Are the regional variations in Central American arc lavas due to differing basaltic versus peridotitic slab sources of fluids?

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ABSTRACT

Central American arc volcanism shows strong regional trends in lava chemistry that result from differing slab contributions to arc melting. However, the mechanism that transfers slab-derived trace elements into the mantle wedge remains largely unknown. By using a dynamic model for mantle flow and fluid release, we model the fate of three different slab-fluid sources: sediment, ocean crust, and serpentinized mantle. In the open subarc system, sediments lose almost all their highly fluid mobile elements by ~50 km depth, so other fluid sources are necessary to explain the slab signal in arc-lava compositions. The well-documented transition from lavas with a strong geochemical slab signature (i.e., high Ba/La ratios) found in Nicaragua to lavas with a weaker slab signature (i.e., low Ba/La ratios) erupted in Costa Rica seems easiest to produce by a higher fraction of serpentine-hosted fluids released from the deeply faulted, highly serpentinized lithosphere subducting beneath Nicaragua than from the less deeply faulted, thicker, amphibolitic oceanic-crust and oceanic-plateau lithosphere subducting beneath Costa Rica.

Keywords: Central America, serpentinization, subduction zone, geochemistry, fluid release, modeling.

INTRODUCTION

Many subduction zones have well-described but poorly understood along-arc trends in the geochemistry of their arc lavas. Arc melting is generally thought to take place in the mantle wedge above the slab, where it is triggered by fluxing of hydrous fluids that are released by metamorphic dewatering reactions inside the downgoing slab. Chemically bound water in the sedimentary, crustal, and mantle parts of the subducting plate is released at different pressure-temperature (*P-T*) conditions that vary with the incoming slab's age, subduction rate, dip angle, and composition. At the Central American volcanic front major geochemical and tectonic variations occur within several hundred kilometers along strike for a plate of nearly constant age and subduction rate.

Figure 1 summarizes the tectonic setting for subduction beneath Central America. The subduction angle changes from steep (~65°) beneath Nicaragua to shallow (~40°) beneath Costa Rica (Barckhausen et al., 2001; Protti et al., 1995). Nicaraguan arc lavas typically have high B/La, Ba/La, and $^{10}Be/^{9}Be$ ratios and low La/Yb ratios, characteristics that smoothly change along the arc toward Costa Rica, where arc lavas show low B/La, Ba/La, and $^{10}Be/^{9}Be$ ratios and high La/Yb ratios (Carr et al., 1990; Herrstrom et al., 1995; Patino et al., 2000). Carr et al. (1990) found that most of these variations can be effectively represented in terms of two parameters: (1) the La/Yb ratio, which represents the mantle source's enrichment in incompatible elements, and (2) the Ba/La ratio, which monitors the slab-derived fluid's contribution to arc chemistry. Nicaraguan arc-lava composition can therefore be explained by having a larger fluid contribution from the slab. The concentration of trace elements added to the produced melts by the slab-derived fluids reaches a minimum beneath Costa Rica (Carr et al., 1990; Leeman et al., 1994; Patino et al., 2000).

Details of trace element transport from the slab into the mantle wedge remain unclear. In this study we further explore the mechanisms of trace element recycling at subduction zones by studying fluid fluxing from the slab with a dynamic model that solves for fluid release. We find that the depth interval and intensity of fluid release from hydrated sediments, amphibolized basalts, and serpentinized peridotites can potentially vary as a function of the incoming plate's composition and the degree of lithospheric bend faulting at the outer rise. Along-strike chemical and tectonic changes in the incoming plate can lead to differing ratios of sediment- and serpentinite- to amphibolite-derived hydrous fluid release, which we suggest is a plausible mechanism to explain the observed changes in lava chemistry.

MODELING

Several different numerical models have been developed to analyze the tectonic, petrologic, and thermal structure of subduction zones (Davies and Stevenson, 1992; Kincaid and Sacks, 1997; van Hunen et al., 2000). To self-consistently model chemical dehydration reactions inside the downgoing slab, we have formulated a two-dimensional,

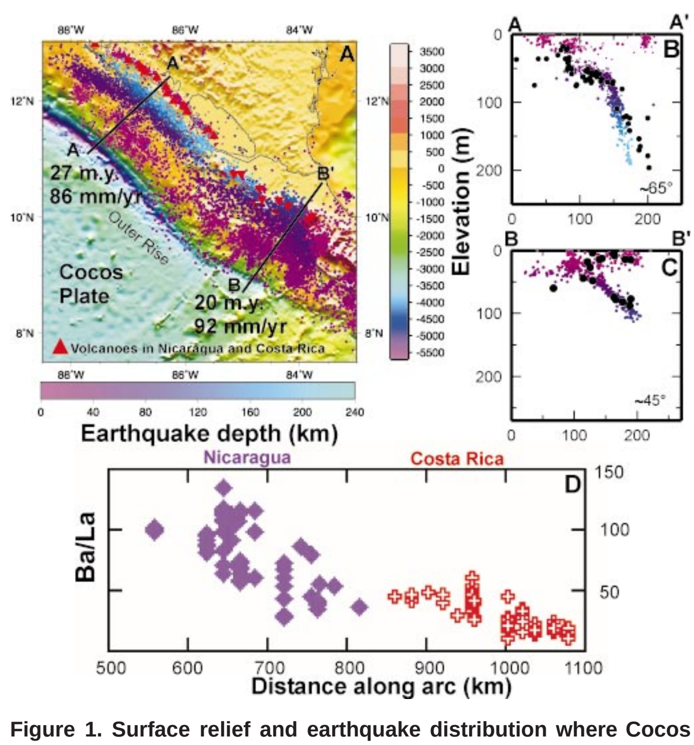

Figure 1. Surface relief and earthquake distribution where Cocos plate subducts beneath Caribbean plate. Transect A–A′ shows subduction beneath Nicaragua where outer rise (seaward from trench) develops numerous flexural faults (von Huene et al., 2000) and dip angle is steep. Beneath Costa Rica, along transect B–B′, dip angle is shallower. Changes in dip angle correlate with geochemical along-arc trends in lava chemistry as shown in D. Ba/La is chosen to exemplify slab-fluid signal in arc melting. Black dots mark newly relocated earthquakes (A. Villasenor, 2002, personal commun.).

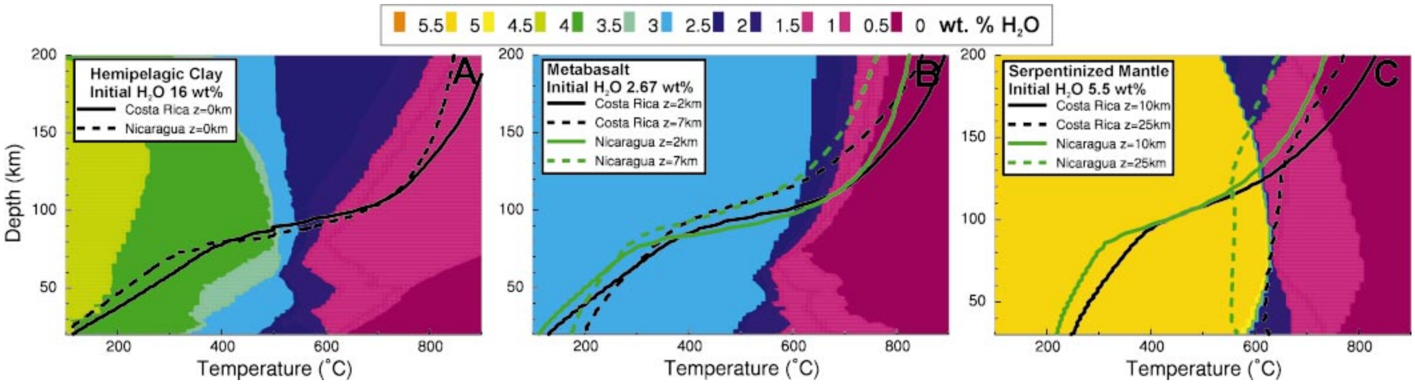

Figure 2. Water content as function of temperature and pressure for three slab-fluid sources used in model calculations. Water contents are calculated using PERPLEX program and following initial compositions: (A) hemipelagic clay at Deep Sea Drilling Project Site 495 (Plank and Langmuir, 1998), (B) Staudigel et al. (1996) super composite metabasalt, and (C) serpentinized mantle (Kerrick and Connolly, 1998). Also shown are geotherms for three different lithologies for subduction beneath Costa Rica and Nicaragua. For details on PERPLEX see Connolly (1990) and http://www.perplex.ethz.ch/.

dynamic model that continuously updates the flow, temperature, and compositional fields (see Data Repository[1] for details).

The flow-field solution is based on the Stokes equation for creeping flow solved by the penalty finite-element method (Zienkiewicz and Taylor, 2000). The thermal evolution of the system is calculated from the heat-transport equation using finite differences (Smolarkiewicz, 1984).

To model fluid release we divide the downgoing lithospheric plate into hydrated sediment, amphibolite-basalt crust, and serpentinized-mantle layers. We model these layers using tracer particles that are advected with the flow field. Each tracer particle starts with an initial volume and hydration. As the *P-T* conditions of a tracer particle change, so may its water content. The model determines the changes in water content of the three different slab fluid sources using look-up tables (see Fig. 2) created with the PERPLEX program (Connolly, 1990).

Fluid-releasing metamorphic reactions are endothermic (they consume latent heat); for proper internal consistency, we include the associated enthalpy consumption of the metamorphic reactions in the temperature solution.

The incoming plate's crustal thickness and the amount of chemically bound water in its oceanic lithosphere can vary along and between different subduction zones; e.g., seamounts and oceanic plateaus may significantly change the local incoming crustal thickness. Initial hydration of basaltic oceanic crust takes place at mid-ocean ridges. However, to hydrate mantle rocks, water has to be transported into relatively cool (<600 °C) mantle. Lithospheric bend faulting at the outer rise is a potentially viable mechanism to create and maintain the conduits for seawater to reach and react with cold lithospheric mantle. Such lithospheric serpentinites can store significant amounts of water

[1]Data Repository item 2002121, methods and illustrations of model formulation and boundary conditions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

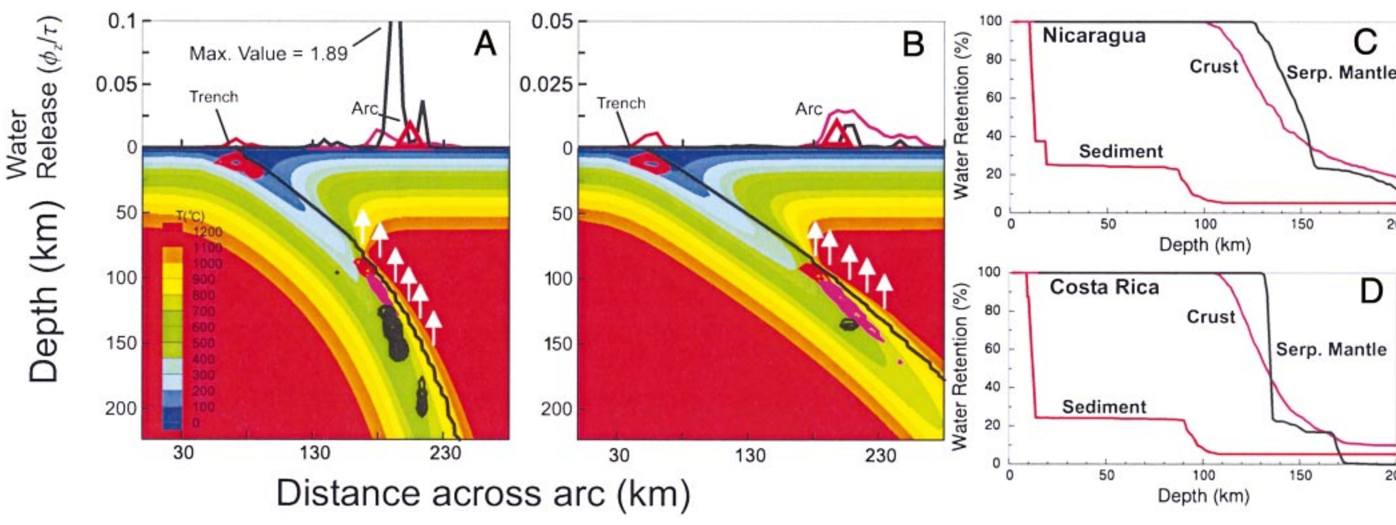

Figure 3. Slab dehydration beneath (A) Nicaragua and (B) Costa Rica. Red contour lines show chemical water release from sediment; purple and black contour lines represent release from crust and serpentinized mantle, respectively. For Costa Rica incoming columns of sediments, crust, and mantle contain 1.1 × 10^5 kg/m², 7.9 × 10^5 kg/m², and 1.3 × 10^5 kg/mg² of water, respectively; for Nicaragua respective incoming columns contain 1.1 × 10^5 kg/m², 3.6 × 10^5 kg/m², and 17.9 × 10^5 kg/m² of chemically bound water. In each plot, upper panel shows depth-integrated rates of dewatering. This value (ϕ_z)/τ is proportional to total amount of water release, where ϕ = fraction of chemically bound water and τ is dimensionless time, τ = *t*/31.5 (where *t* is in millions of years). In C and D, percentages of water retention are plotted. Sediments lose all their chemically bound water; crust and serpentinized mantle are more stable and do not completely dehydrate. Total amount of stored water is, however, highest in serpentinized mantle, so that serpentinized mantle seems to be most efficient lithology to recycle chemically bound water into deep mantle. Note that temperature contour interval is 100 °C; basal asthenosphere temperature is 1300 °C.

that can be subsequently released during subduction (e.g., Ulmer and Trommsdorf, 1995).

FLUID RELEASE BENEATH NICARAGUA AND COSTA RICA

To apply this model to Central America we have to determine the incoming plate's composition. The sediment input is reasonably well defined by Deep Sea Drilling Project (DSDP) Site 495. The sediment contribution can be divided into two layers: an ~200-m-thick layer of hemipelagic clay overlies an ~250-m-thick layer of carbonate oozes (Plank and Langmuir, 1998). Here we only explicitly model the upper hemipelagic layer of the sediments. We use this simplification because (1) most of the chemically bound water is within the hemipelagic clay (16 wt% H_2O) compared to the carbonate oozes (1 wt% H_2O) and (2) most trace elements relevant to this study (i.e., B and ^{10}Be) are mainly enriched within the hemipelagic part of the sediment column.

We assume that the sediments beneath Nicaragua (transect A–A′), a 2-km-thick layer (Walther et al., 2000) of altered basalts (2.67 wt% H_2O), a 3-km-thick (Walther et al., 2000) gabbroic layer (1 wt% H_2O), and a 10-km-thick serpentinized mantle layer (5.5 wt% H_2O), are subducting (note that recent seismic surveys show lithospheric faults extending at least 10 km below the Moho in this region; Ranero et al., 2001). We believe that seawater is transported through these faults into the cold lithospheric mantle to serpentinize it. Unfortunately little is yet known regarding the average degree of serpentinization in this environment. Serpentinites are known to have lower seismic velocities than peridotites, but as yet no good seismic velocity models exist for the subcrustal part of the incoming plate in Nicaragua. We choose the composition of serpentinized peridotites and their initial water content in accordance with experimental and modeling data (Kerrick and Connolly, 1998; Schmidt and Poli, 1998). However, the pattern of slab-dehydration reactions only weakly depends upon the initial degree of hydration, so Figure 3A is likely to be fairly representative of the spatial dehydration pattern within transect A–A′.

Figure 3A shows that the hemipelagic clay component loses ~75% of its initial chemically bound water content during shallow (<50 km) dewatering (red contour lines). The basaltic crust dewaters mainly between 100 km and 140 km depth (purple contour lines) and the serpentinized mantle loses 80% of its initial water content between 130 km and 160 km depth (black contour lines). The upper panel line plot shows the depth-integrated rates of dewatering that correlate with the total amounts of water release. Here serpentinized-mantle rocks are the dominant source of slab-derived fluids that flux the hotter regions of the overlying mantle wedge.

The situation for the transect B–B′ (Fig. 1) across Costa Rica is quite different. Here the outer rise is much smaller, and flexural normal faulting is much less developed than it is to the north (Ranero et al., 2001). We therefore assume a thinner (5 km) and less hydrated (2 wt% H_2O) mantle layer. The crust is slightly thicker (6–8 km) (von Huene et al., 2000), only reaching its maximum >20 km thickness (Cocos Rise) 100 km to the south of this transect. Here the incoming crust's layer 2 is thicker (~4 km), so we assume that a 4-km-thick hydrated (2.67 wt% H_2O) basaltic layer overlies a 4-km-thick gabbroic layer (1 wt% H_2O). Figure 3B shows the modeled situation along this transect. The sediments lose ~75% of their chemically bound water during shallow dewatering; the crust mainly dewaters between 100 km and 140 km depth, whereas the serpentinites lose most of their stored water between 130 km and 150 km depth. The upper panel plot in Figure 3B shows that amphibolites are the main source of the slab-derived fluid flux into this melting region.

IMPLICATIONS FOR TRENDS IN ARC-LAVA CHEMISTRY

Nicaragua Arc

Nicaragua arc lavas show high B/La and Ba/La ratios that both correlate with $^{10}Be/^{9}Be$. Because Ba/La and B/La are ratios of fluid-loving to rock-loving elements, the high values in these ratios in the arc lavas are usually thought to result from hydrous fluid fluxing out of subducting sediments and crust (Leeman et al., 1994; Patino et al., 2000). Figure 3 shows that water release from the basaltic crust, serpentinized mantle, and the deepest tail of the sediments can occur near the proposed depths of arc melting, so that three different scenarios for trace element transport from the slab into the mantle wedge may be possible.

One scenario is that either an aqueous fluid or melt released from the sediment layer produces the arc lava's enrichment in trace elements like B and ^{10}Be. Observed correlations between B/La and $^{10}Be/^{9}Be$ appear to support this (Morris et al., 1990). However, for highly fluid mobile elements, such as boron, this will only work if the bulk sediment reaches the melting region mostly unaltered, i.e., still containing its boron. This is problematic in an open subarc system. Most of the hemipelagic sediment's pore water and chemically bound water is lost at depths of <50 km, and You et al. (1996) showed in a series of experiments that boron is easily mobilized by a hydrous fluid at low temperatures. Thus it seems that shallow sediment dewatering will remove most of the sediment's fluid mobile trace elements and volatiles. For example, we can treat the water loss as open-system Rayleigh fractionation for which $C_{solid}/C_{initial} = (1 - f)^{(1-D)/D}$, where D is boron's the partition coefficient, and $C_{initial}$ and C_{solid} are the initial and residual boron concentration of the rock after loss of a fluid fraction f. We choose $D = 0.1$ as an upper bound and $D = 0.01$ as a lower bound to the likely value (W.E. Seyfried and R.H. James, 2002, personal commun.). If the sediments lose ~12 wt% H_2O (as they do by ~50 km depth), for $D = 0.1$ and $D = 0.01$, they will also lose ~68% and ~99%, respectively, of their initial boron content. This result implies that subducted sediments will retain relatively little of their initial boron by the time they reach the main depths of arc melting, in which case sediments cannot be the enriched source needed to produce the high B/La ratio in some arc lavas.

The second scenario uses two fluid phases, one from the sediments and one from the crust. Figure 3 shows that fluids are released from both potential fluid sources at the supposed depth of arc melting. However, very small amounts of water are released from the sediments at this depth, so a transfer of the relatively immobile ^{10}Be is unlikely; transfer by sediment melts would be possible only for unrealistically high temperatures. Crustal fluids could, however, be enriched in boron, which is also enriched in the altered ocean crust. This model is consistent with the ideas of Ishikawa and Nakamura (1994), who argued on the basis of $\delta^{11}B$ systematics that the generally positive $\delta^{11}B$ values of arc lavas require a boron source of the same isotopic signature (i.e., $\delta^{11}B > 0$). Sediments generally have negative $\delta^{11}B$ values, while the altered ocean crust has $\delta^{11}B > 0$. The biggest problem for this scenario is that transfer of B and ^{10}Be in two separate fluid phases is not easily reconciled with the observed correlations between these two elements. Furthermore, it is not clear how small amounts of subarc fluid released from sediments can transport the observed radiogenic Be anomaly.

Thus, it seems that Nicaragua arc-lava composition cannot be easily explained without yet another fluid source. Much larger amounts of high-temperature hydrous fluids can be released during slab deserpentinization, as shown in Figure 3. Such fluids must pass through overlying crust and sediments on their way to the mantle wedge. During this process, the fluids can potentially interact with and dissolve enough of the sediment's still trapped Be to produce the observed high $^{10}Be/^{9}Be$ ratios (Be only becomes relatively fluid mobile in high-T, reducing fluid environments). Tatsumi and Isoyama (1988) showed that Be is potentially mobile in high-temperature fluids released from a serpentinite. In addition, studies of serpentinites from the Atlantic show that seawater-induced serpentinization enriches the host peridotites in boron and leads to positive $\delta^{11}B$ values (Spivack and Edmond, 1987).

Fluids released during slab deserpentinization are therefore enriched in boron, carry the right (i.e., positive) isotopic signature ($\delta^{11}B$), and have the ability to dissolve enough of the sediment's ^{10}Be to explain the high $^{10}Be/^{9}Be$ and B/La ratios observed in Nicaraguan arc lavas.

Costa Rica Arc

Beneath Costa Rica, subduction is hotter, the dip angle is shallower, and the downgoing slab is younger. Here the erupted lavas do not show a strong slab-fluid signal. Figure 3B shows that, primarily due to the shallower slab dip, dehydration of the slab occurs over a wider horizontal extent, consistent with the idea that a shallower dip leads to less fluid input per unit mantle volume into the melting region (Carr et al., 1990). This provides a possible explanation for the diluted slab signature and the low degree of melting typical for volcanism in Costa Rica (Carr et al., 1990). This interpretation does not, however, explain why the Costa Rican lavas lack a ^{10}Be anomaly, although the slab is hotter and sediment melting would be more likely in this part of the arc. Patino et al. (2000) argued that the missing slab signature may be partly due to a mechanical loss of the uppermost part of the sediment column during accretionary processes. However, a striking modeled difference between fluid release beneath Nicaragua and Costa Rica is the lack of a strong fluid release from serpentinized mantle beneath Costa Rica. Perhaps this is responsible for the lack of a Costa Rican ^{10}Be signal; without high-T serpentine-breakdown–derived fluids fluxing through the slab's sediment layer, more of the sediment's ^{10}Be would simply be subducted instead of being leached mobilized into the subarc melting region.

CONCLUSION

Regional trends in Central American arc lavas can be explained by an outer rise faulting–related change from a serpentinized slab mantle deep fluid source beneath Nicaragua to a basalt-amphibolite source beneath Costa Rica; the difference is caused by a transition from deeply faulted, serpentinized lithosphere steeply subducting beneath Nicaragua to less deeply faulted lithosphere subducting less steeply beneath Costa Rica.

We further show that lithospheric mantle—serpentinized as a by-product of flexural faulting at the outer rise—has the potential to release significant amounts of hydrous fluids into the melting region. Fluxing of these hot, hydrous, serpentine-breakdown–derived fluids through overlying sediments can potentially scavenge and transfer ^{10}Be from the sedimentary layer into the mantle wedge. We infer that this process is perhaps more ubiquitous than sediment melting, because it does not require an extremely high slab surface temperature.

Serpentinites are also the best slab lithology for transferring chemically bound water through the arc-dewatering region to greater mantle depths. Flexural faulting–induced lithospheric mantle serpentinization beneath the outer rise may therefore play an important role in the global water cycle and in recycling processes at subduction zones in general.

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