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Earth surface erosion and weathering from the ^{10}Be (meteoric)/^{9}Be ratio

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ABSTRACT

The isotope ratio of the meteoric cosmogenic nuclide ^{10}Be to the mineral-derived stable isotope ^{9}Be discloses both the Earth surface denudation rate and its weathering intensity. We develop a set of steady state mass balance equations that describes this system from a soil column over the hillslope scale to an entire river basin. The prerequisites making this new approach possible are: (1) the ^{9}Be concentration of parent rock (typically 2.5 ± 0.5 ppm in granitic and clastic sedimentary lithologies) is known; (2) both Be isotopes equilibrate between the fluids decomposing rock and reactive solids formed during weathering; and (3) a critical spatial scale is exceeded at which the fluxes of both isotopes into and out of the weathering zone are at steady state over the time scale of weathering (typically $\sim$10 kyr). For these cases the isotope ratios can be determined in bulk sediment or soil, on leachates from the reactive (adsorbed and pedogenic mineral-bound) phase in sediment or soil, and even on the dissolved phase in river water. The ^{10}Be/^{9}Be ratio offers substantial advantages over the single-isotope system of meteoric ^{10}Be. The latter system allows to directly determine erosion rates only in the case that ^{10}Be is fully retentive in the weathering zone and that riverine sorting has not introduced grain size-dependent ^{10}Be concentration gradients in sediments. We show the feasibility of the ^{10}Be/^{9}Be tracer approach at the river scale for sediment and water samples in the Amazon basin, where independent estimates of denudation rates from *in situ*-produced ^{10}Be exist. We furthermore calculate meaningful denudation rates from a set of published ^{10}Be/^{9}Be ratios measured in the dissolved load of globally distributed rivers. We conclude that this isotope ratio can be used to reconstruct global paleo-denudation from sedimentary records.

1. Introduction

The ratio of the meteoric cosmogenic fallout nuclide ^{10}Be ($T_{1/2}=$ 1.39 Myr) to the stable isotope ^{9}Be is a most promising weathering proxy. The system combines a tracer of known flux to the Earth surface with one that depends on its release rate from rock by weathering. Consequently it was suggested that this isotope ratio depends on global denudation when measured in seawater (Bourlès et al., 1989; Brown et al., 1992b; von Blanckenburg et al., 1996). Moreover, it was proposed that this isotope ratio records denudation back through time when extracted from authigenic ocean sedimentary records (Bourlès et al., 1989; von Blanckenburg and O'Nions, 1999). Following from these observations, Willenbring and von Blanckenburg (2010a) have used the ^{10}Be/^{9}Be isotope ratio in ocean deposits over the past 10 Myr to infer that the global denudation rate was constant over this period. Despite holding so much promise, this system was explored in detail in only two pioneering studies: Brown et al. (1992a) explored the ^{10}Be/^{9}Be ratio in dissolved and suspended loads of the Orinoco and the Amazon river basins, and Barg et al. (1997) used the ratio in the authigenic phase of soils, to infer soil ages and assess open system behaviour of soils. The mechanisms that set this isotope ratio in the compartments of the Earth surface, however, remain to date still widely unexplored.

Improving our understanding of ^{10}Be/^{9}Be ratio system is timely since the single-isotope system meteoric ^{10}Be is currently receiving much renewed interest as a tracer for terrestrial Earth surface stability. This method, explored first by Lal and Peters (1967), was established as a monitor of basin-wide erosion in two pioneering studies of river sediment by Brown et al. (1988) and You et al. (1988), but was partially sidelined in the years that followed by the astounding success of the "sister nuclide", *in situ*-produced ^{10}Be measured in quartz to determine exposure ages and rates of denudation (Lal, 1991). The advantages of the meteoric variety of ^{10}Be over the *in situ*-produced nuclide lie in this isotope's higher concentrations, requiring smaller sample amounts, its applicability to quartz-free lithologies, and the possibility to determine denudation rate time series in fine-grained sedimentary deposits. Recent improvements in our understanding of the spatial and temporal patterns of delivery of the meteoric fallout nuclide (summarised in Willenbring and von Blanckenburg (2010b)) and overviews of its distribution in soils (Graly et al., 2010) are currently triggering new applications in erosional settings (*e.g.* Jungers et al., 2009).

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However, quantitative estimates of erosion using the meteoric ^{10}Be tracer are compromised by the highly variable retention behavior of Be in soils and river sediment. Be is firmly adsorbed onto particles only if the coexisting solution pH exceeds a value of 6 (You et al., 1989; Aldahan et al., 1999; Willenbring and von Blanckenburg, 2010b). Furthermore, once soil particles have been transferred into streams, they will be sorted by grain size, which adds further complexity as the extent of Be adsorption onto solids is highly grain size-dependent (Willenbring and von Blanckenburg, 2010b).

Both retentivity and grain size issues can be circumvented when ^{10}Be concentration is normalised over a second element that has similar partitioning behavior between solid and solution. The optimal normalizing counterpart is, of course, another isotope of the same element, since its chemical properties are identical. The isotope ^{9}Be, the stable counterpart of ^{10}Be, is present in concentrations of a few ppm in most rocks, and is potentially ideal to serve for this purpose, provided we understand the way this stable isotope is released during weathering, mixed with meteoric ^{10}Be, and partitioned between particles and solution. Realising this stable isotope's potential, Bacon et al. (2012) have recently employed ^{9}Be concentrations to quantify the loss of ^{10}Be from a soil profile.

The aim of this study is to provide a quantitative framework that allows to interpret ^{10}Be/^{9}Be ratios as a proxy of denudation rates in bulk soil and in river sediment in their "reactive" phase (*i.e.* adsorbed onto mineral surfaces and precipitated in secondary weathering products), and in solution. Many of the issues and assumptions involving the meteoric single-isotope ^{10}Be tracer were discussed extensively by Willenbring and von Blanckenburg (2010b). Here we first present a simple steady state mass balance for Be isotopes in the weathering zone, and discuss the assumptions that are made to establish this mass balance. We demonstrate the feasibility of this approach by applying it to the tributaries and trunk stream of the Amazon River, for which an exceptional wealth of hydrologic data, meteoric ^{10}Be concentrations, ^{10}Be/^{9}Be ratios, and denudation rates from *in situ*-produced cosmogenic nuclides exist. We finally apply the concept to ^{10}Be/^{9}Be ratios measured in the dissolved and the reactive phase to published data on large rivers. Altogether, we show that both denudation rate and the degree of weathering of an entire river basin can be derived by measuring ^{10}Be/^{9}Be ratios in weathering products.

2. A conceptual framework for the ^{10}Be/^{9}Be system at the Earth surface

We develop a steady state mass balance for both ^{9}Be and ^{10}Be, for which one principal assumption is made that is later explored in detail: over a certain time scale the two isotopes leave the weathering zone at the same rate as they enter the zone (Fig. 1). This time scale can be broadly defined as four to five times the residence time of Be in the weathering zone. For ^{10}Be, the residence time is the ratio of the inventory of ^{10}Be in a vertical soil column divided by the atmospheric flux of ^{10}Be. For ^{9}Be, the residence time is similar to the denudation time scale (the ratio of the depth of the weathering zone divided by the denudation rate D, in kg m^{-2} y^{-1}). Both residence times are typically in the range of 10^3–10^5 yr. ^{10}Be/^{9}Be ratios result for the different Be compartments exported out of the zone: (a) Be contained in bulk solid (typically river sediment), (b) solid secondary weathering products containing Be, and (c) Be dissolved in water.

2.1. ^{10}Be and ^{9}Be mass balance during steady-state weathering

The sole source of meteoric ^{10}Be to the weathering zone is atmospheric fallout, through both wet or dry deposition (Monaghan et al., 1985–86; Field et al., 2006; Heikkilä et al., 2008) (Fig. 1). Production of *in situ* ^{10}Be is regarded as negligible compared to the flux of meteoric ^{10}Be (Willenbring and von Blanckenburg, 2010b). A certain fraction of ^{10}Be atoms delivered to the Earth's surface adsorbs onto mineral surfaces or co-precipitates with Fe- and Al-oxides or hydroxides, with amorphous alumino-silicates, with clays, or with carbonates. This ^{10}Be pool exchanges with dissolved ^{10}Be through dissolution–precipitation or desorption–adsorption reactions and is thus called "reactive" (^{10}Be$_{\text{reac}}$). The remaining ^{10}Be atoms are exported as dissolved compounds (^{10}Be$_{\text{diss}}$). We further assume that the residence time of ^{10}Be in the system is short compared to its radioactive half-life (1.39 Myr) (Chmeleff et al., 2010; Korschinek et al., 2010). This assumption is evaluated in detail by Willenbring and von Blanckenburg (2010b) and was found valid for most eroding settings.

At steady-state, the fluxes of ^{10}Be are balanced:

$$F_{\text{met}}^{^{10}\text{Be}} = E * [^{10}\text{Be}]_{\text{reac}} + Q * [^{10}\text{Be}]_{\text{diss}} \tag{1}$$

where $F_{\text{met}}^{^{10}\text{Be}}$ is the flux of meteoric ^{10}Be to the Earth's surface (in atoms m^{-2} y^{-1}), E is the erosion flux (in kg m^{-2} yr^{-1}), Q is the water flux out of the system (in m^3 m^{-2} yr^{-1} or equivalently in m yr^{-1}), and [^{10}Be]$_{\text{reac}}$ and [^{10}Be]$_{\text{diss}}$ represent the concentrations of reactive and dissolved ^{10}Be (respectively in atoms kg^{-1} and atoms L^{-1}).

In most geomorphic field experiments, [^{10}Be]$_{\text{diss}}$ is not available. We make use of the Be partition coefficient K_d (in L kg^{-1}) that links Be concentrations in the reactive and dissolved phases:

$$K_d = \frac{[\text{Be}]_{\text{reac}}}{[\text{Be}]_{\text{diss}}} \tag{2}$$

In our model weathering system K_d can be used because the reactive phase and water are assumed to be at chemical equilibrium via continuous exchange of Be. K_d depends on the nature of the solid, temperature, chemical composition of the solution (pH, competing ions, presence of organic matter) but not on the solid/fluid ratio. For Be, K_d is highly pH-dependent: its value is 10^3 L kg^{-1} for pH between 4 and 5, 10^4 L kg^{-1} at pH between 5 and 6 and 10^5 L kg^{-1} at pH above 6 (You et al., 1989; Aldahan et al., 1999). Substituting Eq. (2) into Eq. (1) yields:

$$E = \frac{F_{\text{met}}^{^{10}\text{Be}}}{[^{10}\text{Be}]_{\text{reac}}} - \frac{Q}{K_d} \tag{3}$$

Eq. (3) allows to calculate erosion rates E from a measurement of [^{10}Be]$_{\text{reac}}$. Accurate erosion rates can only be determined if Q and K_d are known over the residence time of Be in the weathering zone. However, we can simplify this condition in settings where $Q/K_d \ll E$, meaning either that the water flux Q is low, or that the erosion rate E is high, or that Be has a high affinity for the reactive phase such that K_d is high. Then:

$$E = \frac{F_{\text{met}}^{^{10}\text{Be}}}{[^{10}\text{Be}]_{\text{reac}}} \tag{4}$$

which corresponds to Equation (21) in Willenbring and von Blanckenburg (2010b) or the equation generally used for erosion studies of the single-isotope meteoric ^{10}Be system (Brown et al., 1988). An assessment of the bias introduced by this simplification is presented in Appendix A.1.

The ^{9}Be system can be defined as follows. Bedrock, containing ^{9}Be in its minerals (^{9}Be$_{\text{parent}}$), continuously enters the weathering zone through the advance of the weathering front (Fig. 1). Chemical weathering results in the partial dissolution of bedrock and leads to a release of ^{9}Be. The dissolution of ^{9}Be from bedrock is not necessarily congruent, and a fraction termed ^{9}Be$_{\text{min}}$ remains locked in primary minerals. The released ^{9}Be that adsorbs onto mineral surfaces or is incorporated into precipitates is called