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River fluxes to the sea from the ocean's $^{10}Be/^{9}Be$ ratio

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ABSTRACT

The ratio of the meteoric cosmogenic radionuclide ^{10}Be to the stable isotope ^{9}Be is proposed here to be a flux proxy of terrigenous input into the oceans. The ocean's dissolved $^{10}Be/^{9}Be$ is set by (1) the flux of meteoric ^{10}Be produced in the atmosphere; (2) the denudational flux of the rivers discharging into a given ocean basin; (3) the fraction of ^{9}Be that is released from primary minerals during weathering (meaning the ^{9}Be transported by rivers in either the dissolved form or adsorbed onto sedimentary particles and incorporated into secondary oxides); and (4) the fraction of riverine ^{10}Be and ^{9}Be actually released into seawater. Using published $^{10}Be/^{9}Be$ data of rivers for which independent denudation rate estimates exist we first find that the global average fraction of ^{9}Be released during weathering into river waters and their particulate load is 20% and does not depend on denudation rate. We then evaluate this quantitative proxy for terrigenous inputs by using published dissolved seawater Be isotope data and a compilation of global river loads. We find that the measured global average oceanic dissolved $^{10}Be/^{9}Be$ ratio of about 0.9×10^{-7} is satisfied by the mass balance if only about 6% of the dissolved and adsorbed riverine Be is eventually released to the open ocean after escaping the coastal zone. When we establish this mass balance for individual ocean basins good agreement results between $^{10}Be/^{9}Be$ ratios predicted from known river basin denudation rates and measured ocean $^{10}Be/^{9}Be$ ratios. Only in the South Atlantic and the South Pacific the $^{10}Be/^{9}Be$ ratio is dominated by advected Be and in these basins the ratio is a proxy for ocean circulation. As the seawater $^{10}Be/^{9}Be$ ratio is faithfully recorded in marine chemical precipitates the $^{10}Be/^{9}Be$ ratio extracted from authigenic sediments can now serve to estimate relative changes in terrigenous input into the oceans back through time on a global and on an ocean basin scale.

1. Introduction

The $^{10}Be/^{9}Be$ isotope ratio combines the meteoric cosmogenic radionuclide ^{10}Be ($T_{1/2} = 1.39$ Myr), deposited onto the Earth's surface by precipitation, with its stable counterpart ^{9}Be, released from rocks by weathering. Given this combination, the $^{10}Be/^{9}Be$ ratio in seawater is sensitive to continental denudation rates. The average residence time of Be in seawater being only ca. 600–1000 yrs, the ratio differs between ocean basins (e.g. Bourlès et al., 1989; Brown et al., 1992; Frank et al., 2009; Kusakabe et al., 1990; von Blanckenburg et al., 1996). Correspondingly, dissolved $^{10}Be/^{9}Be$ ratios in seawater are lowest in the Mediterranean Sea, a small ocean basin dominated by high terrigenous input and limited exchange with the global ocean; and highest in the Pacific, which collects a large flux of meteoric ^{10}Be over its vast surface area while receiving comparatively low terrigenous input given the size of the ocean basin. It has been proposed that the $^{10}Be/^{9}Be$ ratio extracted from authigenic marine sediments, recording the surrounding seawaters' $^{10}Be/^{9}Be$ ratio, traces continental denudation back through time (Bourlès et al., 1989; von Blanckenburg and O'Nions, 1999; Willenbring and von Blanckenburg, 2010a). To date only very coarse (Myr) time resolution records of paleo-denudation over the last 10 Myr were reconstructed (Willenbring and von Blanckenburg, 2010a). When applied at higher time resolution the method will allow to evaluate changes in denudation rate as a function of Quaternary climate shifts. Ultimately, the temporal resolution is limited only by the residence time of Be in the respective ocean basin, and by the resolution of the sedimentary record.

A geochemical framework suited to explore how erosion and weathering set the $^{10}Be/^{9}Be$ ratio of soils and rivers was suggested recently by von Blanckenburg et al. (2012). A river drainage basin's denudation rate can be calculated by measuring the $^{10}Be/^{9}Be$ ratio of the dissolved Be or reactive Be carried by rivers (meaning adsorbed or bound to secondary oxyhydroxide precipitates) provided that the flux of meteoric ^{10}Be into this basin and the concentration of ^{9}Be in bedrock are known, and that the fraction of ^{9}Be released from primary minerals during weathering can be estimated. The ^{9}Be thus released and the meteoric ^{10}Be

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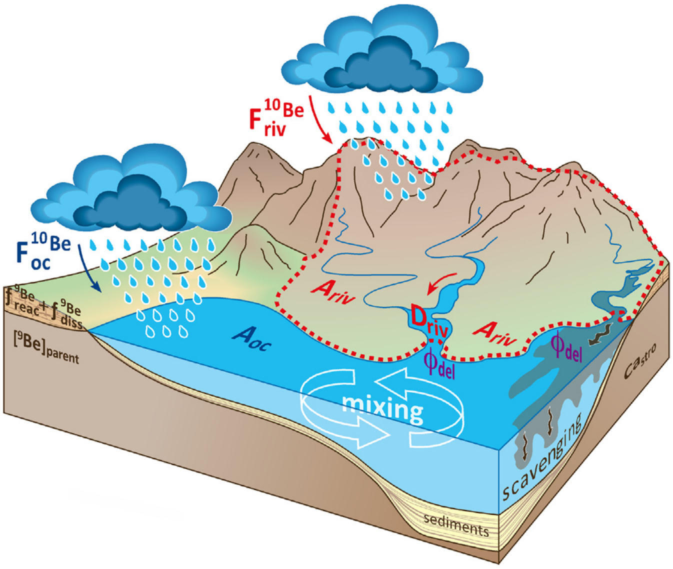
deposited onto the continents are delivered through riverine transport to the oceans, where they mix with ^{10}Be deposited directly onto the ocean surface. Aeolian input only plays a minor role for the modern oceanic ^{9}Be budget (von Blanckenburg et al., 1996; Willenbring and von Blanckenburg, 2010a). After entry into the ocean, particle-reactive Be can be captured in estuaries and shelf areas (Brown et al., 1992; Kusakabe et al., 1991) and at ocean margins (Anderson et al., 1990; Lao et al., 1992). Yet these sites of scavenging are also sites of release of reactive metals from shelf and slope sediments during diagenetic reactions and pore fluid expulsion (Arsouze et al., 2009; Jeandel et al., 2011). Dissolved Be that reaches the open ocean is entrained by the gyres of the major ocean basins that have the remarkable ability to homogenise this isotope ratio despite the reactive nature of Be and the high scavenging intensity at the ocean margins (Igel and von Blanckenburg, 1999). For example, in the Pacific Ocean the Be is mixed to such an extent that the ^{10}Be/^{9}Be ratio exhibits a 13% dispersion only, calculated from measured surface water ratios, despite input ^{10}Be/^{9}Be ratios spanning a range of up to five orders of magnitude (von Blanckenburg and Igel, 1999). At the scale of an ocean basin, Be with a uniform ^{10}Be/^{9}Be ratio is then delivered to deep waters, where ^{9}Be is present at relatively invariant concentrations of 30 pM (Kusakabe et al., 1990). Given that the deep ocean residence time is about 600–1000 yrs (Kusakabe et al., 1990; von Blanckenburg et al., 1996) this Be compartment is characterised by ^{10}Be/^{9}Be ratios that are distinct between ocean basins but that are more or less uniform within a basin (Kusakabe et al., 1990).

Considering this proxy's considerable potential as tracer for terrigenous erosion and weathering, it is timely to develop means for the translation of present and past ^{10}Be/^{9}Be ratios to global estimates of the transfer of terrigenous matter into the oceans. The aim of this contribution is therefore (1) to determine, using global river denudation and oceanic ^{10}Be/^{9}Be data, the terrigenous input fluxes of these two isotopes into the global oceans, as well as into individual ocean basins; (2) to provide estimates of the fractional release of this metal into the dissolved form once delivered into the oceans; (3) to explore the fidelity of the oceanic ^{10}Be/^{9}Be ratio as a quantitative proxy for past terrigenous inputs to the ocean when extracted from authigenic marine sediments. We do this by combining published dissolved ^{10}Be/^{9}Be data from all ocean basins with estimates of the terrigenous fluxes of Be into these basins.



$$\left(\frac{^{10}Be}{^{9}Be}\right)_{oc} = \frac{\left(\frac{A_{oc}}{A_{riv}}\right) * F_{oc}^{10Be} + \phi_{del} * F_{riv}^{10Be}}{\phi_{del} * D_{riv} * [^{9}Be]_{parent} * \left(f_{reac}^{9Be} + f_{diss}^{9Be}\right)}$$

Fig. 1. Cartoon showing the fluxes of ^{9}Be and ^{10}Be. The parameters defined in Eq. (5) are coloured in the cartoon and in the colour version of the equation shown here, with the exception of $f_{reac}^{9Be} + f_{diss}^{9Be}$.

2. The oceanic Be isotope mass balance

The first aim of this study is to characterise the ^{10}Be/^{9}Be ratio established in the oceans following transfer of terrigenous ^{9}Be and ^{10}Be via rivers and the addition of meteoric ^{10}Be deposited directly onto the ocean's surface (Fig. 1). We follow the terminology of von Blanckenburg et al. (2012): $(^{10}Be/^{9}Be)_{diss}$ is the isotope ratio of Be dissolved in river waters (Be_{diss}); and $(^{10}Be/^{9}Be)_{reac}$ is the isotope ratio of reactive Be (Be_{reac}), adsorbed onto the particulate load of rivers and contained in Be-rich secondary phases, such as Fe–Mn oxihydroxides. Provided the contact time between river water and river particles is sufficiently long, $(^{10}Be/^{9}Be)_{reac}$ and $(^{10}Be/^{9}Be)_{diss}$ equilibrate during riverine transport to a common ratio as shown previously (von Blanckenburg et al., 2012). In a given river and at steady state, this ratio is:

$$\left(\frac{^{10}Be}{^{9}Be}\right)_{reac} = \left(\frac{^{10}Be}{^{9}Be}\right)_{diss} = \frac{F_{riv}^{10Be}}{D \cdot [^{9}Be]_{parent} \cdot (f_{reac}^{9Be} + f_{diss}^{9Be})} \quad (1)$$

where F_{riv}^{10Be} describes the atmospheric flux of meteoric ^{10}Be onto the river basin (in atoms $m^{-2}\,yr^{-1}$; note that in von Blanckenburg et al. (2012) we call this flux F_{met}^{10Be}), D the river basin's denudation rate that comprises both physical erosion and chemical weathering (in $kg\,m^{-2}\,yr^{-1}$), $[^{9}Be]_{parent}$ is the mean ^{9}Be concentration of the river basin's parent rock (in atoms kg^{-1} or mol kg^{-1}), and $f_{reac}^{9Be} + f_{diss}^{9Be}$ is the fraction of ^{9}Be released during weathering from the parent rock, meaning the fraction of ^{9}Be that is ultimately available for mixing with dissolved ^{10}Be. Hereafter we call $f_{reac}^{9Be} + f_{diss}^{9Be}$ the mobile fraction of ^{9}Be. We assume for simplicity that the remainder of the ^{9}Be, which is locked in primary minerals, does not enter the oceanic Be cycle. Therefore, the terrigenous Be finally available for release and mixing in seawater is supplied either in the reactive form (Be_{reac}) as borne by the solid erosional load of rivers or in the dissolved form (Be_{diss}) in river water. However, not all mobile Be is ultimately delivered to the open ocean, as in the coastal ocean reactive Be might be deposited with the particles that carry this Be. The fraction of reactive Be thus trapped might differ from the fraction of reactive Be carried by rivers, as reactive and dissolved Be can exchange upon entry in the oceans. We represent the efficiency of overall Be delivery to the open ocean by a fractional factor ϕ_{del} that is identical for both isotopes. Essentially, ϕ_{del} quantifies the fraction of riverine mobile Be surviving the sink provided by the estuaries and the coastal interface. Once in dissolved form in the open ocean, all Be from the continents is rapidly homogenised with the meteoric ^{10}Be deposited directly onto the surface oceans. The average dissolved ^{10}Be/^{9}Be ratio of an ocean basin, termed $(^{10}Be/^{9}Be)_{oc}$, can be calculated as follows:

$$\left(\frac{^{10}Be}{^{9}Be}\right)_{oc} = \frac{A_{oc} \cdot F_{oc}^{10Be} + A_{riv} \cdot (E_{riv} \cdot \phi_{del} \cdot [^{10}Be]_{reac} + Q_{riv} \cdot \phi_{del} \cdot [^{10}Be]_{diss})}{A_{riv} \cdot (E_{riv} \cdot \phi_{del} \cdot [^{9}Be]_{reac} + Q_{riv} \cdot \phi_{del} \cdot [^{9}Be]_{diss})} \quad (2)$$

where F_{oc}^{10Be} is the flux of meteoric ^{10}Be deposited onto the ocean surface (in atoms $m^{-2}\,yr^{-1}$) averaged over A_{oc}, the surface area of the ocean (in m^{2}), E_{riv} is the average erosion rate (in $kg\,m^{-2}\,yr^{-1}$) for the river basins discharging into the ocean, A_{riv} is the total