Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic ^{26}Al and ^{10}Be in alluvial sediment

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ABSTRACT

We used cosmogenic ^{26}Al and ^{10}Be in stream sediment to measure landscape-scale erosion rates for topographically diverse catchments at seven Sierra Nevada sites. At three sites, erosion rates and hillslope gradients are strongly correlated, increasing with proximity to fault scarps and river canyons, which appear to have accelerated local base-level lowering rates, and thus increased catchment erosion rates by up to 15-fold. At four other sites, far from fault scarps and river canyons, erosion rates are much more uniform and less sensitive to average hillslope gradient. Our measurements show that contrasts in landscape erosion rates cannot be inferred from hillslope gradients alone, because landscapes can evolve toward a state of erosional equilibrium, in which steep and gentle slopes erode at similar rates.

Keywords: cosmogenic nuclides, erosion rates, landscape evolution.

INTRODUCTION

Documenting patterns of erosion is essential for understanding how climate and tectonics regulate the evolution of mountainous landscapes. Hillslope evolution models often require long-term average erosion rates for validation and parameter calibration (e.g., Roering et al., 1999). Realistic tectonic modeling may also require long-term erosion-rate data, because isostatic response to erosional unloading can be an important component of tectonic uplift (e.g., Small and Anderson, 1995). Understanding how climate and topography affect erosion rates is also important for understanding patterns of sediment yield and for interpreting paleohydrology from sedimentary records (e.g., Walling and Webb, 1983). Quantifying patterns of erosion is also important for geochemists, because erosion influences chemical weathering by controlling the supply of fresh mineral surfaces (e.g., Stallard and Edmond, 1983). Erosion rates are therefore crucial for the quantitative study of soil formation (e.g., Heimsath et al., 1997), and for understanding patterns of solute fluxes from weathering (e.g., Gaillardet et al., 1999). Because silicate weathering affects atmospheric CO_2 over million-year time scales (Walker et al., 1981), quantifying relationships among erosion rates, mineral weathering, climate, and tectonics is also important for understanding Earth's long-term climatic evolution (Raymo et al., 1988; Molnar and England, 1990).

All else equal, if sediment transport rates are slope-dependent, then steep mountain slopes should be indicative of rapid uplift and erosion, whereas more subdued topography should indicate slower uplift and erosion. That is, landscape erosion rates should increase systematically with hillslope gradient and relief (e.g., Ahnert, 1970), unless differences in other factors offset the effects of slope. For example, rates of erosion and uplift may not be strongly correlated with slope gradients if lithologic differences create large local contrasts in bedrock erodibility. Hack (1960) suggested that erodibility contrasts might help explain how steep and gentle slopes of the lithologically diverse Appalachian Mountains could coexist, despite being graded to a common local base level; he proposed that under uniform erosion rates, transport of less erodible rock (e.g., chert) requires steeper slopes than more erodible rock (e.g., shale). Cosmogenic nuclide techniques permit direct measurement of long-term erosion rates (Lal, 1991), and thus can help in determining whether landscapes have evolved to reflect differences in erosion rates or differences in other factors such as erodibility.

We used cosmogenic nuclides to measure how erosion rates vary with hillslope gradients at seven granitic sites in the Sierra Nevada of California. Our results show that at sites near active faults and river canyons, hillslope gradients and erosion rates are strongly coupled, evidently because fault throw and river incision have locally accelerated lowering rates of erosional base levels. By contrast, at sites that are far from active faults and river canyons, our measurements show that erosion rates are decoupled from hillslope gradients. These sites have apparently evolved toward a state of erosional equilibrium, in which steep and gentle slopes erode at similar rates. Thus, average hillslope gradients are poor indicators of catchment erosion rates at our sites, particularly in landscapes that are from active river canyons and faults.

STUDY SITES

Our seven study sites are developed in Sierra Nevadan granites, granodiorites, and tonalites and lie outside the limits of late Pleistocene and Holocene glaciation (Bateman and Wahrhaftig, 1966). Climate varies widely among the study sites; annual precipitation ranges from 20 to 180 cm/yr (Rantz, 1972), and mean annual temperature spans 4 to 15 °C (Fig. 1). Vegetation also varies widely; oak and chapparal woodlands dominate in the warmer, wetter foothills, conifer forests prevail near the cooler, drier range crest, and desert scrub dominates in the rain shadow. The variations in climate and dominant vegetation within each site are small, compared to the differences from site to site. Variations in bedrock chemistry are also relatively small within each site, as samples from widely distributed outcrops show: abundances of the principal rock-forming elements (i.e.,

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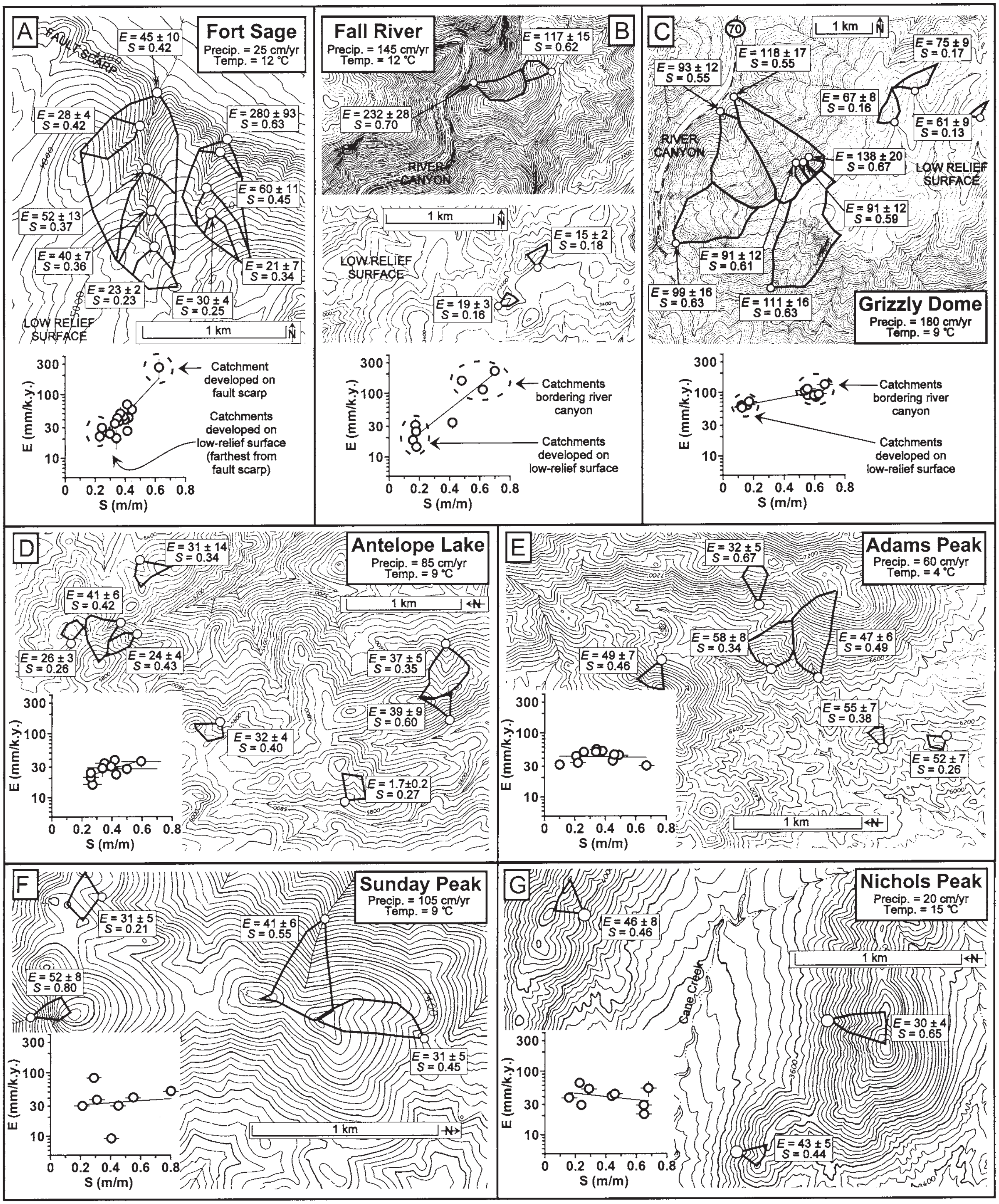

Figure 1. Contour maps (interval = 40 ft except in C, where interval = 80 ft) showing representative catchments (outlined by thick lines), sample locations (open circles), catchment erosion rates (*E*) and average slope gradients (*S*), and relationships between erosion rates and average slope gradients (inset) for each study site. Not all study catchments shown in plots are shown on maps. We provide latitudes and longitudes of all of our study catchments in Supplementary Table 3 (see footnote 1), which also includes names of U.S. Geological Survey 7.5′ quadrangles that we used as base maps. Average precipitation (Precip.) and mean annual temperature (Temp.) are given for each site. Erosion rates increase with average slope gradient and proximity to sources of local base-level forcing for three study areas; erosion rates on low-relief surfaces are distinctly lower than rates near prominent fault scarp (A, after Granger et al., 1996) and two high-relief canyons (B and C). Erosion rates are relatively uniform (see text) and are weakly correlated with average hillslope gradient at Antelope Lake (D), Adams Peak (E), Sunday Peak (F), and Nichols Peak (G).

those with concentrations >1%) vary by less than a factor of 1.7, and trace element concentrations typically vary by less than a factor of 2.[1]

At each study site, we sampled sediment from streams and hollows draining a series of small (0.4 to 112 ha) headwater catchments with average hillslope gradients ranging from 0.1 to 0.8 (see Fig. 1 for maps with representative catchments). We inferred each catchment's erosion rate from the concentrations of cosmogenic ^{26}Al and ^{10}Be in the quartz fraction of its sediment. These data permit us to determine how erosion rates vary with hillslope gradients across each site. Our analysis also incorporates previously published cosmogenic nuclide measurements from the Fort Sage Mountains of the Basin and Range (Granger et al., 1996), where erosion rates increase with hillslope gradients across a series of catchments developed on a granodioritic fault block.

MEASURING EROSION RATES FROM COSMOGENIC NUCLIDES

Cosmogenic ^{26}Al and ^{10}Be accumulate in quartz grains primarily by neutron spallation and muon capture (Lal, 1991). Attenuation of cosmic rays limits ^{26}Al and ^{10}Be production to the upper few meters of the landscape surface; neutron production declines exponentially with a mean free path in rock $\Lambda_n \cong 160$ g/cm^2 (Brown et al., 1992; Nishiizumi et al., 1994), whereas muogenic production attenuates approximately as an exponential with an *e*-folding length scale $\Lambda_m \cong 1300$ g/cm^2 (Brown et al., 1995a). In a steadily eroding rock with density ρ_b, the ^{26}Al and ^{10}Be concentrations at the surface will be

$$N = \frac{P_n}{\left(1/\tau + \rho_b E/\Lambda_n\right)} + \frac{P_m}{\left(1/\tau + \rho_b E/\Lambda_m\right)}\ , \tag{1}$$

where E is the erosion rate, N is the concentration of the radionuclide under consideration, P_n and P_m are its spallogenic and muogenic production rates, and τ is its radioactive mean life (Lal, 1991). Most previous work has overlooked nuclide production by negative muon capture, but doing so can lead to significant errors at quickly eroding sites (Heisinger, 1998). Fast muon reactions also contribute to nuclide production, but they are ignored here for the sake of simplicity.

Provided that the radioactive mean life is long compared to the erosional time scale ($\tau >> \Lambda_n/\rho_b E$), equation 1 reduces to

$$N = \frac{P_n\Lambda_n + P_m\Lambda_m}{\rho_b E}. \tag{2}$$

For typical erosion rates considered here (E >20 mm/k.y.), ignoring radioactive decay of ^{26}Al and ^{10}Be results in no more than 7% error for erosion-rate estimates.

Several studies (Brown et al., 1995b; Bierman and Steig, 1996; Granger et al., 1996) have adapted equation 2 to model nuclide accumulation in sediment draining from steadily eroding catchments. The model can be further modified to account for chemical weathering, which should selectively enrich the regolith with insoluble minerals (like quartz) and thereby increase their residence time near the surface (i.e., in the upper part of the cosmogenic exposure layer):

$$N = \frac{P_n\Lambda_n\left(\frac{f_r}{f_b} + \left(1 - \frac{f_r}{f_b}\right)e^{-\rho_r h/\Lambda_n}\right) + P_m\Lambda_m\left(\frac{f_r}{f_b} + \left(1 - \frac{f_r}{f_b}\right)e^{-\rho_r h/\Lambda_m}\right)}{\rho_b E}\ , \tag{3}$$

where ρ_r is regolith density, h is regolith thickness, and f_r and f_b are the fraction of quartz in regolith and bedrock, f_r/f_b revealing the fractional enrichment of insoluble quartz due to weathering losses (Small et al., 1999). Zr is also insoluble in most weathering reactions, and it can be easily measured by XRF (X-ray fluorescence), making it an ideal tracer for quartz enrichment. Thus, we can estimate f_r/f_b from the regolith-to-bedrock ratio of [Zr] in samples collected from widely distributed locations within each catchment. Quartz enrichment increases our inferred erosion rates by a maximum of 14% (see footnote 1). To infer spatially averaged long-term catchment erosion rates from our sediment samples, we isolated Al and Be from quartz extracts spiked with ^{9}Be, measured ^{26}Al and ^{10}Be concentrations by accelerator mass spectrometry, and then used equation 3. Our cosmogenic nuclide and erosion-rate results are available as supplemental data (see footnote 1).

RESULTS AND DISCUSSION

Our results reveal two distinctly different patterns of catchment erosion rates across our study sites. At three sites (Fort Sage, Fall River, and Grizzly Dome), erosion rates increase systematically with average hillslope gradient (Fig. 1, A–C), whereas at four other sites (Antelope Lake, Adams Peak, Sunday Peak, and Nichols Peak), erosion rates are more uniform and markedly less sensitive to average hillslope gradient (Fig. 1, D–G). We propose that erosion rates are strongly gradient-dependent at the first three sites because their local base-level lowering rates are highly variable. We propose that at the other four sites, local base-level lowering rates are more uniform, and variations in hillslope gradients are largely controlled by bedrock erodibility.

At Fort Sage, Fall River, and Grizzly Dome, marked differences in average hillslope gradients and erosion rates correspond to local contrasts in base-level lowering rates. At these sites, steeper, faster-eroding terrain is located near active fault throw or river canyon cutting, whereas gentler, slower-eroding slopes are located on isolated, low-relief surfaces. The catchments at Fort Sage, for example, are developed in a fault block, and their erosion rates vary by tenfold, increasing systematically with average hillslope gradient and proximity to the fault scarp (Fig. 1A).

At Fall River and Grizzly Dome, in the Sierra foothills, local contrasts in base-level lowering rates are imposed by river incision rather than fault throw, but the erosion-rate patterns are nevertheless similar. At Fall River, steep catchments near the Middle Fork Feather River canyon are eroding as much as 15 times faster than gentle slopes on nearby low-relief surfaces (Fig. 1B). At Grizzly Dome, steep catchments near the North Fork Feather River and Grizzly Creek (a major tributary) are eroding as much as 63 mm/k.y. faster than their gentler counterparts (Fig. 1C). At both of these sites, rapid canyon incision has apparently steepened nearby catchments, but rapid base-level lowering has not propagated to the low-relief uplands. Over the past ~2.5 m.y., river-incision rates near Fall River and Grizzly Dome have averaged 150–500 mm/k.y. (Wakabayashi and Page, 1994; J. Wakabayashi, 1999, personal communication), which is comparable to the erosion rates of our steep catchments, but much faster than those of the low-relief surfaces.

In contrast to the steep scarps and canyons of Fort Sage, Fall River, and Grizzly Dome, the landscapes at Antelope Lake, Adams Peak, Sunday Peak, and Nichols Peak show no clear evidence of local differences in base-level lowering rates; there are no high-relief canyons, fault scarps, or erosionally isolated low-relief surfaces near our study catchments (Fig. 1, D–G). Although these catchments span ranges in hillslope gradients that are as broad as those in our first three sites, their erosion rates are much more uniform and do not correlate strongly with gradients, probably because the individual catchments are not subject to markedly different base-level lowering rates. For example, at both Antelope Lake and Adams Peak (Fig. 1D and 1E), many of the catchments are linked to common streams, which show no clear signs of differential incision (such as knickpoints). Across both sites, catchment erosion rates are roughly uniform, varying by <30 mm/k.y., which is significantly less than the 60–250 mm/k.y. variations at Fort Sage, Fall River, and Grizzly Dome. At Antelope Lake, erosion rates are poorly correlated with hillslope gradients; the slope of the linear regression (Reed, 1992) of Figure 1E is only marginally different from zero (regression slope = 26% ± 13% change in erosion rate per 0.10 m/m change in slope; degrees of freedom = 8; 0.10 > p > 0.05). At Adams Peak, erosion

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[1] GSA Data Repository item 200084, Bedrock element abundances, study catchment morphology, and cosmogenic nuclide data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org/pubs/ft2000.htm.

rates increase slightly with hillslope gradients up to ~0.4, but decrease at higher gradients. Erosion rates at Nichols Peak are also relatively uniform, spanning only a 40 mm/k.y. range, and showing no clear trend; hillslope gradients range from 0.16 to 0.68 (Fig. 1G). At Sunday Peak, the pattern of erosion rates is somewhat complicated by a single, rapidly eroding, low-gradient catchment 2 km north of the catchments pictured in Figure 1F, but the erosion rates at the remaining catchments are more uniform, and they are not correlated with hillslope gradients.

At Antelope Lake, Adams Peak, Nichols Peak, and Sunday Peak, our study catchments are far from high-relief fault scarps and river canyons, drain to meadows and broad alluvial valleys, and in many instances are closely linked by common master streams. Relatively uniform erosion rates should be expected in these landscapes, and our measurements suggest that this is the case. Yet catchment gradients vary greatly, from ~0.2 to ~0.7.

How can erosional equilibrium (that is, uniform erosion rates) prevail across catchments with such widely differing hillslope gradients? Slopes of different gradients could persist under uniform base-level lowering rates if sediment transport were independent of slope, but we observe abundant field evidence of animal and insect burrowing, tree throw, and rainsplash, all suggesting that sediment transport is slope-dependent at our sites. Catchments with different average slopes could also have similar erosion rates, if erosion rates were controlled by other factors in addition to slope, such as catchment area (e.g., Stock and Montgomery, 1999), but we observe no correlation between erosion rates and catchment area at our sites (see footnote 1), so erosional equilibrium must be maintained by some other mechanism. Erosional equilibrium could be maintained if there were contrasts in erodibility across the terrain, such that less erodible bedrock supported steeper slopes under similar erosion rates (Hack, 1960). The fact that the bulk chemistry of the bedrock within each of our sites is relatively uniform (see footnote 1) suggests that any erodibility contrasts between our study catchments are probably not due to differences in bedrock bulk chemistry. Nevertheless, erodibility could be regulated by other bedrock characteristics, including fracture density, joint orientations, grain size, or small differences in mineralogy. Erodibility contrasts may help to explain why hillslope gradients are decoupled from erosion rates, even though sediment transport is slope dependent, at these sites.

CONCLUSIONS AND IMPLICATIONS

Cosmogenic nuclide data from Antelope Lake, Adams Peak, Sunday Peak, and Nichols Peak show that hillslopes with markedly different gradients can erode at similar rates, even within bedrock of roughly uniform chemical composition. Conversely, erosion rates are closely related to hillslope gradients across Fort Sage, Fall River, and Grizzly Dome; at these sites, accelerated river incision and fault throw have apparently left low-relief surfaces behind (at least until rapidly eroding, steep-walled river canyons and fault scarps can consume them and drive the landscape toward a new, faster equilibrium lowering rate).

Our results have implications for landscape modelers, land-use managers, and others who need to quantify patterns of erosion and sediment delivery from hillslopes. Mountain slope gradients can be a misleading guide to patterns of long-term average erosion rates, even if other factors like climate and lithology do not vary from slope to slope. Relief and average catchment slope may be better indicators of erosion rates in landscapes where hillslope gradients reflect strong contrasts in base-level lowering (e.g., as imposed by faults and river canyons). Our results show that cosmogenic measurements of erosion rates can be useful for determining whether differences in hillslope gradients are controlled by contrasts in base-level forcing or by other factors such as differences in erodibility and erosional processes.

ACKNOWLEDGMENTS

This project was supported by National Science Foundation grants EAR-9357931 and EAR-9614442 and was partially performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48. We thank N. Brozovic for field assistance, T. Teague for lab assistance, and W. Dietrich, L. Micheli, L. Sklar, J. Stock, J. Roering, and J. Wakabayashi for thoughtful discussions. Insightful reviews by P. Bierman and D. Montgomery helped us to improve the manuscript.

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Manuscript received January 24, 2000
Revised manuscript received June 1, 2000
Manuscript accepted June 14, 2000