Quantifying quartz enrichment and its consequences for cosmogenic measurements of erosion rates from alluvial sediment and regolith

Clifford S. Riebe [a,*], James W. Kirchner [a], Darryl E. Granger [b]

[a] *Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA*
[b] *PRIME Lab and Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA*

Abstract

In-situ cosmogenic [26]Al and [10]Be record the residence time of quartz grains near the earth's surface, and thus can be used to measure whole-catchment erosion rates averaged over millennial time scales. Quartz is enriched in hillslope regolith by the dissolution of more soluble minerals; thus, its residence time will be longer than the regolith average. It has been noted that this introduces a bias into erosion rate estimates derived from cosmogenic nuclide concentrations in regolith or alluvium [Geomorphology 27 (1999) 131], but the magnitude of this bias has not previously been measured. The enrichment of quartz in regolith, and the resulting bias in cosmogenic erosion rate estimates, can be quantified using concentrations of immobile elements (such as zirconium) in bedrock and regolith. Here we show that the erosion rate bias introduced by regolith dissolution is less than 12%, across 22 granitic catchments that span a wide range of temperate climates. Except in extreme weathering environments, biases due to regolith dissolution will be a small component of the overall uncertainty in cosmogenic erosion rate measurements. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction and methodology

Cosmogenic [26]Al and [10]Be in quartz can be used to infer whole-catchment erosion rates from alluvial sediment samples (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Recent work has proposed that selective dissolution of relatively solu-ble minerals introduces a significant bias in these measurements (Small et al., 1999). Quartz is rela-tively insoluble, so selective mineral dissolution will enrich it near the earth's surface, where most cosmo-genic nuclide production takes place. Selective disso-lution increases the residence time of quartz in re-golith compared to the average mineral grain. As a result, cosmogenic nuclide accumulations in quartz will not exactly reflect the erosion rate of the re-golith as a whole, because more time spent in the regolith also means more time spent exposed to cosmic radiation. If the effects of regolith dissolution

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on nuclide concentrations in quartz are overlooked, landscape erosion rates will be underestimated by a factor of $1/C_d$, with C_d given by (Small et al., 1999):

$$C_d = f_{soil}/f_{rock} + (1 - f_{soil}/f_{rock}) e^{-h \rho_{soil}/\Lambda}, \qquad (1)$$

where f_{soil} and f_{rock} are the concentrations of quartz in regolith and bedrock, respectively; h and ρ_{soil} are regolith thickness and density, respectively; and Λ is an exponential decay constant that quantifies how rapidly nuclide production declines with depth below the surface. The percentage error that results if quartz enrichment is overlooked can be quantified as:

$$\%\text{Error} = 100(E_{uncorrected} - E_{corrected})/E_{corrected}$$
$$= 100(1/C_d - 1). \qquad (2)$$

C_d accurately quantifies the effects of regolith dissolution on whole-catchment erosion rates if (i) regolith is well mixed during erosion, (ii) quartz is insoluble, and (iii) both regolith thickness and ero-

Table 1
Quartz-enrichment correction factors

Sample	Area (ha)	Hillslope gradient (m/m)	$[Zr]_{soil}$ (ppm)	$[Zr]_{rock}$ (ppm)	$[Zr]_{soil}/[Zr]_{rock}$	h (cm)	C_d	%Error
Fall River (39°38′N, 121°16′W; MAT: 12°C; AAP: 145 cm/year; lithology: tonalite)								
FR-2	0.7	0.48 ± 0.03	109 ± 6 (13)	92 ± 7 (15)	1.18 ± 0.11	25 ± 4	1.04 ± 0.03	4 ± 3
FR-5	2.6	0.62 ± 0.02	150 ± 5 (25)	119 ± 3 (11)	1.25 ± 0.05	52 ± 5	1.10 ± 0.03	9 ± 3
FR-6	17.8	0.42 ± 0.03	102 ± 3 (9)	83 ± 5 (3)	1.24 ± 0.08	*41 ± 3*	1.08 ± 0.01	6 ± 1
FR-8	2.2	0.18 ± 0.01	106 ± 3 (9)	87 ± 1 (3)	1.22 ± 0.04	10 ± 5	1.02 ± 0.01	2 ± 1
Antelope Lake (40°10′N, 120°38′W; MAT: 8°C; AAP: 83 cm/year; lithology: granodiorite)								
AL-4	1.9	0.43 ± 0.02	227 ± 8 (9)	166 ± 15 (4)	1.37 ± 0.13	*49 ± 8*	1.14 ± 0.06	12 ± 5
AL-5	4.5	0.34 ± 0.10	211 ± 10 (7)	165 ± 48 (2)	1.28 ± 0.38	45 ± 16	1.11 ± 0.15	10 ± 12
AL-9	1.1	0.60 ± 0.13	271 ± 18 (8)	211 ± 25 (3)	1.29 ± 0.17	*49 ± 8*	1.11 ± 0.07	10 ± 6
AL-10	11.1	0.40 ± 0.06	212 ± 6 (26)	183 ± 9 (10)	1.16 ± 0.07	53 ± 7	1.06 ± 0.03	6 ± 3
Adams Peak (39°53′N, 120°07′W; MAT: 4°C; AAP: 58 cm/year; lithology: granodiorite)								
AP-3	3.3	0.46 ± 0.03	135 ± 3 (20)	111 ± 2 (8)	1.21 ± 0.03	27 ± 9	1.06 ± 0.02	6 ± 2
AP-4	1.9	0.67 ± 0.05	115 ± 4 (9)	108 ± 1 (3)	1.07 ± 0.04	*34 ± 5*	1.02 ± 0.01	2 ± 1
AP-5	7.4	0.34 ± 0.04	129 ± 7 (9)	112 ± 3 (4)	1.14 ± 0.07	*34 ± 5*	1.04 ± 0.02	4 ± 2
AP-11	0.4	0.10 ± 0.01	129 ± 5 (4)	109 ± 6 (2)	1.18 ± 0.08	*34 ± 5*	1.06 ± 0.02	6 ± 2
AP-13	0.4	0.21 ± 0.03	131 ± 3 (4)	112 ± 5 (2)	1.17 ± 0.06	*34 ± 5*	1.06 ± 0.02	6 ± 2
Fort Sage (40°05′N, 120°04′W; MAT: 12°C; AAP: 25 cm/year; lithology: granodiorite)								
A1	2.1	0.25 ± 0.01	118 ± 5 (5)	112 ± 3 (2)	1.06 ± 0.05	*26 ± 2*	1.01 ± 0.01	1 ± 1
A2	4.8	0.30 ± 0.01	135 ± 5 (24)	118 ± 3 (7)	1.14 ± 0.05	20 ± 3	1.03 ± 0.01	3 ± 1
A3	11.7	0.39 ± 0.01	136 ± 4 (40)	116 ± 3 (11)	1.18 ± 0.04	24 ± 2	1.04 ± 0.01	4 ± 1
A4	13.2	0.41 ± 0.01	138 ± 3 (62)	117 ± 2 (17)	1.18 ± 0.03	24 ± 2	1.04 ± 0.01	4 ± 1
Nichols Peak (35°37′N, 118°13′W; MAT: 15°C; AAP: 22 cm/year; lithology: granodiorite)								
NP-1	1.1	0.44 ± 0.02	160 ± 10 (19)	127 ± 7 (7)	1.28 ± 0.10	33 ± 6	1.08 ± 0.04	7 ± 3
NP-18	0.7	0.24 ± 0.02	285 ± 15 (14)	203 ± 19 (5)	1.40 ± 0.15	29 ± 2	1.10 ± 0.04	9 ± 3
Sunday Peak (35°47′N, 118°35′W; MAT: 9°C; AAP: 105 cm/year; lithology: granite)								
SP-1	9.3	0.55 ± 0.05	252 ± 7 (23)	225 ± 12 (11)	1.12 ± 0.06	61 ± 12	1.06 ± 0.03	6 ± 3
SP-3	5.6	0.45 ± 0.05	245 ± 16 (9)	238 ± 12 (3)	1.03 ± 0.08	*61 ± 12*	1.01 ± 0.04	1 ± 4
SP-8	2.2	0.21 ± 0.05	278 ± 7 (8)	244 ± 13 (4)	1.14 ± 0.07	*61 ± 12*	1.06 ± 0.03	6 ± 3

Site characteristics include average annual precipitation (AAP) (Rantz, 1972), and mean annual temperature (MAT).
$\Lambda = 160 \pm 10$ g/cm (Brown et al., 1992; Nishiizumi et al., 1994).
Regolith density (ρ_{soil}) is assumed to be 1.6 ± 0.3 g/cm^3.
Regolith thickness (h) was measured between five and 38 soil pits in at least one catchment at each of the six sites. For catchments where no regolith thickness measurements are available, we use the average (in italics) from other catchments at the same site.
All values are reported as means ± standard errors (with number of samples in parentheses for Zr concentrations).

sion rate are in steady state over the time scale of nuclide accumulation (Small et al., 1999).

Small et al. (1999) showed that the bias introduced by regolith dissolution is potentially large, if the degree of quartz enrichment (f_{soil}/f_{rock}) is high. Thus, it is important to determine whether, in typical weathering environments, quartz enrichment is high enough to introduce significant bias into cosmogenic erosion rate estimates. To this end, we quantified C_d for each of 22 small (0.4–0.18 ha) catchments at six sites in the Sierra Nevada, CA. Bedrock at these sites consists of granites, granodiorites, and tonalites, with quartz concentrations ranging from ∼ 10% to roughly 40% (Hietanen, 1976; Oldenburg, 1995). Our six study sites span a wide range of climates, with mean annual temperatures ranging from 4°C to 15°C and average precipitation spanning 22–145 cm/year (Table 1). The individual study catchments also span a wide range of geomorphic settings, from fault scarps and river canyons to slowly eroding, low-relief surfaces (Riebe et al., 2000), with average hillslope gradients ranging from 0.10 to 0.67. Thus, our study catchments are representative of a broad range of geomorphic and climatic settings in which erosion rates might be inferred from cosmogenic nuclides.

Quantifying the dissolution correction factor (C_d) for each catchment requires estimating f_{soil}/f_{rock}, the enrichment of quartz in the regolith. Zirconium is highly immobile in most weathering environments, because zircon is insoluble, except in the presence of strong, oxidizing acids. Assuming that quartz and zircon are equally insoluble, the quartz enrichment factor f_{soil}/f_{rock} in Eq. (1) can be approximated by the zirconium enrichment factor $[Zr]_{soil}/[Zr]_{rock}$, which can be estimated using [Zr] measured by X-ray fluorescence. Quartz dissolution can be significant in extreme weathering environments, such as the tropics (Schulz and White, 1999), but should be minor in the young catchment soils and temperate climates considered here. If some quartz has dissolved during weathering in our catchments, then our estimates of quartz enrichment are maximums. $[Zr]_{soil}$ and $[Zr]_{rock}$ values used here are catchment-wide averages of [Zr] in regolith (sampled from at least four and as many as 62 widely distributed hillslope surfaces and soil pits) and bedrock (sampled from at least two and as many as 17 widely spaced outcrops

and saprolite horizons). Soil profiles revealed in pits and roadcuts show little or no horizontal zonation, indicating that regolith is well mixed, as required in Eq. (1).

2. Results and discussion

Across our 22 study catchments, the zirconium enrichment ratio $[Zr]_{soil}/[Zr]_{rock}$ averages 1.19, ranging from 1.03 ± 0.08 to 1.40 ± 0.15 (Table 1). Neglecting quartz enrichment at these sites would result in underestimating their erosion rates by an average of 6%, with the percent error at individual sites ranging from $1 \pm 1\%$ to $12 \pm 5\%$ (Table 1).

These erosion rate biases are too small to substantially affect results of previous cosmogenic nuclide studies of whole-catchment erosion rates. For example, at Fort Sage (one of our six study sites), Granger et al. (1996) showed that whole-catchment erosion rates inferred from cosmogenic nuclides agreed (within ∼ 20%) with long-term erosion rates measured from fan sediment accumulation, thus validating the nuclide technique. Quartz enrichment by regolith dissolution at Fort Sage affects the cosmogenic nuclide inferred erosion rates by 1–4% (Table 1), too little to warrant any reassessment of Granger et al.'s (1996) conclusions.

Quartz enrichment could be more significant in tropical environments, where regolith weathering is more intense. For example, at Rio Icacos, Puerto Rico, soil profile data reveal that zirconium is enriched in eroding material by a factor of ∼ 1.7, with a total depth to bedrock of 850 cm (White et al., 1998), implying that quartz enrichment would affect cosmogenic erosion rate estimates by roughly 50%. This suggests that in tropical environments subject to intense chemical weathering, the consequences of quartz enrichment will need to be quantified as part of cosmogenic erosion rate studies. Fortunately, where regolith is thick, accurate estimates of the dissolution correction factor (C_d) may not require measurements of regolith depth and density. Eq. (1) shows that C_d approaches f_{soil}/f_{rock}, independent of regolith depth and density, whenever the regolith is deep compared to the cosmogenic penetration depth (that is, $h\rho_{soil} \gg \Lambda$).

The importance of quartz enrichment biases should be evaluated by comparison with other significant

sources of uncertainty in cosmogenic erosion rate measurements. For example, estimates of sea-level, high-latitude production rates for ^{10}Be in quartz range from ~ 4.6 (Stone et al., 1998a) to ~ 6.0 at g^{-1} year^{-1} (Nishiizumi et al., 1989), with ongoing debate over the sources of the discrepancy (see discussions in Clark et al., 1995; Nishiizumi et al., 1996; Stone et al., 1998a). Furthermore, ^{10}Be and ^{26}Al production by cosmic ray muons has recently been reassessed (Heisinger, 1998; Stone et al., 1998b); in eroding minerals, the muogenic fraction of nuclide production can exceed 20% (Heisinger, 1998), much higher than previous estimates of $\sim 3\%$ (Lal, 1991). Scaling factors for the latitude and altitude dependence of production rate have also been reassessed; analyses presented by Dunai (2000) indicate that erosion rates based on the production rates scaling factors of Lal (1991) may be in error by up to 30%. Nuclide production rates remain the largest source of uncertainty in cosmogenic nuclide studies of erosion rates, introducing uncertainties of order 20–30%, much larger than the error introduced by quartz enrichment at our study sites (Table 1).

Our analysis shows how quartz enrichment, and its consequences for cosmogenic erosion rate estimates, can be quantified using zirconium concentrations in regolith and bedrock. Calculating the dissolution correction factor (C_d) requires measuring regolith thickness, regolith density, $[Zr]_{soil}$, and $[Zr]_{rock}$, all of which require significant investments of time and effort both in the field and in the lab. The decision to make this investment in any individual case will depend on whether the enrichment effect is expected to be significant, compared to the other sources of uncertainty. Our measurements suggest that, in typical temperate weathering environments, the bias introduced by quartz enrichment is relatively small. At tropical sites subject to intense chemical weathering, quartz enrichment effects are potentially large compared to other sources of uncertainty, and therefore merit the effort required to quantify them.

Acknowledgements

References

Bierman, P., Steig, E.J., 1996. Estimating rates of denudation using cosmogenic isotope abundances in sediment. Earth Surf. Processes Landforms 21, 125–139.

Brown, E.T., Brook, E.J., Raisbeck, G.M., Yiou, F., Kurz, M.D., 1992. Effective attenuation lengths of cosmic rays producing ^{10}Be and ^{26}Al in quartz: implications for exposure dating. Geophys. Res. Lett. 19, 369–372.

Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., Yiou, F., 1995. Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest Puerto Rico. Earth Planet. Sci. Lett. 129, 193–202.

Clark, D.H., Bierman, P.R., Larsen, P., 1995. Improving in situ cosmogenic chronometers. Quat. Res. 44, 367–377.

Dunai, T.J., 2000. Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation. Earth Planet. Sci. Lett. 176, 157–169.

Granger, D.E., Kirchner, J.W., Finkel, R., 1996. Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment. J. Geol. 104, 249–257.

Heisinger, B.P., 1998. Myonen-induzierte Produktion von Radionukliden. PhD Thesis, Technischen Universität München, Munich, 153 pp.

Hietanen, A., 1976. Metamorphism and plutonism around the Middle and South Forks of the Feather River, California. U.S. Geol. Surv. Prof. Pap. 920, 30 pp.

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

Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., Arnold, J.R., 1989. Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. J. Geophys. Res. 94 B, 17907–17915.

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

Nishiizumi, K., Finkel, R.C., Klein, J., Kohl, C.P., 1996. Cosmogenic production of ^{7}Be and ^{10}Be in water targets. J. Geophys. Res. 101 B, 22225–22232.

Oldenburg, E.A., 1995. Chemical and petrologic comparison of Cretaceous plutonic rocks from the Diamond Mountains, Fort Sage Mountains and Yuba Pass region of northeastern California. MS Thesis, Humboldt State University, Humboldt, CA, 99 pp.

Rantz, S.E., 1972. Mean annual precipitation in the California

Region, U.S. Geol. Survey, Basic-Data Compilation, 1:1,000,000 Map.

Riebe, C.S., Kirchner, J.W., Granger, D.E., Finkel, R.C., 2000. Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic ^{26}Al and ^{10}Be in alluvial sediment. Geology 28, 803–806.

Schulz, M.S., White, A.F., 1999. Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico: III. Quartz dissolution rates. Geochim. Cosmochim. Acta 63, 337–350.

Small, E.E., Anderson, R.S., Hancock, G.S., 1999. Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope. Geomorphology 27, 131–150.

Stone, J.O., Ballantyne, C.K., Fifield, L.K., 1998a. Exposure dating and validation of periglacial weathering limits, northwest Scotland. Geology 26, 587–590.

Stone, J.O.H., Evans, J.M., Fifield, L.K., Allan, G.L., Cresswell, R.G., 1998b. Cosmogenic chlorine-36 production in calcite by muons. Geochim. Cosmochim. Acta 62, 433–454.

White, A.F., Blum, A.E., Schulz, M.S., Vivit, D.V., Stonestrom, D.A., Larsen, M., Murphy, S.F., Eberl, D., 1998. Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico: I. Long-term versus short-term weathering fluxes. Geochim. Cosmochim. Acta 62, 209–226.