Correlated U-Th and Sm-Nd fractionation in mid-ocean ridge and ocean island basalts: Implications for basalt petrogenesis

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U-Th isotopic patterns in oceanic basalts provide unique and important constraints on the time- and length-scales of basalt petrogenesis. The large U/Th fractionations observed have been difficult to interpret however, because U and Th are thought to be too highly incompatible for these fractionations to occur by crystal-liquid partitioning alone. U/Th fractionations are particularly difficult to interpret in MORBs, where the major-element chemistry suggests that melt fractions are large, 8-20%, whereas the large ^{230}Th activity excesses (up to 35%) require extremely small melt fractions, $\ll$ 5%. Although it has recently been demonstrated that garnet is likely to be the major residual phase responsible for the measured U/Th fractionation, the magnitude of this fractionation is still difficult to reconcile without calling on: (1) other processes such as volatile exsolution and hydrothermal fluid/melt interactions, (2) extreme melt segregation rates and melt fractions, and/or (3) disequilibrium conditions during melt generation and transport. Presently, no clear consensus exists among workers in this field on the mechanism of U/Th fractionation or on the extent to which melting contributes to this fractionation.

To further investigate the controls on U-Th fractionation, we have measured U, Th, and Nd isotopes (by HAS-TIMS) and [U], [Th], [Sm] and [Nd] (by ID-TIMS) in a series of young Hawaiian basalts and axial-MORB which cover a wide range of compositions and, thus, inferred melt-fractions and/or source depths. The Hawaiian basalts are historic or are young and radiocarbon dated, range in composition from tholeiites to basanites, and include all four stages of Hawaiian volcano evolution. The MORBs are axial samples from the Juan de Fuca and Gorda Ridges, and range in composition from N-MORB to E-MORB. We have examined the extent to which U/Th fractionation varies as a function of melt fraction as inferred by: 1) the major-element chemistry of the lava, and 2) model Sm/Nd fractionation,

where the Sm/Nd source ratio is inferred by using the 1.7 Ga source model of DePaolo (1988) and the measured ^{143}Nd/^{144}Nd of the sample. If a high degree of correlation exists between U/Th fractionation and other chemical indices of melting, then the quality of that correlation provides a measure of similarity of processes while its form provides important constraints on the mechanisms, conditions, and timing of chemical fractionation occurring during basalt petrogenesis.

Among the Hawaiian samples a good correlation exists between U/Th fractionation and the major-element chemistry of the lavas. As expected, the tholeiites are least fractionated while alkali basalts and basanites show progressively more fractionation. The Hawaiian lavas also show a good correlation (r^2 = 0.93) between U/Th and Sm/Nd fractionation (Figure 1). In all samples, U/Th fractionation is smaller than Sm/Nd fractionation. Correlation of Sm/Nd fractionation with U/Th fractionation allows the Hawaiian data to be inverted in terms of batch melting models, yielding U and Th distribution coefficients and melt fractions. Assuming D_{Nd} = 0.020 and D_{Sm} = 0.050, we calculate D_U = 0.00143, D_{Th} = 0.0006, with melt fractions varying from 5% (tholeiites) to < 1% (basanites). The similarity of the trend inverted from the Hawaiian data with the trend predicted by batch melting of a garnet lherzolite source, using experimentally determined K_ds, is strong evidence that U/Th fractionation for the Hawaiian basalts is a result of crystal–liquid fractionation associated with partial melting.

The MORB data are not so straightforward; MORBs also show a significant correlation between U/Th fractionation and Sm/Nd fractionation, with N-MORB less fractionated than E-MORB for both U/Th and Sm/Nd (Figure 1). However, E-MORB and some N-MORB are more fractionated than Hawaiian basanites for U-Th, while being less fractionated for Sm-Nd. For
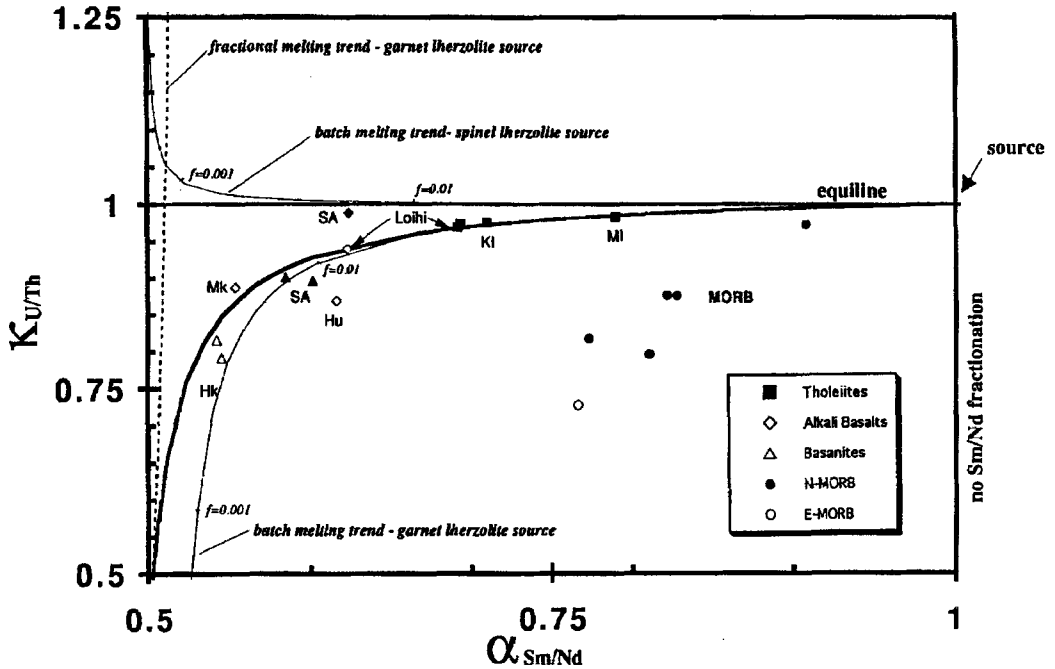
FIG. 1. U/Th fractionation ($K_{U/Th}$) versus Sm/Nd fractionation ($\alpha Sm/Nd$) for Hawaiian and mid-ocean ridge basalts, determined by U-Th and Sm-Nd isotopic systematics. Also shown are batch and fractional melting trends for a spinel and garnet lherzolite source, using experimentally determined K_ds. The solid dark curve represents the inverted batch melting trend for the Hawaiian data.

MORBs U/Th fractionation is approximately equal to Sm/Nd fractionation. The one-to-one form of this correlation cannot be explained by batch melting or fractional melting of either a garnet lherzolite or spinel lherzolite source, even when melt fractions are small (Figure 1). Because these two models represent end-member models it can be concluded by similar reasoning that the MORB data cannot be explained by dynamic or continuous melting processes either. In our initial interpretation of this MORB data we consider two possible mechanisms to explain the observed trend: 1) mixing of melts of different melt fractions (e.g., as from different depths), and 2)

recent depletions in the MORB source not reflected in the Nd isotopic systematics.

Our data indicate that ocean island and mid-ocean ridge basalts are generated by fundamentally different mechanisms. While the Hawaiian basalts can be explained by small degrees of batch melting of a garnet lherzolite source, the mid-ocean ridge basalts require a more complex process such as the mixing of melts of different melt fractions from different depths. These differences are fundamental and are likely to be related to differences in the melting and melt segregation geometry of the ocean island and mid-ocean ridge environments.