

Surface processes control Pb evolution in the mantle

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The position of the Pb isotopic compositions of mid-ocean ridge basalts to the right of the geochron has long puzzled geochemists because U is more incompatible than Pb during magmatic processes, therefore the mantle source of MORB, being depleted in incompatible elements, should have low Pb isotope ratios, to the left of the geochron. Mid-ocean ridge basalts have a second peculiar characteristic: they show a drastic Pb concentration depletion relative to other elements having similar compatibility such as Ce or Nd. We suggest that both characteristics can be explained by preferential migration of Pb out of the oceanic crust during hydrothermal alteration associated with sea-floor spreading, and during subduction. A portion of this Pb is then added to the continental crust. The Pb-depleted recycled oceanic crust then mixes into the mantle to become the MORB source.

Introduction

For most elements, the partitioning between the mantle and the continental crust over Earth history closely parallels the relative incompatibility during mantle melting to form oceanic basalts. This is reflected in long-lived radioactive decay systems such as Rb-Sr and Sm-Nd, and Lu-Hf. Rb, Nd, and Hf are more incompatible than Sr, Sm, and Lu, respectively, and mantle derived rocks generally have low $^{87}\text{Sr}/^{86}\text{Sr}$, and high $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios compared to the continents, providing evidence that the depletion process has been operating for much of Earth history. This is not the case for the U-Pb system. During mantle melting, U acts as a highly incompatible element, like Th, Ba, and Rb, while Pb acts as a moderately incompatible element, like Ce or Nd. Therefore, Pb isotope ratios of mantle derived rocks would be expected to reflect a time-integrated reduction of U/Pb and MORB should lie to the left of the geochron. The position of MORB near the geochron or to the right requires that their source had a U/Pb ratio that was similar to or higher than the bulk Earth value for much of their evolution.

The special behavior of the U-Pb system can also be seen in their elemental abundances. For

most element pairs having similar silicate solid/melt partitioning behavior, the ratio is the same in the bulk Earth, the depleted mantle, and the continental crust. Oceanic basalts have been shown to have Ce/Pb ratios much higher than the bulk Earth, indicating that Pb has partitioned out of the mantle and into the crust over time compared to Ce, despite similar melting behavior. In this paper, we suggest a model that accounts for the radiogenic Pb isotopic compositions of MORB as well as their high Ce/Pb ratios.

Exogene control of Pb between mantle and continental crust.

We suggest that the peculiar behaviour of the U-Pb system results from processes active during the generation, alteration, subduction and recycling of oceanic crust. The essence of the model is that Pb migrates preferentially to Ce from the interior of the oceanic crust to the surface during hydrothermal alteration, concentrates into sulfides and oxides and is thereby separated from other trace elements into distinct mineral phases. When the altered oceanic slab dehydrates in the subduction zone, sulfides and oxides formed by hydrothermal alteration break down, and the Pb dissolves in the fluid phase which then migrates into the overlying mantle wedge. Additional oceanic Pb might also be taken from the oceanic crust by dehydration during subduction. Pb is thus removed from the recycled oceanic crust and enriched in the mantle region that gives rise to island arc magmatism and eventually to continental crust. We suggest, therefore, that the migration of Pb from mantle to continental crust is governed by secondary, non-magmatic processes, and that the Pb enrichment in the continental crust is due to an enrichment in the source and not to a difference in the geochemical behaviour of Pb during partial melting in oceanic and continental environments.

Evolution of Ce/Pb ratios in the mantle

The explanation presented above has important implications for the evolution of the depleted mantle and continental crust. Preferential loss of

Pb from subducted oceanic crust, migration into the mantle wedge, and ultimately to the continental crust are unidirectional processes that change continuously the relative abundances of Pb and other trace elements (e.g. Ce and Nd). Whereas the partitioning of Ce between continental crust and mantle is probably dominated by melting processes, the partitioning of Pb is dominated by secondary processes. Recycled oceanic crust loses a large part of its Pb but little of its Ce, and the residue, which has high Ce/Pb, mixes back into the mantle. The continuous input of such material should result in a gradual increase in Ce/Pb ratios in the mantle. The migration of Pb from the subducted oceanic crust into the overlying mantle results in a low Ce/Pb ratio in the source of island arc magmas and ultimately that of continental crust.

Quantitative model of Ce/Pb ratio of the mantle and Pb concentration of the continental crust. Using estimates for the Ce concentration and Ce/Pb ratio in the continental crust, we can evaluate the total amount of Pb present in the crust. Because Ce and Pb have the same incompatibility level during magma genesis, we can estimate the amount of extra Pb in the crust relative to Ce and use this figure as the amount of Pb that must be extracted from the oceanic crust through the alteration/subduction processes. We can then evaluate the amount of oceanic crust that must have been altered and subducted through Earth history to account for the enrichment seen in the continental crust.

REE contents in the continental crust are relatively well constrained and for Ce, concentration estimates range between 33 and 55 ppm. Ce/Pb ratios in crustal materials are not often measured with a high precision but available data scatter about 5. This provides an estimated content of 6.6 to 10 ppm for Pb. Excess Pb relative to Ce is therefore about 3.3 to 5 ppm. We can now quantify our model using this value as the Pb that should be lost from the subducted oceanic crust. We make the following assumptions: (a) The Ce concentration of the oceanic crust is assumed to be 10 times higher than that of the mantle source region. The Ce concentration of the mantle source of oceanic crust through time is taken as 1.6 ppm at the beginning of Earth history and decreases linearly through time to mimic the depletion process that affected the mantle due to the formation of the continental crust. (b) The Ce/Pb ratio of melts of the primitive mantle was chondritic (~ 11). Pb loss during subduction increases the μ value in the subducted oceanic crust and the Ce/Pb ratio by a factor of about 2. (c) The proportion of oceanic crust affected by hydrothermal alteration is

assumed, on the basis of oxygen isotopic studies, to be about 50%. (d) The proportion of the mantle affected by the process is assumed to be equal to that of the upper mantle, a situation corresponding to a two-layered convection.

A Ce/Pb ratio of 25 is obtained for the upper mantle if higher temperatures and faster crustal production rates are assumed in the Archean. We used here recycling rates starting at high values at the beginning of Earth history and decreasing through time to reach present-day production rate. Ce/Pb ratios of about 25 can also be obtained if we keep production and recycling rate of the oceanic crust constant through time. It is then required to either alter a larger portion of the oceanic crust or to produce this crust by lower degrees of partial melting: leaching of Pb out of 70% of the oceanic crust produces a Ce/Pb ratio of 25 and extracts an acceptable amount of Pb at 7.4×10^{19} g; similarly, acceptable values (25 and 7.9×10^{19} g) are obtained if the oceanic crust were to be produced by lower degrees melts ($\approx 7\%$).

Clearly, the present-day MORB-OIB value of Ce/Pb = 25 can be reproduced by the model. If the production rates of oceanic crust were higher in the early Earth history, the model produces Pb extraction curves that are comparable to early growth of the continental crust. Our model does not integrate the effects of recycling of continental material into the mantle but we can estimate that its influence would require even higher recycling rates to balance for the decrease in Ce/Pb ratio of the mantle induced by mixing of low Ce/Pb crustal material into the high Ce/Pb mantle.

Pb isotopic compositions of MORB

For simplicity, we assume that the depleted mantle would fall on the geochron if the Pb depletion process described here had not existed. The present-day composition of subducted oceanic crust with various ages can be calculated as well as variations in Pb isotopic compositions due to different μ values for a given age of the recycled oceanic crust. The evolution path of the recycled MORB crust with time coincides with the field of present-day MORB data.

Because any recycled oceanic crust will be thinned and elongated by convection in the upper mantle, the source of any present-day MORB cannot be pure recycled oceanic crust but must be a mixture of old recycled oceanic crust and peridotite. Mixing trends between peridotite and older recycled crust using reasonable proportions between peridotite and old oceanic crust lead to Pb isotopic compositions comparable to those of present-day MORB.