isolated by a method modified from Kohl and Nishiizumi (1992).
[b] ^{26}Al and ^{10}Be concentrations (means ± standard errors) calculated from $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ ratios were measured by accelerator mass spectrometry (AMS) (Davis et al. 1990), and total Al and Be concentrations were measured by flame atomic absorption spectrophotometry (AAS).
[c] Erosion rates (means ± standard errors) calculated from equation (1). Production rates of ^{26}Al and ^{10}Be are taken as $P_0 = 81 \pm 17$ and 13.4 ± 2.8 atoms $g^{-1}yr^{-1}$, respectively, from newly revised estimates by Clark et al. (1995), scaled to 40°N latitude and 1400 m altitude (Lal 1991). (Previous estimates of production rates [Nishiizumi et al. 1989] are 20% higher.) Absorption mean free paths of ^{26}Al and ^{10}Be are $\Lambda = 63.9 \pm 3.8$ and 61.2 ± 3.8 cm, respectively (Nishiizumi et al. 1994) in rock of density 2.6 g cm^{-3}. Averages are weighted by inverse variance (Bevington 1969). Uncertainties are propagated from one standard deviation AMS and AAS measurement uncertainties; single-sample measurements are assigned an additional 15% uncertainty estimated from the pooled intersample variability of A-4(a–d), B-2(a–c), and B-5(a–d).
[d] Erosion rates averaged from multiple grain sizes were weighted by inverse variance and by grain size abundance in the alluvial fans (14% <0.125 mm, 20% 0.125–0.25 mm, 24% 0.25–0.5 mm, 21% 0.5–1.0 mm, 11% 1.0–2.0 mm, and 9% >2.0 mm). In contrast to results reported by Brown et al. (1995), there is no significant correlation between cosmogenic nuclide concentration and grain size in samples A-4 and B-2, and only a slight negative correlation in sample B-5.
[e] Subcatchment erosion rates calculated from equation (4).

As figure 2 shows, erosion rates in our subcatchments vary by an order of magnitude, with the slowest erosion rates corresponding to the shallowest slopes, and the fastest erosion rates corresponding to the steepest slopes. While our data are insufficent to describe the exact relationship between erosion rates and hillslope gradient, and we have not yet accounted for other important factors such as soil depth, figure 2 suggests that erosion rates at these catchments are roughly an exponential function of average hillslope gradients.

Discussion

Our analysis of cosmogenic nuclide concentrations in stream sediment provides an important validation of a powerful new technique for inferring catchment erosion rates. Because cosmogenic nu-

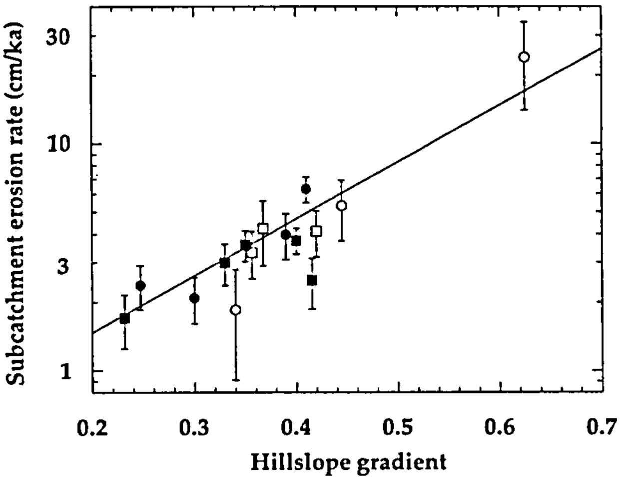

Figure 2. Semi-logarithmic plot of subcatchment erosion rates versus average hillslope gradient, showing that erosion rates increase exponentially as hillslope gradient increases from 20% near catchment heads to 60% near catchment mouths at the fault scarp. Erosion rates are calculated from ^{26}Al and ^{10}Be concentrations in quartz stream sand collected at subcatchment boundaries (figure 1). Subcatchment erosion rates and hillslope gradients have been calculated both for differential subcatchment areas (according to equation 4, and plotted as open symbols), and for each sample's total upstream contributing area (closed symbols). Erosion rates from catchment A are plotted as circles, and those from catchment B are plotted as squares. The best fit line was regressed by standard error-weighted least squares (Bevington 1969) and indicates that erosion rates increase according to the equation: Erosion rate = $(0.53 \pm 0.27)\, e^{(5.1 \pm 1.4)\text{hillslope gradient}}$. Removing the high gradient data from subcatchment A-4 changes the regression only slightly, to: Erosion rate = $(0.63 \pm 0.37)\, e^{(4.6 \pm 1.6)\text{hillslope gradient}}$

clides in sediment record the average time taken to lower the landscape by a cosmic ray mean free path, the inferred erosion rates are averaged over a timescale that is useful for understanding catchment evolution. Furthermore, because cosmogenic nuclide concentrations reflect long-term average rates of erosion, they are insensitive to recent erosion rates and are independent of the present-day sediment flux; thus they are particularly valuable as a baseline for determining whether erosion rates have recently changed (Granger and Kirchner 1994; Brown et al. 1995).

The only previous attempt to validate cosmogenic nuclide erosion rate estimates from stream sediment is that of Brown et al. (1995). Their study, at the Icacos River in Puerto Rico, reports average erosion rates of 4.3 ± 1.5 cm ka^{-1}, inferred from ^{10}Be concentrations in sediment, compared to mass-balance estimates of 7.5 ± 3.8 cm ka^{-1} derived from four years of runoff solute concentrations. However, they also report that the 3.26 km^2 catchment yields an annual sediment flux of 1.68 × 10^6 kg yr^{-1}, which implies an average erosion rate of roughly 20 cm ka^{-1}. In any event, the three estimates reflect timescales that differ by over three orders of magnitude, so precise agreement should not be expected. We have posed a more exacting test, by comparing erosion rates estimated from cosmogenic nuclides with independent estimates (from fan accumulation) over comparable timescales. The precision of any such test, however, is ultimately limited by uncertainty in nuclide production rates (10–20%), sample-to-sample variability (here ≈15%), uncertainty in sample preparation and analysis (typically 5–10%), and temporal fluctuations in erosion rates.

Our analysis of erosion rates from cosmogenic nuclides provides a new perspective on the relationship between hillslope erosion and surface gradient, because we can accurately and reliably measure erosion rates over timescales relevant to hillslope processes. Previous work exploring erosion rate and gradient has been limited to measuring short-term sediment flux from river basins or small experimental plots (e.g., Schumm and Hadley 1961; Ahnert 1970; Abrahams and Parsons 1991), or measuring long-term rates of catchment incision (Ruxton and McDougall 1967; Seidl et al. 1994). Because hillslope processes occur on timescales that are long with respect to fluvial sediment transport, and short with respect to catchment formation, it is unclear whether these earlier results can be extrapolated to rates of hillslope erosion.

Measuring catchment erosion rates using cosmogenic nuclides does not require special geological circumstances, although we have used such a circumstance here (the datable Lahontan lake surfaces) to confirm the reliability of the technique. However, this technique cannot be uncritically applied. For example, if the mineral being analyzed is unequally distributed in the catchment, then the inferred erosion rate will be weighted toward locations where that mineral is more abundant. Most importantly, this technique cannot be straightforwardly applied where the characteristic timescales of sediment transport and storage are comparable to the cosmogenic nuclide's radioactive meanlife, or to the erosional timescale Λ/E. This precludes direct application to many large lowland river systems. However, our field test indicates that cosmogenic nuclide techniques should provide reliable estimates of long-term erosion rates when applied to homogeneously distributed minerals in small catchments.

A stream's present-day sediment load reflects recent or contemporary erosion rates, whereas the same sediment's cosmogenic nuclide signature reflects average erosion rates over millennial timescales. The erosional effects of land use can therefore be measured by comparing these two erosion rates, which can be inferred from modern sediment samples. Other potential applications for this technique include measuring changes in erosion rates over past climatic cycles (by comparing cosmogenic nuclide signatures of datable alluvial deposits of different ages), and measuring the effects of topography, lithology, tectonics and climate on erosion rates (by comparing erosion rates among different sites), thereby furthering our understanding of landform evolution. Cosmogenic nuclides in present-day stream sediments record their erosional history, providing an accurate and widely applicable new method for measuring long-term spatially averaged erosion rates.

ACKNOWLEDGMENT

We thank J. Koning for laboratory assistance, F. Booker, R. Torres, C. Riebe, and B. Roy for field assistance, and W. Dietrich for stimulating discussion. This work was partially performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48 and was also supported by a NASA Global Change Fellowship to D.E.G. and NSF Grant EAR-9357931 to J.W.K.

REFERENCES CITED

Abrahams, A. D., and Parsons, A. J., 1991, Relation between sediment yield and gradient on debris-covered hillslopes, Walnut Gulch, Arizona: Geol. Soc. America Bull., v. 103, p. 1109–1113.

Ahnert, F., 1970, Functional relationships between denudation, relief, and uplift in large mid-latitude drainage basins: Am. Jour. Sci., v. 268, p. 243–263.

———, 1976, Brief description of a comprehensive three-dimensional process-response model of landform development: Zeits. Geomorph., v. 25, p. 29–49.

Bard, E.; Arnold, M.; Fairbanks, R. G.; and Hamelin, B., ^{230}Th-^{234}U and ^{14}C ages obtained by mass spectrometry on corals: Radiocarbon, v. 35, p. 191–199.

Benson, L., 1993, Factors affecting ^{14}C ages of lacustrine carbonates: timing and duration of the last highstand lake in the Lahontan Basin: Quat. Res., v. 39, p. 163–174.

Berner, R. A.; Lasaga, A. C.; and Garrels, R. M., 1983, The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the last 100 million years: Am. Jour. Sci., v. 205, p. 641–681.

Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences: New York, McGraw-Hill, 336 p.

Bierman, P. R., 1992, Use of in situ-produced cosmogenic isotopes to determine rates of geomorphic processes: Snowbird, Utah: Am. Geophys. Union, Chapman Conf. Tectonics and Topography, p. 34.

———, 1994, Using in situ produced cosmogenic isotopes to estimate rates of landscape evolution: A review from the geomorphic perspective: Jour. Geophys. Res., v. 99B, p. 13,885–13,896.

———, and Gillespie, A., 1991, Range fires: A significant factor in exposure-age determination and geomorphic surface evolution: Geology, v, 19, p. 641–644.

———, and Steig, E.J., 1995, Estimating rates of denudation using cosmogenic isotope abundances in sediment: Earth Surf. Proc. Landforms, in press.

Brown, E. T.; Stallard, R. F.; Larsen, M. C.; Raisbeck, G. M.; and Yiou, F., 1993, Denudation rates based on accumulation of in-situ produced ^{10}Be compared with watershed mass balance results in the Luquillo Experimental Forest, Puerto Rico: EOS (Trans., Am. Geophys. Union), v. 74, p. 295.

———; ———; ———; ———; and ———, 1995, Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico: Earth, Planet. Sci. Lett., v. 129, p. 193–202.

Cerling, T. E., and Craig, H., 1994, Geomorphology and in situ cosmogenic isotopes: Ann. Rev. Earth Planet, Sci., v. 22, p. 273–317.

Clark, D.; Bierman, P. R.; and Larsen, P., 1995, Improving in situ cosmogenic chronometers: Quat. Res., v. 44, in press.

Davis, J. C.; Proctor, I. D.; Southon, J. R.; Caffee, M. W.; Heikkinen, D. W.; Roberts, M. L.; Moore, T. L.; Turteltaub, K. W.; Nelson, D. E.; Loyd, D. H.; and Vogel, J. S., 1990, LLNL/UC facility and research program: Nuc. Instr. Meth. Phys. Res., v. B52, p. 269–272.

Dietrich, W. E.; Dunne, T.; Humphrey, N. F.; Reid, L. M., 1982, Construction of sediment budgets for drainage basins, *in* Swanson, F.; Janda, R.; and Dunne, T., eds., Proceedings of a workshop on sediment routing in forested catchments: U.S. Forest Service, Gen. Tech. Rept. PNW-141, p. 5–23.

Gilbert, G. K., 1877, Report on the Geology of the Henry Mountains: U.S. Geog. and Geol. Survey, 160 p.

Granger, D. E., and Kirchner, J. W., 1994, Estimating catchment-wide denudation rates from cosmogenic isotopes in alluvial sediment: Fort Sage Mountains, California, *in* Eighth Int. Conf. on Geochronology, Cosmochronology, and Isotope Geology: U.S. Geol. Survey Circ. 1107, p. 116.

Judson, S., 1968, Erosion rates near Rome, Italy: Science, v. 160, p. 1444–1446.

Kirkby, M. J., 1971, Hillslope process-response models based on the continuity equation: Inst. British Geog. Spec. Pub. 3, p. 15–30.

Kohl, C. P., and Nishiizumi, K., 1992, Chemical isolation of quartz for measurement of in situ-produced cosmogenic nuclides: Geochim. Cosmochim, Act, v. 56, p. 3583–3587.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models: Earth Planet. Sci. Lett., v. 104, p. 424–439.

———, and Arnold, J. R., 1985, Tracing quartz through the environment: Proc. Indian Acad. Sci., Earth Planet. Sci., v. 94, p. 1–5.

———, and Peters, B., 1967, Cosmic ray-produced radioactivity on the earth, *in* Flugge, S., ed., Handbuch der Physik: Berlin, Springer-Verlag, p. 551–612.

Meade, R. H., 1988, Movement and storage of sediment in river systems, *in* Lerman, A., and Meybeck, M., eds., Physical and Chemical Weathering in Geochemical Cycles: Dordrecht, Kluwer, p. 165–179.

Meyer, W. B., and Turner, B. L., II, 1992, Human population growth and global land-use/cover change: Ann. Rev. Ecol. Syst., v. 23, p. 39–61.

Nishiizumi, K.; Finkel, R. C.; Caffee, M. W.; Southon, J. R.; Kohl, C. P.; Arnold, J. R.; Olinger, C. T.; Poths, J.; and Klein, J., 1994, Cosmogenic production of ^{10}Be and ^{26}Al on the surface of the earth and underground, *in* Eighth Int. Conf. on Geochronology, Cosmochronology, and Isotope Geology: U.S. Geol. Survey Circ. 1107, p. 234.

———; Kohl, C. P.; Arnold, J. R.; Dorn, R.; Klein, J.; Fink, D.; Middleton, R.; and Lal, D., 1993, Role of in situ cosmogenic nulides ^{10}Be and ^{26}Al in the study of diverse geomorphic processes: Earth Surf. Proc. Landforms, v. 18, p. 407–425.

———; Winterer, E. L.; Kohl, C. P.; Klein, J.; Middleton, R.; Lal, D.; and Arnold, J. R.; 1989, Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks: Jour. Geophys. Res., v. 94B, p. 17,907–17,915.

Pillans, B., 1988, Slope evolution of a flight of marine terraces in South Taranaki, New Zealand: Zeits. Geomorph., v. 69, p. 87–103.

Raymo, M. E.; Ruddiman, W. F.; and Froelich, P. N., 1988, Influence of late Cenozoic mountain building on ocean geochemical cycles: Geology, v. 16, p. 649–653.

Reneau, S. L.; Dietrich, W. E.; Rubin, M.; Donahue, D. J.; and Jull, J. T., 1989, Analysis of hillslope erosion rates using dated colluvial deposits: Jour. Geology, v. 97, p. 45–63.

Ruxton, B. P., and McDougall, I., 1967, Denudation rates in northeast Papua from potassium-argon dating of lavas: Am. Jour. Sci., v. 265, p. 545–561.

Schumm, S. A., and Hadley, R. F., 1961, Progress in the application of landform analysis in studies of semiarid erosion: U.S. Geol. Survey Circ. 437, 14 p.

Seidl, M. A.; Dietrich, W. E.; and Kirchner, J. W., 1994, Longitudinal profile development into bedrock: An analysis of Hawaiian channels: Jour. Geology, v. 102, p. 457–474.

Trimble, S. W., 1977, The fallacy of stream equilibrium in contemporary denudation studies: Am. Jour. Sci., v. 277, p. 876–887.

Willgoose, G.; Bras, R. L.; and Rodriguez-Iturbe, I., 1991, A coupled channel network growth and hillslope evolution model: 1. Theory: Water Resour. Res., v. 27, p. 1671–1684.