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Cosmogenic nuclide methods for measuring long-term rates of physical erosion and chemical weathering

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Abstract

Understanding the evolution of geochemical and geomorphic systems requires measurements of long-term rates of physical erosion and chemical weathering. Erosion and weathering rates have traditionally been estimated from measurements of sediment and solute fluxes in streams. However, modern sediment and solute fluxes are often decoupled from long-term rates of erosion and weathering, due to storage or re-mobilization of sediment and solutes upstream from the sampling point. Recently, cosmogenic nuclides such as ^{10}Be and ^{26}Al have become important new tools for measuring long-term rates of physical erosion and chemical weathering. Cosmogenic nuclides can be used to infer the total denudation flux (the sum of the rates of physical erosion and chemical weathering) in actively eroding terrain. Here we review recent work showing how this total denudation flux can be partitioned into its physical and chemical components, using the enrichment of insoluble tracers (such as Zr) in regolith relative to parent rock. By combining cosmogenic nuclide measurements with the bulk elemental composition of rock and soil, geochemists can measure rates of physical erosion and chemical weathering over 1000- to 10,000-year time scales.

Keywords: Denudation; Erosion; Chemical weathering; Cosmogenic nuclides

1. Introduction

Cosmogenic nuclides such as ^{10}Be and ^{26}Al are produced in situ within mineral grains by cosmic ray bombardment. Because the cosmic ray flux reaching a mineral grain is attenuated by the mass overlying it, the accumulated cosmogenic nuclide concentration records how rapidly the overlying mass (and thus the cosmic ray shielding) has been removed (Lal, 1991), either by physical erosion or chemical weathering. The total denudation flux D (in units of mass per landscape area per time) is approximately

$$D = \frac{P_0 \Lambda}{N} - \frac{\Lambda}{\tau}, \quad (1)$$

where P_0 is the production rate of a cosmogenic nuclide at the Earth's surface (atoms per mass per time), N is its measured concentration (atoms per mass), τ is its radioactive mean life (time), and Λ is the cosmic ray attenuation constant (in units of mass per area). The calculation that is used in practice is somewhat more complex than Eq. (1); see the Electronic Appendix of Riebe et al. (2003) for details. This approach yields the long-term denudation rate, exponentially averaged over the time required to exhume roughly one mean cosmic ray penetration

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length scale (approximately 60 cm in rock). This corresponds to a time scale on the order of 10^3–10^4 years in actively eroding terrain.

We have recently shown how cosmogenic estimates of total denudation flux can be partitioned into rates of physical erosion and chemical weathering, using the enrichment of insoluble tracers in regolith relative to parent rock (Kirchner et al., 1997; Riebe et al., 2003, 2004a,b, 2001b). Mass balance considerations lead directly to the following simple expressions for the chemical weathering flux W_X and physical erosion flux E_X of a given element X:

$$W_X = D\left([X]_{\text{rock}} - [X]_{\text{soil}}\frac{[\text{Zr}]_{\text{rock}}}{[\text{Zr}]_{\text{soil}}}\right) \quad \text{and}$$

$$E_X = D\left([X]_{\text{soil}}\frac{[\text{Zr}]_{\text{rock}}}{[\text{Zr}]_{\text{soil}}}\right)$$

where $[X]_{\text{rock}}$ and $[X]_{\text{soil}}$ are the concentrations of element X in parent material and regolith, and $[\text{Zr}]_{\text{rock}}$ and $[\text{Zr}]_{\text{soil}}$ are the corresponding concentrations of an insoluble element (in this case, zirconium). Eq. (2) can be summed over all the rock-forming elements, yielding the total fluxes of chemical weathering and physical erosion:

$$W = D\left(1 - \frac{[\text{Zr}]_{\text{rock}}}{[\text{Zr}]_{\text{soil}}}\right) \quad \text{and} \quad E = D\left(\frac{[\text{Zr}]_{\text{rock}}}{[\text{Zr}]_{\text{soil}}}\right). \qquad (3)$$

To estimate landscape-scale denudation rates using Eq. (1), we measure cosmogenic nuclide concentrations in samples of mobile regolith from small headwater channels, or from un-channeled swales draining 0.5–10 ha catchments (Ferrier et al., 2005; Granger et al., 1996; Kirchner et al., 2001; Riebe et al., 2000). To partition these denudation rates into their physical and chemical components using Eqs. (2) and (3), we measure the average elemental composition of many (typically 10–30) bedrock and regolith samples distributed throughout the same catchment area that contributed to

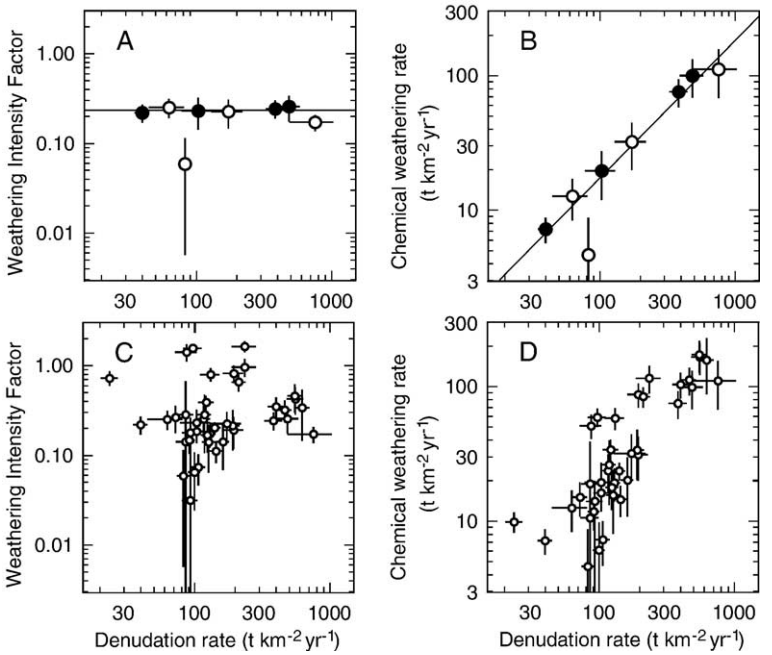

Fig. 1. Weathering intensity factors (WIFs) (left panels, A and C) and chemical weathering rates (right panels, B and D) plotted against denudation rates for sites at two particular Sierra Nevada localities where denudation rates vary substantially (top panels, A and B), and for all 42 field sites (bottom panels, C and D). In the top panels, field sites at the two Sierra Nevada localities, Fort Sage and Fall River (Riebe et al., 2001b), are shown by open and closed symbols, respectively; the bottom panels include too many localities to distinguish them with unique symbols. Panel A shows that WIFs are roughly uniform across the two Sierra Nevada localities, implying that chemical weathering rates are tightly coupled with denudation rates (as shown in B). Panels C and D show that the full 42-site data set shows the same general patterns observed at the two localities shown in A and B. Across the full suite of sites, WIFs are not strongly correlated with denudation rates (panel C), indicating that the ratio of weathering to erosion, and thus the degree of chemical depletion of soils, is not sensitive to the rate of supply of minerals by erosion of rock. This implies that chemical weathering rates are generally higher in areas of more rapid denudation, as panel D shows; to achieve the same degree of chemical depletion when denudation rates are faster, chemical weathering rates must also be faster.