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Cosmogenic Isotope Methods for Measuring Catchment Erosion and Weathering Rates

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Understanding human perturbations of catchment biogeochemical cycles requires some way to estimate "natural" rates of weathering and erosion, for comparison with current solute and sediment fluxes. 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 remobilisation of sediment and solutes upstream from the sampling point. Long-term erosion rates have sometimes been inferred from stream valleys incised into datable surfaces such as volcanoes (e.g., Seidl *et al.*, 1994); similarly, weathering rates have been inferred from weathering profiles developed into datable deposits such as moraines (e.g., Taylor & Blum, 1995). However, such datable features and deposits are rare.

Cosmogenic isotope techniques provide new opportunities for quantifying catchment erosion and weathering rates. Cosmogenic nuclides (such as ^{10}Be, ^{26}Al, ^{3}He, ^{14}C, ^{21}Ne, and ^{36}Cl) are produced *in-situ* inside mineral grains by secondary cosmic radiation bombarding the Earth's surface. Because the cosmic ray flux decreases exponentially with depth below the surface, the accumulated cosmogenic nuclide concentration in a mineral grain records how quickly that grain has been unearthed; slower erosion rates imply longer exposure times, and thus higher nuclide concentrations. Geologists have used cosmogenic nuclides to determine exposure ages and/or erosion rates of outcrops (Nishiizumi *et al.*, 1993; Bierman, 1994; Cerling and Craig, 1994), but these cannot be translated directly into landscape erosion rates, since outcrops "crop out" precisely because their erosion history is anomalous. However, it can be shown that the cosmogenic isotope signature of alluvial sediment reflects the spatially averaged erosion rate of the contributing catchment, according to the formula (Bierman & Steig, 1996; Granger *et al.*, 1996):

$E = P_o(Lambda)/N$ (1)

where E is the average catchment erosion rate, P_o is the nuclide production rate at the surface, *Lambda* is the 1/*e* attenuation length for cosmic radiation (*Lambda*~60 cm in rock), and N is the cosmogenic nuclide concentration. Cosmogenic nuclides measure erosion rates averaged over time scales of order (*Lambda)*/*E*, the time required to erode a layer of thickness *Lambda* from the surface ((*Lambda)*/*E*~1,000's of years for typical catchments). Because cosmogenic nuclide concentrations are insensitive to recent changes in erosion rates, they are particularly useful for estimating long-term "background" rates of erosion, and thus can be used as a benchmark for evaluating the erosional effects of land use (e.g., Brown *et al.*, 1995).

We have shown that erosion rates inferred from cosmogenic nuclides accurately (± 25 %) reflect the actual erosion rates of small upland catchments, as determined by direct mass-balance erosion rate measurements over 10,000-year timescales (Granger *et al.*, 1996). We are now using cosmogenic nuclides to measure how erosion rates respond to climatic gradients across eight sites (annual average temperatures ranging from 0 to 15 °C, and annual precipitation ranging from 15 to 230 cm yr^{-1}) in the Sierra Nevada mountains of California (Riebe, Granger & Kirchner, 1996). Preliminary results from this study will be presented.

Where erosion rates can be measured using cosmogenic nuclide methods, long-term weathering rates may also be inferred from mass-balance considerations. As bedrock is weathered to saprolite and then to soil, all of its chemical constituents must ultimately leave the catchment either through physical erosion (as mobile sediment) or through chemical weathering (as solutes in streamwater). If, over long timescales, bedrock weathering approximately keeps pace with surface erosion (such that the interface between fresh bedrock and weathered bedrock moves downward at the same rate that the surface is eroding), then one can directly calculate the long-term weathering flux of any element X as,

$$W_X = E\,(rho)_{rock}\,([X_{rock}]-[X_{sediment}][Ti_{rock}]/[Ti_{sediment}]) \quad (2)$$

where rho_{rock} is the density of bedrock, $[X_{rock}]$ and $[X_{sediment}]$ are the concentrations of the element of interest X in bedrock and in the eroding sediment, and $[Ti_{rock}]$ and $[Ti_{sediment}]$ are the concentrations of an immobile tracer (such as Ti or Zr) in the bedrock and sediment (which are used to measure volume changes due to chemical dissolution). Cosmogenic isotope methods may thus permit long-term rates of physical erosion and chemical weathering to be measured at catchment scale.

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