

Appendix 1: Sampling Rationale and Cosmogenic Nuclide Methodology

(Supplemental information for "Strong tectonic and weak climatic control of long-term chemical weathering rates")

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Introduction:

Here we report (1) detailed study site descriptions, (2) our rationale for sampling representative parent rock and weathered soil for average [Zr] and [Si] concentrations, (3) measurements of the [Zr] and [Si] of the individual rock and soil samples, (4) an extension of the mass-balance approach that permits us to partition our chemical weathering rates into contributions from individual chemical elements, (5) an evaluation of the assumption that soil depth is constant, (6) an evaluation of the assumption that eolian fluxes contribute negligibly to soil bulk chemistry, (7) our methods for measuring mean annual temperatures at the sites, (8) our methods for inferring whole-catchment denudation rates from cosmogenic nuclide concentrations in the quartz fraction of stream sediment samples, (9) the cosmogenic nuclide production rates that we used, (10) the cosmogenic nuclide concentrations, and (11) the inferred denudation rates, including all geographic and morphologic data required in the calculations.

Study Site Descriptions

The six study sites are developed in Mesozoic granites, granodiorites and tonalites of the Sierra Nevada and Basin and Range, California. Four of the six study sites are located at approximately 40 °N, along an East-West transect of the western Basin and Range and northern Sierra Nevada. The other two sites are located at ~36 °N, at the southern end of the Sierra Nevada Batholith.

All of the study sites lie outside the limits of late Pleistocene and Holocene glacial ice advance, as mapped by Bateman and Wahrhaftig (1966), and as attested by the absence of cirques, glacial lakes, moraines, and allocthonous sediments that would likely characterize an area that has recently been covered or eroded by alpine ice. The absence of topographic and

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sedimentological evidence of glacial erosion further indicates that, if any of the sites were eroded by glacial ice before the late Pleistocene, all traces of that early glacial erosion have been removed by subsequent non-glacial erosion. Thus, the denudation rates that are inferred from cosmogenic nuclide concentrations in sediment draining from catchment streams should be representative of non-glacial erosion. This is important because shielding by thick ice inhibits nuclide production in eroding rock, and erosion by ice may be episodic and deep and could thereby violate the steady-state denudation assumptions of the simple cosmogenic nuclide accumulation model presented later in this appendix. Erosion by periglacial mass wasting could also deviate significantly from steady state, but we observe no evidence of periglacial mass wasting at any of the sites (only the highest sites –Adams Peak and Sunday Peak– are likely to have had any permanent snow during recent glacial advances). Thus, it seems unlikely that our cosmogenic denudation rate estimates are strongly affected by pre-Holocene ice or snow shielding, or by glacial or periglacial erosion.

Climate varies widely among the study sites due to altitudinal and orographic effects; mean annual temperature spans 4 to 15 °C and annual precipitation ranges from 22 to 145 cm/yr (*Rantz, 1972*). Vegetation also varies widely among the sites; oak and chaparral woodlands dominate in the warmer, wetter foothills, conifer forests prevail near the cooler, drier range crests, 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. Large differences in climate across the sites imply that erosional processes differ from site to site; for example, sediment transport by tree throw is probably important at forested sites, but unimportant at desert sites, which are instead prone to rainsplash erosion because they lack protective vegetative cover.

Logging has been extensive in the areas surrounding the study sites (except at Fort Sage and Nichols Peak, which are in treeless deserts). Cosmogenic nuclides measurements average denudation rates over thousands of years and therefore are insensitive to the effects of recent land use (e.g., *Brown et al., 1998*), such as timber harvesting. Nevertheless, care was taken to avoid areas that have recently been disturbed by logging, because such activity could conceivably confound drainage patterns and thus bias the denudation rate estimates toward unrepresentative portions of the contributing area. We also avoided areas that show signs of intense soil disturbance, which could unearth material that has been shielded from cosmic radiation and thus cause denudation rates inferred from the methods presented here to be overestimated.

Hillslopes at all of our sites are soil mantled. With the exception of AP-4 (at the Adams Peak site) and AL-9 (at the Antelope Lake site), where boulder and bedrock outcrops cover 30-40% of the catchment area (*Granger et al., 2001*), the abundance of bare rock on slopes is everywhere low (less than 20%). Field observations suggest that, at all of the sites (including AP-4 and AL-9), sediment transport is dominated by diffusive processes such as tree throw, rainsplash, and soil creep. Bedrock landsliding and rockslides are not important sediment transport agents. If they were, we would observe accumulations of boulders and rock at the base of slopes and at catchment mouths. We observe no such accumulations in any of our catchments. Thus, erosion is apparently dominated by the removal of comminuted rock fragments (i.e., the chemically weathered soil that covers slopes). This implies that our sampling rationale, which targets weathered soils on the slopes (and is described below), should be sufficient to characterize

material leaving the catchments by erosion, and is therefore useful in obtaining representative long-term chemical weathering rates.

In a separate study we documented strong sensitivity of denudation rates to tectonic forcing at Fall River and Fort Sage, two of our sites (*Riebe et al., 2000*). The Fall River study catchments are centered around the confluence of the Fall River and the Middle Fork of the Feather River, which have incised steep-walled, 300-750 m deep canyons into a conspicuous, low-relief surface. Proximity to these canyons and their tributaries is apparently a surrogate for incision rate, an important control on catchment denudation rates; steep catchments near the canyons are eroding 15 times faster than catchments developed on the low-relief, intra-canyon surfaces. At the Fort Sage study site, catchments are inset into the north facing escarpment of the Fort Sage Mountains (see *Riebe et al., 2000*, Figure 1), a Basin and Range fault block situated on the edge of Honey Lake Basin. Cosmogenic nuclides show that denudation rates vary by roughly 10-fold across the Fort Sage catchments, increasing with average hillslope gradients (*Granger et al., 1996*) and proximity to a prominent fault scarp (*Riebe et al., 2000*). As is the case at Fall River, the Fort Sage landscape is marked by a low-relief upland surface, which is juxtaposed by steeper terrain with incised streams that are apparently cutting down in response to rapid base-level lowering (in this case localized along the fault scarp, rather than along a river canyon). As at Fall River, denudation rates at Fort Sage apparently depend on local stream incision rates, with the fastest denudation rates closest to the source of base-level lowering, and the slowest further away (presumably because rapid incision has not yet propagated distally through the drainage network). The Fort Sage study catchments have also been described by Granger (*1996*), who used cosmogenic nuclide concentrations in catchment stream sediment to estimate catchment-wide denudation rates from a nuclide accumulation model similar to that presented later in this appendix.

Sampling Soil and Rock for Representative Element Concentrations:

Measurements of the rock-to-soil enrichment of insoluble elements permit us to quantify the "chemical depletion fraction", or the fraction of total denudation that is accounted for by chemical weathering. Estimates of chemical depletion fractions in turn permit us to infer chemical weathering rates from estimates of total denudation rates (see main manuscript text for further details). Our measurements of denudation rates, inferred from cosmogenic nuclides in alluvial sediment, are catchment-wide averages, so the measurements of soil and rock chemistry that we use to infer chemical weathering rates should also be representative, catchment-wide averages. In other words, for consistency between the cosmogenic nuclide and weathering depletion measurements, we need representative element concentrations of pre-weathered rock and of weathered soil. Therefore, we sampled material from widely distributed rock outcrops, soil surfaces, and soil pits, and, after measuring the bulk chemical composition of each sample, we used catchment-wide averages of soil and rock composition for our weathering rate calculations.

Soil surfaces were sampled semi-randomly: we divided our watersheds into grids (e.g., with four equi-spaced points for small catchments and nine for larger catchments), occupied the approximate grid point locations in the field and sampled soil surfaces from randomly chosen 1-2 m² areas. In at least one catchment at each site, we also dug several soil pits, so that we

could sample subsurface soil material (i.e., colluvium) and saprolite (i.e., the chemically altered, but physically intact bedrock material at the base of mobile colluvium). Soil pits were located at high, mid, and low altitudes within each catchment, in an effort to sample material from the widest possible range of conditions. These soil pits revealed that the colluvium generally lacks strong vertical zonation.

Outcrops were also generally chosen from high, mid, and low elevation localities in each catchment, in an effort to sample as much of any lithologic variability as possible. We chose fresh outcrops wherever possible, but were occasionally limited to slightly altered material showing discoloration and staining (likely due to iron oxidation of mafic accessory minerals). Alteration was occasionally sufficient to induce a noticeable loss in grain-to-grain cohesion (compared to that of fresher rock), possibly due to biotite hydration, which presumably causes expansive stresses that can shatter granite along grain-to-grain contacts (*Larsen, 1948; Wahrhaftig, 1965*). Nevertheless, wherever both altered and fresh rocks were sampled in a catchment, they together have tight distributions of [Zr] and [Si] (Table A1), probably because the observed alteration (e.g., iron oxidation and biotite hydration) changes the mineralogy but does not substantially deplete the rock of soluble constituents. We further observe that average [Zr] in saprolite roughly equals average [Zr] in rock outcrops from the same catchment (Table A1), indicating that, like the altered outcrops, the saprolite is also largely undepleted of soluble constituents, even though its appearance and its friability suggest that its mineralogy has been altered. The fact that the bulk chemistry of fresh outcrops, slightly altered outcrops, and saprolite all roughly agree suggests that little weathering depletion occurs until material is incorporated into colluvium by soil production processes (e.g., animal burrowing, tree throw, freezing and thawing, and wetting and drying). These observations suggest that weathering rates may be limited by soil production rates, thus establishing a plausible mechanism for the strong coupling of weathering and erosion.

Within a catchment, element concentrations are more variable in soils than in rocks (Table A1). Compared to rocks, subsurface and surface soils alike show distinctly higher [Zr] on average (Table A1), consistent with enrichment of Zr by weathering in our catchments. Furthermore, the average [Zr] of subsurface soil material is, for the most part, very similar to that of soil on the surface, indicating that Zr concentrations from surface samples alone are generally representative of the [Zr] of soils and can therefore be used to infer representative weathering rates.

Our weathering rate measurements use average element concentrations that are based on the combined pool of rock and saprolite samples for $[Zr]_{\text{rock}}$ and the combined pool of surface and subsurface samples for $[Zr]_{\text{soil}}$. Sampling density ranges between ~0.5 to 20 samples/ha for soils and ~0.2 to 22 samples/ha for rocks.

Measurements of [Zr] and [Si] From Soil and Rock Samples:

We collected ~0.5 kg per sample of rock and soil, and, back in the lab, after oven drying the samples at ~110 °C for twelve hours, we used sample splitters to subsample ~30 g for analysis by X-ray fluorescence (XRF). After powdering each sample in a tungsten carbide grinding mill for ~5 minutes (resulting grain size: ~50 microns), samples were placed in ceramic crucibles and ignited in a muffle furnace at 550 °C for twelve hours, thus eliminating any organic material.

Concentrations of Si and other major rock-forming elements were measured from homogeneous glass specimens that were fused from mixtures of 0.5 g powdered sample and 3.5 g $\text{Li}_2\text{B}_4\text{O}_7$ flux in platinum crucibles at $\sim 1000^\circ\text{C}$ (Karathanasis and Hajek, 1996). Concentrations of Zr and other trace elements were measured from pressed powdered samples (~ 3 g each, encased in boric acid binder).

Element abundances were measured by XRF using a Phillips model PW 2400. Table A1 lists [Zr] in ppm and [Si] in weight % normalized for loss on ignition.

Calculating Chemical Weathering Rates of Silicon

The mass balance approach, as presented in the manuscript text, yields estimates of the bulk chemical weathering rate of eroding catchments. We can also write the mass balance for individual chemical elements that comprise the rock and soil. For example,

$$[\text{Si}]_{\text{rock}} \cdot D = [\text{Si}]_{\text{soil}} \cdot E + W_{\text{Si}}, \quad (\text{A1})$$

where $[\text{Si}]_{\text{rock}}$ and $[\text{Si}]_{\text{soil}}$ are representative concentrations of, in this case, silicon, in the rock and soil, and W_{Si} is the silicon weathering rate. Using equation 2 of the main text (i.e., $[\text{Zr}]_{\text{rock}} \cdot D = [\text{Zr}]_{\text{soil}} \cdot E$) we can show that

$$W_{\text{Si}} = D \cdot ([\text{Si}]_{\text{rock}} - [\text{Si}]_{\text{soil}} \cdot [\text{Zr}]_{\text{rock}} / [\text{Zr}]_{\text{soil}}). \quad (\text{A2})$$

Thus, flux rates of Si reported in Table 1 (main text) are inferred from [Zr] and [Si] in rock and soil and the denudation rates.

Steady-State Soil Depth Assumption

Equation 1 (main text) assumes that soil depth is constant. If soil production rates decrease with increasing soil thickness, as theory has predicted (Gilbert, 1877; Dietrich et al., 1995) and as soil production rates from hilly landscapes have shown (Heimsath et al., 1997), then soils should maintain relatively stable depths over the long term (Dietrich et al., 1995), even if soil production and removal become unbalanced from time to time. For example, if the rate of soil loss (i.e., by physical erosion and chemical weathering) decreases, soils will begin to thicken, causing soil production to decrease until it again balances soil removal, thus stabilizing soil depth at a slightly thicker value. If soil removal rates instead increased, soil depth would also stabilize, but at a slightly thinner value. Field observations suggest that soil forming processes at our sites are dominated by biogenic activity, freeze-thaw processes, and the infiltration of water (all of which presumably decrease in effectiveness with increasing soil thickness). These observations imply that soil production rates probably vary inversely with depth, and that soil depth should therefore be stable at our sites.

If steady-state assumptions were violated at our sites, chemical weathering rates inferred from equation 3 (main text) would be in error. Equation 1 of the main text would become

$$P_{\text{soil}} = E + W + \rho_{\text{soil}} \cdot dh/dt \quad (\text{A3})$$

where ρ_{soil} is soil density, h is soil depth, and dh/dt is the rate of change of soil depth. The magnitude of the weathering rate error will depend on the extent of the deviation from steady state. If the rate of change of soil depth is small compared to the actual weathering rate, the weathering rate error that is introduced by steady-state violations will be small enough to ignore. If steady-state soil depth assumptions were invalid at our sites, and rates of change of soil depth were rapid, we would expect to observe pervasive areas of bare rock or very thick soils, but this is not the case. Note that the sense of the weathering rate error, if present, will depend on whether soils are thickening (which would lead to overestimates) or thinning (which would lead to underestimates).

Eolian Fluxes

Our mass balance approach also assumes that eolian fluxes have a negligible effect on soil bulk chemistry. Eolian fluxes can affect the composition of moraines (*Burkins et al., 1999*) and marine terraces (*Merritts et al., 1992*), which have negligible erosion rates. However, in the mountainous catchments considered here, denudation rates are not negligible, so soil formation continually supplies fresh material as physical erosion and chemical weathering remove altered products from catchment hillslopes. If eolian fluxes were large compared to rates of soil formation, we would observe abundant field evidence of eolian deposition and remobilization, but no such evidence is present within our catchments. As long as eolian flux rates are small compared to total denudation rates, they should only minimally affect soil bulk chemistry. [Zr] and other trace element concentrations in soils would also be minimally affected by small eolian fluxes, unless the trace element concentrations in the eolian material were very different from those in the chemically weathered rock. Although such a possibility is difficult to rule out without knowing the deposition rates and bulk chemistry of eolian material, the patterns of weathering enrichment across our catchments suggest that eolian fluxes are probably not an important factor in our analysis. Figure 1 (main text) shows that chemical depletion fractions (and thus zirconium enrichments) are roughly uniform across our sites. To produce these patterns from the effects of eolian fluxes alone, rather than from chemical weathering rates being strongly coupled with denudation rates, eolian flux rates would have to differ from catchment to catchment in a way that selectively increased the apparent chemical weathering rate of the more rapidly eroding catchments. Such a coincidence seems unlikely.

Measuring Mean Annual Temperature

To measure mean annual temperatures, we first logged soil temperatures hourly between November, 1996 and June, 1999. Then, to estimate what mean annual temperatures have been over longer timescales, we first quantified the temperature differences between our sites and nearby weather stations using contemporaneously recorded data, and then used those temperature differences to derive long-term records for our sites from the 40-68 year-long weather station records.

How Cosmogenic Nuclide Concentrations in Quartz Reflect Long-Term Denudation Rates:

Cosmogenic ^{26}Al and ^{10}Be are produced 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 $\Lambda_n \cong 160 \text{ g/cm}^2$ (Brown et al., 1992; Nishiizumi et al., 1994), while muogenic production attenuates in what can be approximated as an exponential with an e -folding lengthscale $\Lambda_m \cong 1300 \text{ g/cm}^2$ (Brown et al., 1995a). In a steadily eroding rock, the ^{26}Al and ^{10}Be concentration at the surface will be

$$N = \frac{P_n}{(1/\tau + D/\Lambda_n)} + \frac{P_m}{(1/\tau + D/\Lambda_m)}, \quad (\text{A4})$$

where D is the total denudation 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 this can lead to significant errors at quickly eroding sites (Heisinger, 1998). Fast muon reactions also contribute a small fraction to nuclide production, but are ignored here for the sake of simplicity.

Provided that the radioactive meanlife is long compared to the erosional timescale ($\tau \gg \Lambda/D$), equation (A4) reduces to

$$N = \frac{P_n \Lambda_n + P_m \Lambda_m}{D}. \quad (\text{A5})$$

For typical denudation rates considered here ($D > 60 \text{ T/km}^2/\text{yr}$ or $\sim 20 \text{ mm/kyr}$), ignoring radioactive decay of ^{26}Al and ^{10}Be results in no more than 7% error for denudation rate estimates.

Measuring Whole-catchment Denudation Rates From Cosmogenic Nuclide Concentrations in Sediment:

Several studies (Brown et al., 1995b, Bierman and Steig, 1996; Granger et al., 1996) have adapted equation A5 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 insoluble minerals (like quartz) in soil and thereby increase their residence time near the surface (Small et al., 1999):

$$N = \frac{P_n \Lambda_n (f_s/f_b + (1 - f_s/f_b) e^{-D/\Lambda_n}) + P_m \Lambda_m (f_s/f_b + (1 - f_s/f_b) e^{-D/\Lambda_m})}{D}, \quad (\text{A6})$$

where f_s and f_b are the fraction of quartz in soil and bedrock, with (f_s/f_b) revealing the fractional enrichment of insoluble quartz due to weathering losses.

Zirconium is insoluble in most weathering reactions, making it an ideal tracer for quartz enrichment. We estimate (f_s/f_b) from the soil-to-bedrock ratio of $[\text{Zr}]$ in each of our catchments.

Cosmogenic ^{26}Al and ^{10}Be Production Rates in Quartz at the Earth's Surface:

Solving equation A6 for D also requires estimates of P_n and P_m . Cosmogenic nuclide production rates in quartz at the earth's surface depend on altitude and latitude (Lal, 1958; Lal and Peters, 1967). Spallogenic production rates are scaled from sea-level, high latitude (SLHL) reference values to sample altitude and geographic latitude using Table 2 of Lal (1991). The cosmic ray muon flux to Earth's surface is not strongly sensitive to latitude (see Granger et al., 2001 for further discussion). We therefore neglect latitude scaling of muogenic production rates in this analysis. Altitude scaling of muogenic production is best approximated by assuming

exponential attenuation in the atmosphere, with a mean free path of 247 g/cm^2 (Rossi, 1948). Nuclide accumulation on sloped surfaces is affected by topographic shielding, which effectively reduces production both at depth and at the surface. We account for these effects using shielding correction factors that depend on hillslope angle (Dunne et al., 1999).

SLHL muogenic production rates are estimated here to be (in $\text{atoms}\cdot\text{g}^{-1}\cdot\text{yr}^{-1}$) $P_m = 0.11\pm 0.01$ for ^{10}Be and $P_m = 0.81\pm 0.11$ for ^{26}Al , based on sea level stopping rates reported by Barton and Slade (1965), chemical compound factors and nuclear capture probabilities summarized by Heisinger et al. (1997), and branching ratio estimates for production of ^{26}Al (Strack et al., 1994) and ^{10}Be (Heisinger et al., 1997). For a detailed summary of muogenic production systematics, see Stone et al. (1998a).

Based on these SLHL muogenic production rates, the overall contribution of muons to ^{26}Al and ^{10}Be production at the surface is only $\sim 3\%$, in agreement with estimates of Brown et al. (1995a) and Stone et al. (1998a), but much lower than early estimates of $\sim 20\%$ (Lal, 1991). Previous production rate calibration studies (Nishiizumi et al., 1989; Kubik et al., 1998) used the early estimate of 20% production by muons. Here we use revised estimates of SLHL spallogenic production rates, that reflect the new estimate of $\sim 3\%$ contribution by muons. SLHL spallogenic production rates used here are (in $\text{atoms}\cdot\text{g}^{-1}\cdot\text{yr}^{-1}$) $P_n = 4.72\pm 0.38$ for ^{10}Be and $P_n = 28.45\pm 2.71$ for ^{26}Al . The SLHL P_n for ^{10}Be used in this study is an average of recalibrated estimates from four previous studies: (1) the Nishiizumi et al. (1989) work on glacial retreat in the Sierra Nevada, (2) the Clark et al. (1995) work on Laurentide ice retreat in New Jersey, U.S.A., (3) the Stone et al. (1998b) work on glacial retreat in Scotland, and (4) the Kubik et al. (1998) work on the K ofels landslide in Austria. SLHL P_n for ^{26}Al is calculated as the product of SLHL P_n for ^{10}Be and the spallogenic production rate ratio of $^{26}\text{Al}/^{10}\text{Be}$, which we take to be 6.03 ± 0.31 from data reported in the Sierra Nevada calibration study of Nishiizumi et al. (1989). Note that to rescale the Sierra Nevada production rates, we used ^{10}Be and ^{26}Al concentrations reported by Nishiizumi et al. (1989), revised glacial retreat ages reported by Clark et al. (1995), and, as suggested by Nishiizumi et al. (1996), geographic latitude of the calibration samples.

Cosmogenic Nuclide Concentrations:

Table A2 lists the cosmogenic nuclide concentrations in quartz from sediment draining our study catchments. To measure nuclide concentrations, we first physically and chemically isolated quartz from our stream sediment samples using the techniques of Kohl and Nishiizumi (1992) and Granger (1996), and then spiked the isolates with $\sim 1.25 \mu\text{g } ^9\text{Be}$ per gram of quartz. We then dissolved the quartz and extracted its Be and Al using ion exchange chromatography. BeO and Al_2O_3 targets were prepared for Accelerator Mass Spectrometry, which yields measurements of $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ (Davis et al., 1990). ^{10}Be concentrations are calculated using the $^{10}\text{Be}/^9\text{Be}$ and concentrations of Be in the quartz, which we know precisely from measurements of quartz masses and Be spike masses. ^{26}Al concentrations are calculated using $^{26}\text{Al}/^{27}\text{Al}$ and the concentration of aluminum in each quartz sample, which we measured from sample aliquots using Atomic Absorption Spectrophotometry and Inductively Coupled Plasma - Atomic Emission Spectrometry.

Long-term Denudation Rates:

Table A3 lists our denudation rate estimates, along with the geographic, morphologic and cosmogenic data that are necessary for estimating dissolution corrections, altitude and latitude scaling factors, and slope correction factors. Average hillslope gradients were measured by field surveys and from U.S. Geological Survey 7.5' quadrangles. Map names are listed after site names. Soil depths were measured in 5 to 38 pits per catchment at a subset of our study catchments. For catchments where no soil depths are available, we used site-wide averages (listed after site names) that were calculated using soil depths from other catchments at the same site (not all soil depth measurements from our sites are reported here, but are presented elsewhere; *Riebe et al., 2000*). Soil density is assumed to be $1.6 \pm 0.4 \text{ g/cm}^3$.

Denudation rates in Table A3 are inverse-variance-weighted averages \pm standard errors of erosion rates calculated from equation A5 for each nuclide. Denudation rate uncertainties were propagated using random and analytical uncertainties, and ignoring systematic uncertainties in production rates. Uncertainties on absolute denudation rates are typically ~ 1.2 times higher, but the climatic and erosional effects analysis is based on site-to-site comparisons between denudation rates, so relative uncertainty is what matters.

Cosmogenic nuclide data for the Fort Sage study site are reported in Granger et al. (1996). Fort Sage denudation rates have been revised for this analysis using equation A5 and our new estimates of production rates.

Table A1. Concentrations of zirconium and silicon

Fall River											
FR-2			FR-5			FR-6			FR-8		
Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]
type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)
o	90	33.4	o	112	31.7	o	74	34.4	o	89	34.0
o	73	33.8	o	124	32.2	o	83	34.4	o	86	33.9
o	92	34.8	o	109	32.6	o	91	34.4	o	85	33.7
r	97	34.5	o	111	32.3	s	83	34.1	s	93	35.3
r	81	35.3	r	98	36.7	s	112	34.7	s	105	33.6
r	119	33.6	r	120	32.7	s	112	31.9	s	116	34.1
r	119	33.8	r	126	32.5	s	107	33.7	s	101	34.4
r	109	32.5	r	130	32.6	s	96	34.2	s	102	34.3
r	148	31.4	r	136	32.3	s	103	32.9	s	122	34.1
r	54	34.4	r	115	32.2	s	100	34.8	s	98	34.3
r	54	34.1	r	125	32.1	s	101	34.0	s	103	34.2
r	57	37.4	s	144	32.5	s	106	34.1	s	111	34.5
r	88	33.6	s	133	33.1						
r	85	33.6	s	157	32.2						
r	119	32.3	s	132	32.2						
s	90	34.6	s	140	32.7						
s	126	35.4	s	150	32.8						
s	126	34.4	s	154	32.4						
s	92	35.1	s	166	33.0						
s	122	34.0	s	134	32.8						
s	134	32.9	s	147	32.9						
s	141	33.7	s	142	32.2						
s	122	33.9	s	142	31.7						
s	104	34.7	s	131	N.D.						
s	110	35.6	s	149	33.0						
s	72	35.1	s	153	33.9						
s	74	34.2	s	138	32.1						
s	100	32.1	c	150	32.3						
			c	140	32.9						
			c	235	28.8						
			c	130	32.5						
			c	223	29.1						
			c	151	32.7						
			c	131	32.6						
			c	136	32.2						
			c	143	32.0						
Avg. rock:	92	33.9		119	32.7		83	34.4		87	33.9
±	7	0.4		3	0.8		5	0.0		1	0.1
Avg. "o":	85	34.0		114	32.2		83	34.4		87	33.9
±	6	0.4		3	0.2		5	0.0		1	0.1
Avg. "r":	94	33.9		121	33.0						
±	9	0.4		5	0.6						
Avg. soil:	109	34.3		150	32.3		102	33.8		106	34.3
±	6	0.3		5	0.1		3	0.3		3	0.2
Avg. "s":	109	34.3		145	32.6		102	33.8		106	34.3
±	6	0.3		2	0.1		3	0.3		3	0.2
Avg. "c":				160	31.7						
±				13	0.5						

Table A1 (continued). Concentrations of zirconium and silicon

Fort Sage											
A1			A2(s)			A3(s)			A4(s)		
Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]
type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)
o	114	30.8	o	114	30.8	o	115	31.1	o	119	31.3
o	109	31.3	o	109	31.3	o	100	31.4	o	124	31.0
s	136	32.8	r	109	31.6	o	117	31.0	r	118	30.8
s	114	33.1	r	128	31.3	o	119	N.D.	r	118	31.2
s	114	32.8	r	115	31.2	s	115	32.3	r	109	31.2
s	104	33.2	r	132	31.2	s	133	32.5	r	128	30.6
s	122	32.7	r	114	31.1	s	138	31.4	s	144	30.6
			s	155	31.9	s	116	32.5	s	112	31.1
			s	115	33.0	s	136	31.0	s	142	30.8
			s	119	32.5	s	106	31.5	s	154	30.3
			s	123	32.2	s	134	31.3	s	132	30.9
			s	136	31.7	s	106	32.3	s	142	31.1
			s	156	31.8	s	127	31.1	s	136	31.0
			s	135	32.1	s	148	30.9	s	154	31.0
			s	121	32.4	s	130	31.5	s	139	31.0
			s	91	34.7	s	195	30.4	s	180	30.9
			s	168	31.8	s	134	31.1	s	134	30.9
			s	144	31.8	s	195	30.5	s	153	30.3
			s	160	31.1	s	173	30.5	s	141	30.3
			c	123	32.0	s	131	N.D.	s	139	30.7
			c	120	N.D.				c	153	30.3
			c	142	30.9				c	151	30.2
			c	132	31.5				c	134	30.3
			c	152	31.3				c	128	31.0
			c	173	30.8				c	161	30.2
			c	184	30.5				c	132	30.6
									c	143	30.3
									c	129	30.6
Avg. rock:	111	31.1		118	31.2		113	31.2		119	31.0
±	3	0.3		3	0.1		4	0.1		3	0.1
Avg. "o":	111	31.1		112	31.1		113	31.2		122	31.2
±	3	0.3		3	0.3		4	0.1		3	0.2
Avg. "r":				120	31.3					118	31.0
±				4	0.1					4	0.1
Avg. soil:	118	32.9		139	31.9		138	31.4		142	30.7
±	5	0.1		5	0.2		7	0.2		3	0.1
Avg. "s"	118	32.9		135	32.3		138	31.4		143	30.8
±	5	0.1		6	0.3		7	0.2		4	0.1
Avg. "c"				147	31.2					141	30.4
±				9	0.2					4	0.1

Table A1 (continued). Concentrations of zirconium and silicon

Antelope Lake											
AL-4			AL-5			AL-9			AL-10		
Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]	Sample	[Zr]	[Si]
type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)	type	(ppm)	(%)
o	198	28.6	o	212	30.3	o	261	28.5	o	198	28.8
o	163	28.5	o	117	29.6	o	185	27.7	o	185	27.1
o	176	28.6	s	220	28.8	o	187	28.5	r	207	28.0
r	126	31.7	s	207	30.4	s	339	28.6	r	181	27.7
s	233	29.2	s	177	30.2	s	316	29.2	r	202	28.2
s	245	29.0	s	183	31.8	s	254	28.1	r	129	27.1
s	199	30.1	s	205	30.9	s	247	28.0	r	145	27.3
s	237	28.6	s	237	29.7	s	340	28.2	r	183	28.5
s	230	28.8	s	251	29.8	s	211	28.5	r	182	27.7
s	231	28.9				s	237	N.D.	r	223	27.9
s	217	29.1				s	224	28.0	s	227	27.6
s	185	28.2							s	252	28.3
c	263	28.7							s	222	28.4
									s	217	28.6
									s	220	27.3
									s	229	28.5
									s	194	27.7
									s	220	27.9
									s	123	32.4
									s	217	27.4
									s	215	27.2
									s	225	27.3
									s	223	27.3
									s	161	27.5
									s	229	28.6
									s	215	28.1
									c	130	32.4
									c	205	28.3
									c	244	27.8
									c	230	27.4
									c	237	27.5
									c	203	27.4
									c	220	28.6
									c	230	28.6
									c	212	28.5
									c	224	28.2
Avg. rock:	166	29.4	165	29.9		211	28.2		183	27.8	
±	15	0.8	48	0.4		25	0.3		9	0.2	
Avg. "o":	166	29.4	165	29.9		211	28.2		192	28.0	
±	15	0.8	48	0.4		25	0.3		7	0.8	
Avg. "r":									182	27.8	
±									11	0.2	
Avg. soil:	226	29.0	211	30.2		271	28.4		212	28.0	
±	8	0.1	11	0.4		19	0.2		6	0.3	
Avg. "s":	226	29.0	211	30.2		271	28.4		212	28.1	
±	8	0.1	11	0.4		19	0.2		8	0.3	
Avg. "c":									214	28.5	
±									10	0.5	

Table A1 (continued). Concentrations of zirconium and silicon

Sunday Peak									Nichols Peak					
SP-1			SP-3			SP-8			NP-1			NP-18		
Sample type	[Zr] (ppm)	[Si] (%)	Sample type	[Zr] (ppm)	[Si] (%)	Sample type	[Zr] (ppm)	[Si] (%)	Sample type	[Zr] (ppm)	[Si] (%)	Sample type	[Zr] (ppm)	[Si] (%)
o	203	34.3	o	246	34.1	o	232	N.D.	o	136	31.0	o	229	27.7
o	228	33.5	o	254	33.5	o	256	33.1	o	144	31.3	r	169	33.3
o	212	33.6	o	215	34.0	o	215	34.1	r	113	30.8	r	260	31.7
r	240	33.5	s	264	33.1	o	272	32.8	r	96	32.3	r	202	28.7
r	163	33.5	s	296	33.1	s	259	33.2	r	137	31.7	r	156	27.2
r	219	35.2	s	219	33.9	s	261	34.1	r	138	31.2	s	202	33.7
r	254	33.9	s	333	33.3	s	291	34.6	r	113	31.4	s	343	31.1
r	286	33.7	s	208	34.3	s	268	34.7	s	148	32.1	s	276	29.3
r	162	32.6	s	258	33.2	s	270	33.9	s	161	32.5	s	213	33.4
r	247	36.8	s	188	34.3	s	322	33.6	s	172	32.0	s	211	31.6
r	254	34.6	s	200	33.8	s	283	33.0	s	98	33.5	s	298	31.7
s	256	34.5	s	245	33.8	s	270	34.2	s	152	32.3	s	300	30.8
s	264	35.6							s	226	30.9	s	323	31.6
s	276	33.9							s	91	33.5	s	322	30.9
s	275	33.5							s	188	31.0	s	336	30.5
s	208	35.1							s	223	30.6	s	265	31.1
s	218	35.4							s	182	30.3	s	384	32.5
s	237	33.9							s	129	32.0	c	278	30.3
s	211	35.0							s	214	30.3	c	243	31.4
s	189	35.3							s	210	30.7			
s	286	33.5							s	86	32.9			
s	264	33.9							c	140	31.3			
s	233	34.7							c	135	31.4			
s	214	34.4							c	170	29.8			
s	305	32.8							c	152	31.0			
s	278	33.7							c	159	30.7			
c	229	34.7												
c	276	34.2												
c	232	34.2												
c	234	34.6												
c	293	32.8												
c	276	33.6												
c	280	33.5												
c	262	33.6												
<hr/>														
Avg. rock:	225	34.1		238	33.9		244	33.3		125	31.4		203	29.7
±	12	0.3		12	0.2		13	0.4		7	0.2		19	1.2
Avg. "o":	214	33.8		238	33.9		244	33.3		140	31.2		229	27.7
±	7	0.3		12	0.2		13	0.4		4	0.2			
Avg. "r":	228	34.2								119	31.5		197	30.2
±	16	0.5								8	0.3		23	1.4
<hr/>														
Avg. soil:	252	34.2		246	33.6		278	33.9		160	31.5		285	31.4
±	7	0.2		16	0.2		7	0.2		10	0.2		15	0.3
Avg. "s":	248	34.3		246	33.6		278	33.9		163	31.8		289	31.5
±	9	0.2		16	0.2		7	0.2		13	0.3		17	0.4
Avg. "c":	260	33.9								151	30.8		261	30.9
±	9	0.2								6	0.3		18	0.5

[Si] reported in weight percent and normalized for loss on ignition.

Samples types: "o" = rock outcrops, "r" = saprolite, "s" = soil surfaces, and "c" = colluvium (i.e., subsurface soil material).

N.D. = not determined.

"Avg. rock" incorporates outcrop and saprolite data, whereas "Avg. soil" incorporates soil surface and colluvium data. Uncertainties (\pm) are standard errors of their respective means.

Table A2. Cosmogenic nuclide data for study catchments

Sample	$^{10}\text{Be}/^9\text{Be}$ (10^{-15})	$^{26}\text{Al}/^{27}\text{Al}$ (10^{-15})	$[^{10}\text{Be}]$ (10^5 atoms/g)	$[^{26}\text{Al}]$ (10^6 atoms/g)	$[^{26}\text{Al}]/[^{10}\text{Be}]$
<u>Fall River:</u>					
FR-2	48±7	302±29	0.517±0.084	0.234±0.025	4.52±0.88
FR-5	33±7	663±60	0.395±0.085	0.258±0.027	6.53±1.56
FR-6	279±12	1009±34	2.562±0.169	0.980±0.059	3.83±0.34
FR-8	556±15	2835±89	5.523±0.314	2.898±0.171	5.25±0.43
<u>Adams Peak:</u>					
AP-3	205±13	1484±72	3.030±0.192	1.990±0.220	6.57±0.84
AP-4	297±14	1870±55	4.090±0.193	2.642±0.280	6.46±0.75
AP-5	167±8	1229±46	2.538±0.122	1.584±0.170	6.24±0.73
AP-11	540±26	2342±61	5.915±0.411	2.993±0.169	5.06±0.45
AP-13	234±10	1460±42	3.239±0.209	1.813±0.105	5.60±0.48
<u>Antelope Lake:</u>					
AL-4	402±17	2213±55	5.328±0.349	2.847±0.159	5.34±0.46
AL-5	374±20	1563±39	4.189±0.307	2.444±0.137	5.84±0.54
AL-9	275±13	1341±35	3.122±0.215	1.843±0.104	5.90±0.53
AL-10	278±13	1323±35	4.008±0.274	2.359±0.133	5.89±0.52
<u>Sunday Peak:</u>					
SP-1	284±16	1060±28	3.189±0.242	2.167±0.123	6.80±0.64
SP-3	522±11	1809±47	5.063±0.275	2.673±0.151	5.28±0.41
SP-8	921±33	3734±92	6.063±0.373	3.417±0.190	5.64±0.47
<u>Nichols Peak:</u>					
NP-1	81±9	745±38	1.647±0.194	0.977±0.070	5.93±0.82
NP-18	116±7	1269±77	2.612±0.208	1.557±0.122	5.96±0.67
Cosmogenic nuclide data for the Fort Sage mountain site are reported elsewhere (<i>Granger et al., 1996</i>).					
Uncertainties in $[^{26}\text{Al}]/[^{10}\text{Be}]$ are propagated from analytical uncertainties in the Al and Be analyses.					

Table A3. Study catchment morphology and denudation rates

Sample	Location			Area (ha)	Average gradient (m/m)	$\frac{[Zr]_{soil}}{[Zr]_{rock}}$	Soil depth (cm)	Dissolution factor	Shielding factor	Denudation rate ($t \cdot km^{-2} \cdot yr^{-1}$)
	Altitude (km)	Lat (° N)	Long (° W)							
Fall River (Map = Brush Creek; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.23 \pm 0.03$; Average soil depth = 41 ± 3 cm)										
FR-2	0.93	39.6604	121.3607	0.7	0.48±0.03	1.18±0.11	25±4	1.04±0.03	0.87±0.01	393±82
FR-5	0.60	39.6361	121.2714	2.6	0.62±0.02	1.25±0.05	52±5	1.10±0.03	0.80±0.01	293±36
FR-6	0.87	39.6385	121.3322	17.8	0.42±0.03	1.24±0.08	41±3	1.08±0.03	0.89±0.01	89±25
FR-8	1.06	39.6586	121.3230	2.2	0.18±0.01	1.22±0.04	10±5	1.02±0.01	0.98±0.00	38±5
Antelope Lake (Map = Kettle Rock; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.21 \pm 0.07$; Average soil depth = 49 ± 8 cm)										
AL-4	1.74	40.1775	120.6382	1.9	0.43±0.02	1.37±0.13	N.D.	1.14±0.06	0.89±0.01	66±8
AL-5	1.69	40.1785	120.6288	4.5	0.34±0.10	1.28±0.38	N.D.	1.11±0.15	0.93±0.04	78±12
AL-9	1.80	40.1546	120.6450	1.1	0.60±0.13	1.29±0.17	N.D.	1.11±0.07	0.82±0.07	98±13
AL-10	1.80	40.1548	120.6376	11.1	0.40±0.06	1.16±0.07	53±7	1.06±0.03	0.90±0.03	81±8
Adams Peak (Map = Constantia; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.15 \pm 0.03$; Average soil depth = 34 ± 5 cm)										
AP-3	2.14	39.8987	120.1351	3.3	0.46±0.03	1.21±0.03	27±9	1.05±0.02	0.88±0.01	124±12
AP-4	2.19	39.8917	120.1409	1.9	0.67±0.05	1.07±0.04	N.D.	1.02±0.01	0.78±0.03	83±8
AP-5	2.05	39.8904	120.1339	7.4	0.34±0.04	1.14±0.07	N.D.	1.04±0.02	0.93±0.02	148±13
AP-11	2.25	39.8917	120.1443	0.4	0.10±0.01	1.18±0.08	N.D.	1.05±0.03	0.99±0.00	90±12
AP-13	1.89	39.8802	120.1275	0.4	0.21±0.03	1.17±0.06	N.D.	1.05±0.02	0.97±0.01	117±12
Sunday Peak (Map = Tobias Peak; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.11 \pm 0.05$; Average soil depth = 61 ± 12 cm)										
SP-1	2.27	35.7938	118.5899	9.3	0.55±0.05	1.12±0.06	61±12	1.06±0.03	0.84±0.03	108±12
SP-3	2.33	35.7981	118.5833	5.6	0.45±0.05	1.03±0.08	N.D.	1.01±0.04	0.88±0.02	82±10
SP-8	2.42	35.7830	118.5915	2.2	0.21±0.05	1.14±0.07	N.D.	1.06±0.03	0.97±0.01	82±8
Nichols Peak (Map = Cane Canyon; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.32 \pm 0.11$; Average soil depth = 30 ± 1 cm)										
NP-1	1.12	35.5922	118.2255	1.1	0.44±0.02	1.28±0.1	33±6	1.08±0.04	0.88±0.01	113±11
NP-18	1.18	35.5221	118.2014	0.7	0.24±0.02	1.4±0.15	29±2	1.10±0.04	0.96±0.01	81±8
Fort Sage (Map = Doyle; Average $\frac{[Zr]_{soil}}{[Zr]_{rock}} = 1.18 \pm 0.03$; Average soil depth = 26 ± 2 cm)										
A1	1.53	40.0898	120.0624	2.1	0.25±0.01	1.06±0.05	N.D.	1.01±0.01	0.96±0.00	77±7
A2(s)	1.51	40.0916	120.0615	2.7	0.34±0.01	N.A.	N.A.	N.A.	N.A.	56±15
A3(s)	1.48	40.0938	120.0606	6.9	0.45±0.01	N.A.	N.A.	N.A.	N.A.	152±27
A4(s)	1.45	40.0946	120.0601	1.5	0.63±0.01	N.A.	N.A.	N.A.	N.A.	680±211
Map names refer to U.S. Geological Survey 7.5' quadrangles (topographic) of the study areas.										
(s) after sample name indicates denudation rate is calculated by subtraction of areas technique. See Granger et al. (1996) for details.										
N.D. = not determined.										
N.A. = not applicable.										

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