$^{231}Pa/^{235}U$ constraints on mantle melting

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Where and how the mantle melts have important geodynamic implications. ^{238}U decays to ^{230}Th (half life of 75 ka), which in turn decays to ^{226}Ra (half life of (1.6 ka). ^{235}U decays to ^{231}Pa (half life of 33 ka). The U-series elements have contrasting geochemical properties with half lives with times scales appropriate for mantle melting and magma transport. Mid-ocean ridge basalts (MORB), ocean island basalts (OIB) and continental basalts show variable degrees of ^{230}Th over ^{238}U enrichment. The large ^{230}Th enrichment in MORB, OIB and continental basalts would require small degrees of melting, in the range of the D values for U (~ 0.01). Alternatively, it is also argued that much of the enrichment may be 'in grown' after initial melting in the garnet stability field, *as long as the source is upwelling* [e.g. Spiegelman and Elliott, 1993]. Aside from the point that melting starts within the garnet stability field, there is no consensus on the exact mechanism on modes of mantle melting to generate these lavas. The other short-lived nuclide, such as ^{226}Ra and ^{231}Pa, may provide additional constraints that may help clarify the mechanism by which the mantle melts.

Continental basalts, unlike their oceanic counterparts, may sample portions of the mantle – the lithospheric continental mantle – that have remained isolated from the convecting upper mantle, possibly since the time of the accretion of the overlying crust. Thus, in older crustal settings, the lithospheric mantle may have domains that have distinctly different isotopic composition, such as lower $^{143}Nd/^{144}Nd$, compared to the asthenosphere. The contrast in Nd isotopic values between the lithospheric mantle and asthenosphere, thus provides additional constraint on depth of melting. Here we present high-precision $^{231}Pa/^{235}U$ data on well-characterized young, < 20 ka old, continental basalts. The first group consist of alkali basalts from the Pinacate volcanic field (PVF), Mexico, and the central and southern Rio Grande rift. These flows have high ε_{Nd} values, from +6 to +4, and show large Th over U enrichment, $(^{230}Th/^{238}U)$ values 1.10 to 1.25 (Asmerom and Edwards, 1995; Asmerom, in preparation). Based on isotopic and geophysical arguments, these flows are thought to be derived from an asthenospheric mantle source. The large Th enrichments, similar to those seen MORB, are consistent with these flows representing small degrees of melting or dynamic melting, with initial melting within the garnet stability field (Spiegelman and Elliott, 1993). The second group of samples consist of alkali basalts from the Colorado Plateau, a setting with thick lithosphere, and a tholeiitic basalt from the central Rio Grande Rift, where an attenuated lithospheric mantle is thought to still exist. These flows have low ε_{Nd} values, from −1 to +0.5 and show no Th enrichment, $(^{230}Th/^{238}U) = 1$ (Asmerom and Edwards, 1995; Asmerom, in preparation). The equilibrium $(^{230}Th/^{238}U)$ values are not due to decay as these samples are either historical flows or have excellent age constraints (800 to 3,000 yrs old). Moreover, as discussed below, they show significant ^{231}Pa enrichment. These flows are thought to be derived from the lithospheric mantle. The lack of Th enrichment is consistent with their being derived from a spinel peridotite source – the $D_U^{CPX}/D_{Th}^{CPX} = \sim 1$ (Beattie, 1993; LaTourette *et al.*, 1993; Hauri *et al.*, 1994; Lundstrom *et al.*, 1994).

All the alkali basalts from both groups have a near uniform $(^{231}Pa/^{235}U)$ values, from 1.82 to 2.15, and similar U concentrations, 0.85 to 1.1 ppm. The tholeiitic basalt has $(^{231}Pa/^{235}U) = 1.4$ and U concentration of 0.6 ppm. We run most of the samples in replicates and their values agree within 1%. These results are very surprising, given the second group of alkali and tholeiitic basalts are perfectly in equilibrium with respect to $(^{230}Th/^{238}U)$! Moreover, flows with variable $(^{230}Th/^{238}U)$ from 1.1 to 1.2X, have similar $(^{231}Pa/^{238}U)$. At the moment there are no well-established Pa partitioning data for cpx and garnet. It is generally agreed that Pa is more

incompatible than both Th and U. If we assume Pa partitioning values close to zero, these important points may be made:

(1) If the melts represent simple equilibrium batch melting, the Pa-U would argue that data $D_{Pa}^{Garnet}/D_{U}^{Garnet} \sim D_{Pa}^{CPX}/D_{U}^{CPX}$, unless Pa partitioning is controlled by other accessory minerals, although the uniformity of the ($^{231}Pa/^{235}U$) data would argue for control by a major phase.

(2) The contrast between the ($^{231}Pa/^{235}U$) ~ 2 and U concentration of 0.85–1.1 ppm of the alkali basalts, regardless of the tectonic environment, and the ($^{231}Pa/^{235}U$) = 1.4 and U concentration of 0.6 ppm of the tholeiitic basalt, would seem to suggest that degree of melting play an important role in Pa-U partitioning.

(3) If we assume, for a moment, equilibrium batch melting, and given the initial $(^{231}Pa/^{235}U)_{source} = 1$, then

$$\left(\frac{^{231}Pa}{^{235}U}\right)_{melt} = \frac{D_U(1-F)+F}{D_{Pa}(1-F)+F},$$

and assuming D_U to be much greater than D_{Pa}, it is evident from the above relationship, that the degree of melting, F, is in the range of D_U (~ 1%) for $(^{231}Pa/^{235}U)_{melt} = 2$. Ultimately, we need to reconcile the F values derived from Th and Pa isotopic data with those inferred from major and trace element compositions.

(4) The data from the lithospheric mantle derived flows rule out source upwelling driven 'in growth' enrichment of ^{231}Pa. The lithospheric mantle under the Colorado Plateau is mechanically coherently rigid. *This is an important and powerful constraint that may also likely be relevant for MORB and OIB generation.* Any theory of mantle melting, has now to account for the large ^{231}Pa enrichment shown by basalts derived from the non-upwelling lithospheric mantle.

(5) The near uniform ($^{231}Pa/^{235}U$) of ~ 2, for basalts derived from sources with contrasting trace element composition (e.g. the lithospheric mantle source has had long standing lower Sm/Nd ratio compared to the asthenospheric source), may indicate that there is a critical threshold melt fraction, or thermally driven critical extent of melt – wall rock interaction. The enrichment pattern contrasts with the Th enrichment pattern; the latter is correlated with Nd isotopic values locally, and Sr isotopic composition globally. The contrast may have to do with the behaviour of Th and Pa during mantle melting and possibly post-melting histories. Similar disparity is observed with Th and Ra isotopic data.

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