Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales

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ABSTRACT

We used cosmogenic ^{10}Be to measure erosion rates over 10 k.y. time scales at 32 Idaho mountain catchments, ranging from small experimental watersheds (0.2 km^2) to large river basins (35 000 km^2). These long-term sediment yields are, on average, 17 times higher than stream sediment fluxes measured over 10–84 yr, but are consistent with 10 m.y. erosion rates measured by apatite fission tracks. Our results imply that conventional sediment-yield measurements—even those made over decades—can greatly underestimate long-term average rates of sediment delivery and thus overestimate the life spans of engineered reservoirs. Our observations also suggest that sediment delivery from mountainous terrain is extremely episodic, sporadically subjecting mountain stream ecosystems to extensive disturbance.

Keywords: erosion rates, sediment yield, Idaho batholith, variability, time scales.

INTRODUCTION

Documenting erosion rates, patterns, and processes is crucial for understanding how mountainous regions evolve (Molnar and England, 1990; Small and Anderson, 1995), for assessing the erosional impacts of land use (Brown et al., 1998; Montgomery et al., 2000; Pimentel et al., 1995), and for predicting how sediment loading will affect stream ecosystems. Hillslope erosion impairs soil fertility (Pimentel et al., 1995); it also delivers sediment to streams, thus altering aquatic habitats (Meehan, 1991) and limiting the operational life of reservoirs. Concern over the erosional consequences of land use (such as farming, grazing, logging, and road building) highlights the need to better understand natural rates of sediment yield and their natural range of variability (Trimble and Crosson, 2000).

METHODS

Whole-catchment sediment yields are normally calculated from sediment accumulation rates in reservoirs (sediment trapping) or from measurements of suspended sediment and bedload fluxes in streams (sediment gauging) (Meade, 1988). These direct measurements of sediment yield are typically available only for a few years or decades at any one site. A longer term perspective on erosion and sediment yield can be derived from the concentrations of in situ cosmogenic radionuclides, such as ^{10}Be, in sediment carried by streams. In situ ^{10}Be is produced from ^{16}O within mineral grains by bombardment by secondary cosmic rays (Lal and Peters, 1967). Because minerals at depth are shielded from cosmic rays, their ^{10}Be concentration when they reach Earth's surface indirectly records their exhumation rate (Lal, 1991). Concentrations of ^{10}Be have been widely used for determining exposure ages and erosion rates of rock outcrops, but these are difficult to translate into landscape erosion rates, because rocks crop out precisely because their erosion history differs from that of the surrounding terrain. Spatially averaged sediment yields can instead be inferred from ^{10}Be concentrations in alluvial sediments (Bierman and Steig, 1996; Brown et al., 1995a; Clapp et al., 2000; Granger et al., 1996; Riebe et al., 2000), which integrate the erosional products of an entire catchment, such that

$$\overline{q_s} = \frac{\overline{P_n}\Lambda_n + \overline{P_m}\Lambda_m}{\overline{N}} - W, \quad (1)$$

where $\overline{q_s}$ is the average sediment yield (mass per unit area per time), $\overline{P_n}$ and $\overline{P_m}$ are the area-averaged production rates of cosmogenic ^{10}Be by neutron spallation and negative muon capture, respectively, at the ground surface, $\Lambda_n = 160$ g·cm^{-2} and $\Lambda_m = 1300$ g·cm^{-2} are the effective mean free paths of neutrons and muons (Brown et al., 1995b), $\overline{N}$ is the ^{10}Be concentration in the sediment, and W is the rate of mass loss due to chemical denudation. Weathering fluxes W can be estimated either from catchment input-output mass balances (e.g., Clayton and Megahan, 1986) or from cosmogenic nuclide measurements coupled with bulk rock and soil geochemistry (Kirchner et al., 1997; Riebe et al., 2001a). Sediment yields inferred from equation 1 average erosion over a characteristic time scale of $\overline{N}/(\overline{P_n} + \overline{P_m})$, roughly corresponding to the time required to erode a layer of thickness $\Lambda_n/\rho_{rock} \approx 60$ cm from the surface. Decay of ^{10}Be can be ignored because its half-life (1.5×10^6 yr) is much longer than the erosion time scale at our sites.

FIELD SITES

We compared cosmogenic and conventional sediment-yield measurements at 32 forested granitic catchments in the mountains of central

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TABLE 1. LONG-TERM AND SHORT-TERM SEDIMENT YIELDS

Catchment*		Area (km^2)	Conventional: Record length (yr)	Conventional: Sediment yield ($t \cdot km^{-2} \cdot yr^{-1}$)	Cosmogenic: Time scale (yr)	Cosmogenic: Sediment yield ($t \cdot km^{-2} \cdot yr^{-1}$)
Silver Creek						
1	SC-2	1.2	27	13.2 ± 2.2	5 100	327 ± 42
2	SC-3	1.3	28	8.9 ± 1.4	9 400	174 ± 23
3	SC-5	1.1	28	10.9 ± 1.6	12 000	136 ± 18
4	SC-6	1.6	27	9.3 ± 1.7	11 000	152 ± 22
5	SC-7	0.23	22	14.4 ± 2.5	17 000	90 ± 12
6	SC-8	1.1	13	30.0 ± 10.6	13 000	121 ± 16
Horse Creek						
7	HC-2	0.57	10	7.3 ± 1.3	16 000	97 ± 13
8	HC-4	1.4	10	3.5 ± 0.6	18 000	89 ± 12
9	HC-6	1.0	15	3.3 ± 0.6	19 000	80 ± 11
10	HC-8	1.5	12	11.0 ± 3.0	17 000	90 ± 13
11	HC-9	0.23	10	8.6 ± 1.3	19 000	80 ± 11
12	HC-10	0.65	12	9.9 ± 2.4	17 000	92 ± 13
13	HC-12	0.83	14	8.2 ± 2.3	16 000	101 ± 14
14	HC-14	0.62	12	7.5 ± 2.3	19 000	80 ± 12
15	HC-16	0.21	13	25.1 ± 6.7	27 000	55 ± 8
16	West Fork	17	23	5.0 ± 0.5	18 000	87 ± 12
17	East Fork	14	23	2.5 ± 0.3	20 000	76 ± 11
Tailholt & Circle End Creeks						
18	Tailholt A	2.2	21	11.0 ± 2.5	6 300	264 ± 36
19	Tailholt B	1.6	22	14.6 ± 3.3	6 400	262 ± 34
20	Tailholt C	1.4	22	13.7 ± 2.4	8 200	202 ± 26
21	Tailholt Main	6.6	28	14.0 ± 2.8	7 000	239 ± 32
22	Circle End A	0.8	N.D.†	N.D.	7 300	226 ± 29
23	Circle End B	2.3	N.D.	N.D.	7 300	229 ± 30
24	Circle End Main	3.8	25	6.5 ± 1.1	7 700	215 ± 29
Larger Streams and Rivers						
25	Trapper Creek	20	10	9.8 ± 1.6	26 000	57 ± 8
26	South Fk. Red River	98	14	8.0 ± 1.4	25 000	58 ± 8
27	Upper Red River	129	14	10.1 ± 1.6	18 000	87 ± 12
28	Johns Creek	293	10	7.6 ± 1.3	15 000	108 ± 15
29	S. Fk. Clearwater R.	2 149	25	7.6 ± 2.3	17 000	91 ± 12
30	Lochsa River	3 055	72	26.3 ± 2.8	6 700	250 ± 32
31	Selway River	4 945	70	24.5 ± 3.2	8 100	205 ± 28
32	Salmon River	35 079	84	13.7 ± 4.1	6 300	261 ± 36

*Identification numbers are coded to Figure A and Table A (see footnote 1). Sampling and analytical details are given as notes accompanying Table A.
†N.D. = not determined.

Idaho (Table 1; see also Table A and Fig. A[1]; sampling and analytical details are given as notes accompanying Table A). Our catchments are rugged; average hillslope gradients range from 23% to 57%, and the valleys are characteristically narrow, steep, and V shaped. Opportunities for sediment storage in alluvial deposits are minimal, implying that sediment production and sediment delivery must be in approximate equilibrium over the 10 k.y. time scales of our cosmogenic measurements. Field observations indicate that soils are typically thin and hillslopes erode mainly by rain splash, tree throw, bioturbation, dry ravel, and shallow landsliding. Some sediment accumulates in small hollows and steep headwater channels, which in turn are episodically evacuated by shallow debris flows; this storage and episodic release of sediment has no measurable effect on its cosmogenic nuclide concentration (Appendix A; see footnote 1). Neither field evidence nor mapped topography indicates widespread bedrock landsliding, which would complicate the interpretation of our cosmogenic data.

RESULTS AND DISCUSSION

At every one of our sites, sediment yields measured by cosmogenic ^{10}Be over time scales of 5–27 k.y. are 2.2–38 (average = 17) times greater than sediment yields measured over 10–84 yr (average = 24 yr) by conventional sediment-trapping and sediment-gauging methods (Table 1; Fig. 1). At all scales, from small experimental catchments (0.2 km^2) to large river basins (35 000 km^2), long-term sediment yields are consistently much greater than conventional measurements over years or decades would suggest (Fig. 1).

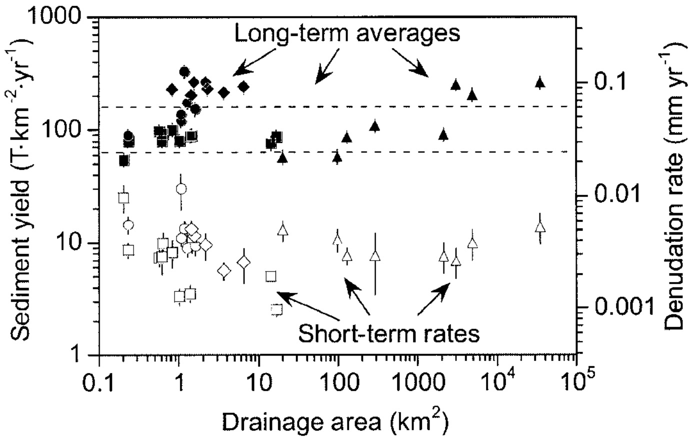

Figure 1. Short-term and long-term sediment yields for Idaho catchments. Catchment sediment yields were measured over 5–27 k.y. using cosmogenic ^{10}Be in alluvial quartz grains (closed symbols) and over shorter periods by conventional methods (open symbols): sediment trapping at Silver Creek (circles), Horse Creek (squares), and Tailholt and Circle End Creeks (diamonds), and sediment gauging at larger rivers (triangles). Data and methods are given in Table A (see footnote 1); standard errors are shown where larger than plotting symbols. Dotted lines indicate range of expected climate-driven variability in long-term sediment yields, inferred from cosmogenic ^{10}Be and ^{26}Al measurements at seven Sierra Nevada sites with average annual temperatures ranging from 4 to 15 °C and average annual precipitation ranging from 22 to 178 cm/yr (Riebe et al., 2001b).

This discrepancy cannot be attributed to artifacts in either of the measurement methods. We previously tested our cosmogenic sediment yield estimates for two small catchments against the accumulation rates of their debris fans, which have functioned as sediment traps for ~16 k.y. similar to the cosmogenic time scale (Granger et al., 1996). Both measurements agreed within 20%, indicating that our cosmogenic method accurately measures whole-catchment sediment yields over millennial time scales. Our cosmogenic measurements are corrected for present-day snow shielding; one could hypothesize greater snow depths in the distant past, but to account for the 18-fold discrepancy with the conventional sediment-yield measurements would require continuous year-round burial under more than 10 m of snow. Paleoclimate records indicate that, if anything, the region was somewhat warmer and drier throughout the middle Holocene (Doerner and Carrara, 1999; Fall et al., 1995; Sea and Whitlock, 1995; Whitlock, 1993), so snow shielding was even less significant in the past than it is at present. Our cosmogenic erosion measurements are consistent, within a factor of two, with much longer term (~10 m.y.) exhumation rates inferred from apatite fission tracks (Sweetkind and Blackwell, 1989), suggesting that they are not anomalously high (Fig. 2). These longer term exhumation rates are based on a somewhat uncertain geotherm, but for them to be consistent with the conventional sediment yields would require a geotherm of ~500 °C/km, which is unrealistic. Conventional sediment-yield measurements are also subject to many uncertainties (Meade, 1988), but none that could plausibly account for such a large discrepancy with the long-term rates across such a diverse array of catchments. Thus we conclude that the mismatch between the long-term and short-term measurements is not an artifact of the measurement methods.

Could this mismatch between long-term and short-term sediment

[1]GSA Data Repository item 2001064, Figure A (site location map), Table A (catchment characteristics and sediment yield data), and Appendix A (effects of shallow debris flows on cosmogenic nuclide measurements), is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

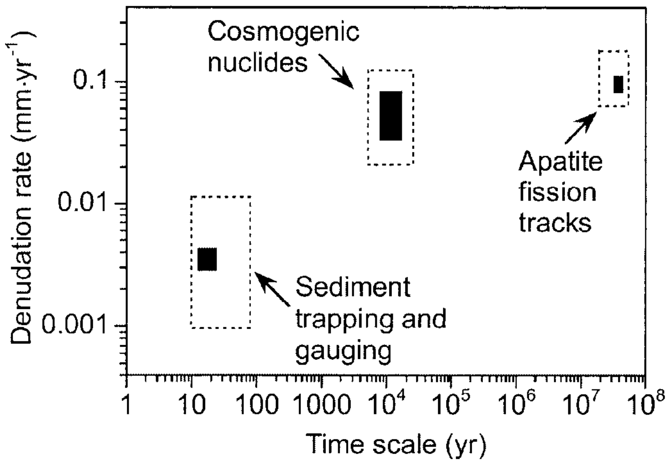

Figure 2. Idaho batholith erosion rates over 10 yr, 10 k.y., and 10 m.y. time scales. Dotted rectangles delimit ranges of measurements and corresponding time scales for conventional sediment-trapping and sediment-gauging methods, which average over decades, cosmogenic nuclides, which average over thousands of years or ~60 cm of erosion, and apatite fission tracks (Sweetkind and Blackwell, 1989), which average over tens of millions of years or ~3.6 km of erosion. Solid rectangles indicate middle 50% of each of three classes of measurements. Fission-track data do not include samples considered by Sweetkind and Blackwell (1989) to have anomalous thermal histories.

yields reflect climatic differences over the different time scales? Glaciation is unlikely to account for the differences we observe, because only 5 of our 30 catchments show evidence of Pleistocene glaciation, and their average erosion rates (both long term and short term) are similar to the other catchments (Table A; see footnote 1). Nonglacial erosion rates are not sensitive enough to climate to account for our results. In a separate study (Riebe et al., 2001b), we used cosmogenic nuclides to measure long-term erosion rates at seven unglaciated granitic Sierra Nevada sites that span a range of 4–15 °C in average temperature and 22–178 cm/yr in annual precipitation; across these diverse climatic regimes, long-term erosion rates vary by a factor of only 2.5 (indicated by the dashed lines in Fig. 1) and are uncorrelated with both temperature and precipitation ($r < 0.17$, $p > 0.5$). Even though, as the Sierran data indicate, long-term average climatic regimes have little effect on mountain erosion rates, one could still speculate that a recent shift in climate and vegetation may have transiently suppressed sediment delivery from hillslopes or channels at our sites. However, to account for the low present-day sediment yields, such a climate shift would need to reduce sediment delivery by an average of 94% throughout our study area, and paleoclimate proxy records from central Idaho (Biondi et al., 1999; Doerner and Carrara, 1999) and the northern Rockies and Cascades (Beiswenger, 1991; Fall et al., 1995; Sea and Whitlock, 1995; Whitlock, 1993; Whitlock and Bartlein, 1997) do not show dramatic changes in climate or vegetation over the past 2–3 k.y. One might suspect that the present-day sediment yields reflect anthropogenic influences; 10 of the 15 small catchments at Silver Creek and Horse Creek have been partially logged, and logging activities are scattered across most of our larger catchments. However, one would expect timber harvests to increase, rather than decrease, present-day sediment yields. We cannot definitively exclude the possibility that, for some as-yet undiscovered reason, there has been a recent shift in erosional processes that has dramatically lowered the present-day sediment yields in our study catchments, but we have no evidence that this is the case.

Episodic Nature of Sediment Yield

If the mismatch between long-term and short-term sediment yields is neither a measurement artifact nor a result of climate change, it must arise from extremely episodic sediment delivery, dominated by events that are large but rare—so rare that they are unlikely to be reflected in measurements over years or decades. For example, the sediment trap at Circle End Creek (catchment 24 in Table 1) measured a total sediment flux of 614 t over its 25 yr of operation, but in January 1997, an intense winter rainstorm triggered a debris flow on one of its tributaries (catchment 22 in Table 1) and released an estimated 6250 t of sediment, which dwarfed the 25 yr cumulative sediment flux by 10-fold and destroyed the sediment trap and gauging station. Catastrophic erosion events can also be triggered by convective storms following intense forest fires, which leave the soil surface unprotected until vegetation can regrow; one such storm eroded more than 100 000 t from 8 km^2 of catchments near Glenwood Springs, Colorado (Cannon et al., 1998). Our measurements suggest that events such as these are a normal (though infrequent and unpredictable) part of the erosional regime of mountain landscapes. That is, our measurements suggest that present-day sediment yields are not anomalously low, but instead are highly episodic, such that short-term measurements do not accurately capture the average sediment yield. For our long-term and short-term measurements to be even approximately compatible with one another, 70%–97% of sediment delivery must occur during episodes that are too infrequent to be detected by conventional sediment-yield measurements.

If these episodes were uncorrelated with each other, sediment yield would be less episodic in larger catchments, because they would average out stochastic fluctuations in sediment delivery from their component subcatchments (Benda and Dunne, 1997). Instead, the discrepancy between short-term and long-term sediment yields persists even in our largest catchments, suggesting that the factors driving episodic erosion events, such as extreme storms and catastrophic wildfire, must be highly correlated in space and time. For example, the same 1997 storm that triggered the debris flow at Circle End Creek also triggered debris flows to 100 km away, including one that released more than 7500 t of sediment from a 0.5 km^2 catchment (Wood and Meyer, 1997), and caused severe flooding as far away as California. Extreme precipitation events are spatially correlated over tens of thousands of km^2 (Dai et al., 1997), and large wildfires are similarly extensive; the Big Burn of 1910 scorched 12 000 km^2 of northern Idaho and western Montana.

The consistency between our cosmogenic erosion measurements and the much longer term fission-track exhumation rates (Fig. 2) implies that, as one might expect, sediment delivery is much less episodic over 10^4–10^7 yr time scales than it is over decades or centuries. Over human time scales, sediment delivery by hillslopes and channels is dramatically out of equilibrium with long-term sediment production at our study sites, but the disequilibrium is in the opposite direction from what one might expect (Clapp et al., 2000; Trimble, 1977); present-day short-term sediment yields are substantially below the long-term average.

Implications

Our results show that the erosional regime of mountain landscapes encompasses two distinct styles of sediment delivery. Incremental erosion prevails most of the time, but accounts for a small fraction of the total sediment yield; by contrast, catastrophic erosion events are rare and brief, but dominate the long-term sediment yield. Aquatic habitats subjected to such catastrophic sediment loads will be episodically disrupted, and the species that recolonize such disturbed habitats may differ from those that thrive under more stable, incremental sediment fluxes. Thus the episodic disturbance regime imposed by catastrophic sediment delivery may be more than just a cruel fact of life for montane aquatic ecosystems—it may also be essential for maintaining their diversity and productivity in the long term (Reeves et al., 1995). The episodic nature of sediment yield has practical consequences for human endeavors as well; our findings show that conventional sediment-yield data, even when collected over decades, can greatly underestimate the long-term sediment load, and thus overestimate the operational lifespan of reservoirs.

Mountain sediment yields are naturally episodic, but this should not be taken to imply that human impacts on erosion are inconsequential. Instead, our results suggest that anthropogenic effects on erosion need to be considered from two different perspectives. First, if human activities increase the rate of day-to-day incremental erosion, they may contribute little to the long-term average sediment yield (because catastrophic events dominate), but still significantly disrupt aquatic ecosystems that have evolved to cope with episodic upheaval rather than persistent low-level disturbance (Yount and Niemi, 1990). Second, human activities may alter the risk or the size of catastrophic erosion events (Hartman et al., 1996). Because these events are rare, quantifying the human impact on their magnitude or frequency will be inherently difficult.

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