Oxygen isotope geochemistry of oceanic arc lavas

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There is abundant evidence that the upper portions of subducted oceanic crust and its associated sediments and fluids contribute to the chemistry of subduction-zone lavas (e.g. 1,2). This contribution is thought to be introduced as fluids and/or melts (enriched in some elements relative to crustal rocks and sediments) that are distilled from the down-going slab and mixed with peridotite in the overlying mantle wedge. Given the likely thermal state of the subducting slab and overlying mantle, melting in the sub-arc environment may in some cases be limited by the introduction of these volatile- and incompatible-element-rich fluid/melt phases (3).

Efforts to identify and characterize the contribution of subducted materials to arc volcanism have emphasized the abundance and isotopic composition of minor and trace elements that are relatively abundant in altered basaltic rocks and sediments and concentrated into fluids and silicate melts relative to common silicate minerals (e.g. K, B, Ba). Oxygen isotopes offer additional constraints on the sources of arc volcanism that are qualitatively different from and complementary to trace element evidence. These constraints derive from the strong isotopic contrast between oxygen in typical upper-mantle and many crustal materials, the fact that oxygen concentrations are roughly constant in common magmas and minerals, and the small high-temperature, equilibrium isotopic fractionation of oxygen among minerals, melts, and fluids. For these reasons, relationships between $\delta^{18}O$ and other geochemical and petrologic variables have the potential to define the absolute amounts of slab components in the mantle sources of arc lavas, which in turn can constrain the concentrations of solutes in slab components, help distinguish between metasomatic fluids and melts, and help define the mechanisms by which slab phases interact with the mantle wedge.

We have studied the oxygen isotope geochemistry of glasses and phenocrysts from 72 arc and back-arc lavas from several ocean-ocean convergent margins (the Marianas, South Sandwich, Vanuatu, and New Caledonian arcs; and arc-related rocks from Papua New Guinea). This suite includes a large petrologic and geochemical range of lavas, and most are well-characterized for trace-element and/or radiogenic-isotope compositions. Values of $\delta^{18}O$ were measured for olivine and other phenocrysts and glasses using laser fluorination (4). All values of $\delta^{18}O$ determined for this study have a precision of $\pm 0.07‰$ (1σ) based on measurements of two working standards and six other materials of known isotopic composition.

Eighty percent of our samples have values of $\delta^{18}O$ for any given phase that are within 0.2‰ of values for the same phase in average upper-mantle peridotites and MORB. All samples fall within a range of 1.0‰ or less for any given phase. Similar results were found previously by us for ocean-island (OIB) lavas using the same methods (4). These results for arc and back-arc lavas contrast with many previous studies of whole-rock samples (which have more than 10x the range in $\delta^{18}O$ values found here) and demonstrate that most lavas from oceanic arcs contain 1-2% of oxygen from upper crustal sediments or altered rocks, whether through assimilation or subducted contributions.

Oxygen isotope variations observed in this study show some correlations with the commonly-studied monitors of slab contributions to the sources of arc-related lavas. Observed relationships can be subdivided into two classes: (1) highly hyperbolic correlations (e.g. $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ in the Vanuatu arc) that suggest mixing between an NMORB mantle source and a high-$\delta^{18}O$, slab-derived component that is enriched in at least some trace elements compared to normal mantle peridotite; and (2) suites of samples that show no significant range in $\delta^{18}O$ but that exhibit large ranges in indices thought to be sensitive to slab contributions(e.g. Ba/Nb vs. $\delta^{18}O$ in the Mariana arc and trough). Suites exhibiting this latter behaviour could be explained either by highly hyperbolic
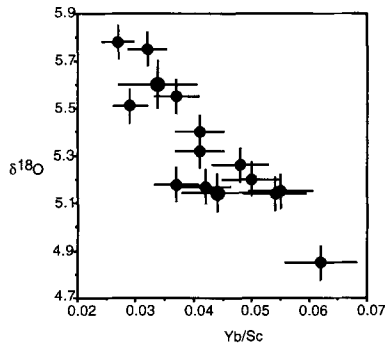
FIG. 1. Comparison of values of $\delta^{18}O$ for olivine phenocrysts with Yb/Sc ratios in host lavas. Small symbols are data for individual samples on which both variables were measured. Large symbols are averages for a suite of related samples. Low Yb/Sc ratios in lavas reflect high extents of melting or previous depletion of their sources. We have excluded from this plot one sample that has an anomalously low Sc content (23 ppm), perhaps indicating modification by fractional crystallization of pyroxene.

mixing trends for which the high-$\delta^{18}O$ limb has not been sampled or the absence of any crustal oxygen signal (e.g. due to an origin of trace element variability from non-slab sources or due to chromatographic separation of oxygen and trace elements during flow of a slab component in the mantle).

Variations in $\delta^{18}O$ in our samples are well correlated with chemical indices that are sensitive to the extent of melting of peridotites. For example:(1) Among samples containing chromite phenocrysts, high $\delta^{18}O$ is only seen in samples with chromites having molar Cr/[Cr+Al] >0.80. Such values are high relative to chromites in typical peridotites and typical basaltic lavas and are only common in boninites and a small subset of island arc basalts (IABs) (5). High Cr/[Cr+Al] in Cr-rich spinels from peridotites are interpreted as an indication that those rocks are residual to high extents of melting. When found in phenocrysts in basic lavas, such spinels may similarly reflect derivation of these lavas from sources that have undergone high extents of melting.

(2) Enrichments in [18]O are associated with relatively low concentrations of TiO_2 in the host lavas. Similar correlations exist between $\delta^{18}O$ and other major element indices. For example, all suites of samples from our study having $Na_2O^{(8.0)}$ values <2.0 (including IABs from Tongoa, shoshonites from Tavua, and boninites from the Hunter ridge and New Caledonia) are ^{18}O-enriched.

(3) There is a strong negative correlation between

$\delta^{18}O$ and the Yb/Sc ratio (Fig. 1). The Yb/Sc ratio in basaltic lavas is expected to decrease with increasing extent of melting (or prior source depletion) of their peridotitic sources because Yb is moderately incompatible during peridotite melting, whereas Sc is moderately compatible (6).

The sense of the correlation in Fig. 1 (and the related correlations described above) is that enrichments in [18]O relative to typical mantle values are associated with high apparent extents of melting and/or low apparent source fertility (i.e. previous source depletion). In our view, the most straightforward interpretation of these observations is that relatively fertile peridotites in the sub-arc mantle span a restricted range in $\delta^{18}O$ (~5.0–5.2‰ for olivine; 5.3–5.5 for the bulk peridotite), and addition of a high-$\delta^{18}O$, slab-derived component is closely and quantitatively linked to extraction from these peridotitic sources of incompatible elements. A simple explanation for this relationship is that melting in the sub-arc mantle is fluxed by addition of a high-$\delta^{18}O$ slab component, i.e. because addition of this component lowers the solidus temperature of the peridotite. An aqueous fluid could have this effect, as could a silicate melt rich in Na, Al and other incompatible elements and/or water. We have constructed forward models for such a process in order to quantify and test this hypothesis. Correlations such as that in Fig. 1 are well explained by fluxing of initially fertile peridotite by solute-rich water with a $\delta^{18}O$ of ~20‰. Common IAB are derived from sources that have been fluxed by ~0.25-0.5 wt.% of this phase, while low-Ti IAB, low-Ti shoshonites, and boninites are derived from sources that have been fluxed by ~1.0-2.0 wt.% of this fluid. A fluid with a chemical composition similar in most respects to the water-rich component that Stolper and Newman (2) inferred to contribute to the Mariana back arc can account quantitatively for the oxygen isotopes and the minor and trace element geochemistry of most of the samples in our suite.

Our results suggests that, in at least the cases that we have studied so far, the extent of melting in the sub-arc mantle is in large part controlled by the extent to which it has been fluxed by a slab component. This conclusion is significant in several respects; most concretely it can serve as the basis for a quantitative model linking arc basalt petrogenesis with the extent of input from subducted components, providing a detailed and mechanistic context for linking slab signatures with petrology. More generally, our results are an unusual observational insight into how arc magmatism 'works'; i.e. they link an isotopic tracer for subducted components with the igneous processes that are generally studied through consideration of major element geochemistry and phase equilibria.