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^{231}Pa-^{235}U Systematics and the Time Scales of Melting Processes Beneath the Tonga-Kermadec Arcs

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Introduction

Understanding the process of melt generation beneath subduction zone should help constrain the thermal and convective structure of the mantle wedge and the adjacent slab. In this respect, the combination of U-series nuclides are particularly useful for several reasons: (1) the fractionation of U-Pa and U-Th depends on the mineralogy of the mantle source and is thus sensitive to the depth of melting; (2) the relative importance of fluid induced-melting and decompression melting by upwelling beneath the arc depends on the convective pattern of the mantle wedge. In this study, we have focused on the Tonga-Kermadec arc which is particularly depleted and hence more sensitive to the subducted slab inputs. It is thus an ideal location for looking at the 'intrinsic' arc processes.

Analytical results

We have measured Pa-U disequilibria in a selection of lavas from the Tonga-Kermadec arc representing the wide compositional range described by previous studies (Turner et al., 1997). Pa concentrations were measured by ID-TIMS technique described in Bourdon et al. (1999). The Pa concentrations range between 40 and 123fg/g for the Tonga-Kermadec lavas, while the (^{231}Pa/(^{235}U) ratios range from 0.789 to 1.69. Most of the Kermadec samples have (^{231}Pa/(^{235}U) greater than 1. In contrast, the Tonga samples have (^{231}Pa/(^{235}U) close to or less than 1 (0.807-1.10). The (^{231}Pa/(^{235}U) ratios are positively correlated with (^{230}Th/(^{238}U) ratios and fall in the general trend defined for arc lavas by Pickett and Murrell (1997).

Constraints on the time scale since fluid addition in the Tonga arc

The origin of inclined arrays in the U-Th equiline diagram has often been discussed in the literature. It has been proposed that the slope indicates the time since U-rich slab fluid addition. There are other suggestions that Th is added with the fluid or that the initial mantle wedge composition is strongly heterogeneous in ^{230}Th/ ^{232}Th ratios (Turner and Hawkesworth, 1997 , Elliott et al. 1997, Turner et al. 1997). Here, we have used U-Pa 'isochron' diagram constructed by normalizing both Pa and U to Nb. The only assumption that is made here is that Pa is immobile in slab dehydration fluid. Strikingly, the age we derive from this diagram is 60kyr which is close to the age given by U-Th data (30-50kyr). This suggests that, subsequently to fluid addition, the fractionation of Pa-U due to melting which is seen in other arcs must have been limited to preserve the age relationship. One could envision a more complex process that would involve both 231Pa decay after fluid addition and Pa-U fractionation during melting but the consistency with U-Th data would appear to be coincidental since U-Pa fractionation during melting is far more pronounced than for U-Th.

Constraints on melting processes

Several processes can be thought of for describing U-series fractionation taking place during melting in the mantle wedge: (1) batch melting by fluxing of the mantle wedge with slab-fluid, (2) flux-melting followed by interaction with the lithosphere during ascent of the melts, (3) flux melting followed by adiabatic decompression and melting of the mantle column. It can be shown using standard models that none of the first two models produce a large enough ^{231}Pa/^{235}U fractionation unless unreasonable parameters are being used (very small degree of melting for model (1) and large degrees of olivine fractionation for model (2)). Thus, given our knowledge of U and Pa partitioning through experiments and modeling, it seems more likely that ^{231}Pa excesses as observed in the Kermadec lavas are generated during adiabatic melting. REE modeling and the absence of ^{230}Th excess in the Kermadec lavas suggests that melting took place with little or no garnet in the residue. In-growth models with a cpx residue are capable of generating the required (^{231}Pa)/(^{235}U) ratios (up to 1.69) with a mantle upwelling velocity of about 3cm/yr. Decompression melting could occur as a result of increased buoyancy and lower viscosity of the ambient mantle. This might lead to the formation of a diapir in which melt and residue can travel upwards at different velocities allowing dynamic melting and radiogenic daughter ingrowth to produce the large ^{231}Pa excesses found in the Kermadec lavas. In the case of the Tonga lavas, the mantle wedge is more depleted and thus the effect of melt-induced fractionation is more subdued since the amount of cpx responsible for Pa-U fractionation must be lower.

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