Oxygen isotope constraints on the sources of Central American arc lavas

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[1] Oxygen-isotope ratios of olivine and plagioclase phenocrysts in basalts and basaltic andesites from the Central American arc vary systematically with location, from a minimum $\delta^{18}O_{olivine}$ value of 4.6 (below the range typical of terrestrial basalts) in Nicaragua near the center of the arc to a maximum $\delta^{18}O_{olivine}$ value of 5.7 (above the typical range) in Guatemala near the northwest end of the arc. These oxygen-isotope variations correlate with major and trace element abundances and with Sr and Nd isotope compositions of host lavas, defining trends that suggest variations in $\delta^{18}O$ reflect slab contributions to the mantle sources of these lavas. These trends can be explained by a model in which both a low-$\delta^{18}O$, water-rich component and a high-$\delta^{18}O$, water-poor component are extracted from the subducting Cocos slab and flux melting in the overlying mantle wedge. The first of these components dominates slab fluxes beneath the center of the arc and is the principal control on the extent of melting of the mantle wedge (which is highest in the center of the arc); the second component dominates slab fluxes beneath the northwestern margin of the arc. Fluxes of both components are small or negligible beneath the southeastern margin of the arc. We suggest that the low-$\delta^{18}O$ component is a solute-rich aqueous fluid produced by dehydration of hydrothermally altered rocks deep within the Cocos slab (perhaps serpentinites produced in deep normal faults offshore of Nicaragua) and that the high-$\delta^{18}O$ component is a partial melt of subducted sediment on top of the plate.

1. Introduction

[2] The geochemistry of mafic lavas from the Central American arc (Figures 1a, 1b, and 1c) varies systematically with distance along the arc and covaries in general both with the dip of the subducting Cocos slab (Figure 1d) and the crustal thickness of the overriding Caribbean and (in the northwestern end of the arc) North American plates (Figure 1e; geophysical parameters are based on estimates from *Carr* [1984], *Carr et al.* [1990], and *Carr et al.* [2004] and are likely to be revised soon on the basis of recent and planned geophysical experiments in Central America). For example, strong "slab" trace element signatures (e.g., high U/Th and Ba/La) and low Na contents are typical of lavas in the center of the arc, where the slab dip is high and crustal thickness low; whereas weaker "slab" trace element signatures and higher Na contents are typical of lavas from the margins of the arc, where slab dip is low and crustal thickness high. In addition, there are subtle geochemical differences between the two ends of the arc, and these are not simply correlated with slab dip or crustal thickness (which are not significantly different at the northern and southern ends of the arc). For example, whereas Costa Rican lavas (the southeast end) have U/Th and Ba/La ratios approaching those typical of mid-ocean-ridge and ocean-island basalts (referred to as MORB and OIB), Guatemalan lavas (the northwestern end) are similarly low in U/Th but higher in Ba/La.

[3] The covariations of lava chemistry and slab dip shown in Figure 1 have been interpreted as evidence that subduction-zone geometry controls fluxes of slab-derived fluids through the overlying mantle wedge. For example, *Carr et al.* [1990] hypothesized that fluids released from a steeply dipping slab are focused over a narrow interval of the mantle wedge (measured perpendicular to the trench) whereas a flatter slab distributes the fluids over a wider interval; this behavior is plausible if fluids are released from the slab over a constant range of depths. Highly focused fluxes of slab-derived fluids would lead to relatively high integrated extents of melting in the infiltrated parts of the mantle wedge, producing lavas with low abundances of Na and trace-element ratios dominated by subducted components (i.e., similar to Nicaraguan lavas). In contrast, less focused fluxes of the same total amounts of fluid would result in more widely distributed, smaller degrees of melting, producing more Na-rich magmas having trace element ratios more influenced by the mantle

wedge (i.e., similar to Guatemalan and Costa Rican lavas, although, as mentioned above, these two suites differ from one another in some aspects of their geochemistry). In addition, recent geophysical evidence shows that the Cocos slab beneath Nicaragua has an exceptionally high degree of hydration [*Abers et al.*, 2003], providing a second reason why fluxes of slab-derived fluid might be unusually high beneath the center of the arc. Nevertheless, although it can account for key aspects of the geochemistry of Central American lavas, without modification, this hypothesis does not account for the contrasting behaviors of the U/Th ratio (which varies symmetrically about the center of the arc; Figure 1b) and the Ba/La ratio and perhaps $Na_{6.0}$ (which differ between the northwest and southeast ends of the arc; Figures 1a and 1c).

[4] An alternative hypothesis that might explain some of the trends in Figure 1 is that the degree of melting of the mantle wedge is influenced by the distance over which it upwells (i.e., as for decompression melting beneath mid-ocean ridges) rather than being dominantly set by the availability of slab-derived fluids, and that this distance is controlled by the thickness of the overriding plate (which might equal or correlate with, crustal thickness [*Plank and Langmuir*, 1988]). In this context, high-degree melts with low Na contents would be produced by the longer and on average lower pressure columns of upwelling mantle wedge underlying thinner crust (i.e., as in Nicaraguan), whereas low-degree melts with high Na contents would be produced by shorter and on average higher pressure upwelling columns underlying thicker crust (i.e., as in Guatemala and Costa Rica). Variations in the vertical distance over which melting takes place could also plausibly depend on slab dip if the depth of the base of the melting column is related to the depth of the slab. This hypothesis, at least as detailed by *Plank and Langmuir* [1988], does not make specific predictions about the distribution of slab trace element signatures along the length of the arc. However, one can easily imagine variants of this hypothesis that combine processes of fluxed and decompression melting and that might also explain these geographic variations in trace elements.

[5] The fluxed-melting hypothesis of *Carr et al.* [1990] predicts a strong relationship between the degree of partial melting in the mantle wedge and the amount of slab-derived fluid or hydrous melt added to the wedge, whereas the decompression-melting hypothesis does not require such a rela-
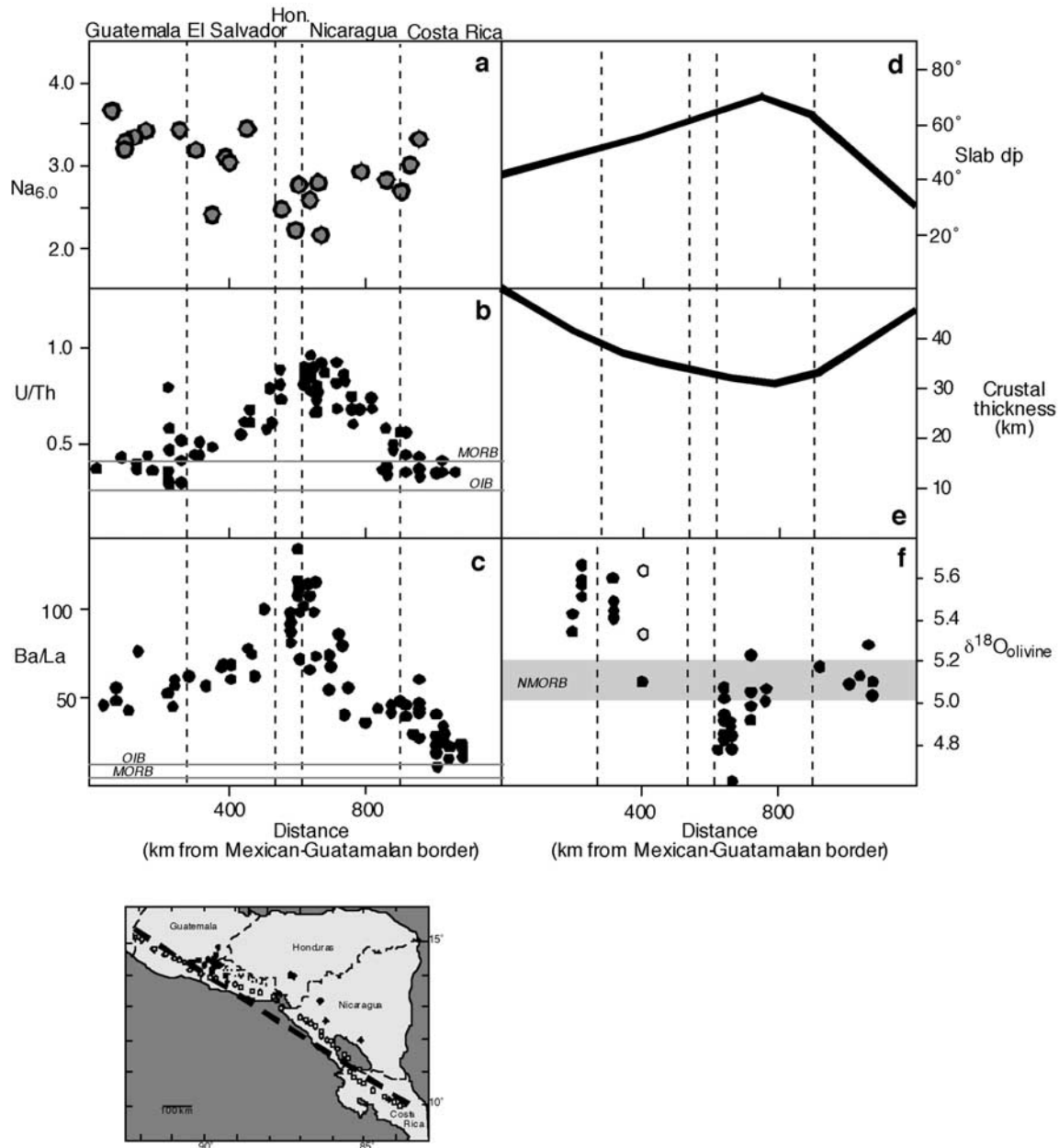
Figure 1. Geographic distribution of compositions of Central American arc lavas (Figures 1a–1c and 1f) and geophysical properties of the subducting slab and overriding plate (Figures 1d and 1e). Note that strong trace element signatures of subducted components (high U/Th and Ba/La ratios), low Na contents, and low $\delta^{18}O$ values are concentrated in the center of the arc, where slab dip is steep and the Caribbean plate is thin. Each data point in Figure 1a is the average Na_2O content, in wt.%, of a suite of lavas from a single volcanic center, normalized to 6 wt.% MgO (the average MgO content of the lavas we analyzed). These $Na_{6.0}$ values were calculated on the basis of linear regressions of measurements of wt.% Na_2O versus wt% MgO for several lavas from each volcano, based on data from a database maintained by M. J. Carr (http://www.rci.rutgers.edu/~carr/index.html). U/Th and Ba/La ratios (Figures 1b and 1c) are for individual samples of basalt and basaltic andesite from the M. J. Carr database. Slab dip and crustal thickness (Figures 1d and 1e) are estimates taken from *Carr and Stoiber* [1990] and *Carr et al.* [2004]. Values of $\delta^{18}O_{olivine}$ (Figure 1f) are from this study and are compiled in Table 1. Two lavas from behind the volcanic front in Honduras are distinguished by open symbols in Figure 1f. The geographic distribution of $\delta^{18}O_{plagioclase}$ values (Table 1) resembles that for $\delta^{18}O_{olivine}$ in Figure 1f. The inset is a map of the Central American arc; the heavy dashed line was used to measure distances from the Mexican-Guatemalan border.

tionship. Therefore determination of the amounts of slab-derived components sampled by lavas produced by known degrees of partial melting of peridotites in the mantle wedge would provide a test of the Carr et al. hypothesis and valuable constraints on any model to explain the connections between geochemical and geophysical features of the Central American arc.

[6] Oxygen-isotope ratios of arc lavas provide a potentially powerful means of characterizing and, under certain circumstances, quantifying the input of slab-derived components into their sources [*Eiler et al.*, 2000a; see also *Eiler*, 2001, and references therein]. Oxygen-isotope ratios, especially in conjunction with other geochemical indicators that constrain source composition and degree of melting, are particularly useful for two reasons:

[7] 1. All common rocks and geological fluids contain similar concentrations of oxygen. Consequently, mixing trajectories are roughly linear functions of oxygen-isotope ratios, making it relatively easy to relate variations in $\delta^{18}O$ of lavas to amounts of isotopically exotic fluids or melts added to their sources. This is not usually the case for radiogenic-isotope ratios or abundance ratios of incompatible elements because their concentrations can differ significantly in various slab-derived and mantle components [*Elliott*, 2004].

[8] 2. The oceanic lithosphere is heterogeneous in $\delta^{18}O$, so the $\delta^{18}O$ values of slab-derived components could provide information on the part(s) of the slab from which they come. Although $\delta^{18}O_{SMOW}$ values of most mantle peridotites span a narrow range (~5.5 ± 0.2‰ [*Mattey et al.*, 1994]; see *Eiler et al.* [1996a] and *Ducea et al.* [2002] for exceptions), many of the candidates for the sources of slab-derived components are distinct from this range. For example, marine carbonates ($\delta^{18}O_{SMOW}$ = 25–32‰), siliceous oozes ($\delta^{18}O_{SMOW}$ = 35–42‰), pelagic clays ($\delta^{18}O_{SMOW}$ = 15–25‰) [*Kolodny and Epstein*, 1976; *Arthur et al.*, 1983], and weathered and hydrothermally altered upper oceanic crust ($\delta^{18}O_{SMOW}$ = 7–15‰) [*Gregory and Taylor*, 1981; *Alt et al.*, 1986; *Staudigel et al.*, 1995] are all richer in ^{18}O than typical upper mantle peridotites, whereas hydrothermally altered lower oceanic crust ($\delta^{18}O_{SMOW}$ = 0–6‰) [*Gregory and Taylor*, 1981; *Alt et al.*, 1986; *Staudigel et al.*, 1995], hydrothermally altered ultramafic rocks (e.g., serpentinites) from the ocean lithosphere ($\delta^{18}O_{SMOW}$ = 0–6‰, although these are poorly known [*Magaritz*

and Taylor, 1974; *Cocker et al.*, 1982]), and pore waters in marine sediments ($\delta^{18}O$ = 0 to −3‰; perhaps as low as −15‰ [*Schrag et al.*, 1992]) are all poorer in ^{18}O than typical upper mantle peridotites. Thus oxygen-isotope ratios can help to distinguish among various choices of possible sources of slab-derived components, especially in the context of other geochemical discriminators among these components.

[9] In this paper, we report measurements of oxygen-isotope ratios in phenocrysts from 51 Central American arc basalts and basaltic andesites from Costa Rica to Guatemala. We focus on phenocrysts because they are less susceptible to posteruptive alteration than groundmass or glass [*Eiler*, 2001]. These samples span most of the geographic range of the arc and have been characterized geochemically in previous studies. These measurements allow us to revisit existing hypotheses for the origins of geographically correlated geochemical variability of Central American lavas and have the potential to constrain the amounts of slab-derived components in the mantle sources of these lavas, the properties of slab-derived fluids and/or melts, and the part(s) of the slab from which they were derived.

2. Samples and Methods

[10] We analyzed oxygen-isotope ratios of olivine and/or plagioclase phenocrysts from 51 lavas from the volcanic front in Guatemala, El Salvador, Nicaragua and Costa-Rica, and from behind the volcanic front ("bvf") in Honduras (Table 1). All of the analyzed samples are relatively mafic members (average MgO = 5.8 wt.%; average Mg# = 0.54) of a suite that has been previously characterized for major and trace element and radiogenic-isotope geochemistry by M. J. Carr and colleagues. A database containing these previous measurements is available on request from M. J. Carr (http://www-rci.rutgers.edu/~carr/index.html).

[11] Oxygen-isotope ratios were measured on hand-picked olivine and plagioclase mineral separates of ~200–500 μm grains. Minerals containing visible inclusions of fluid, glass, or other minerals were avoided when recognized. Adhered dust was removed from the mineral separates by blowing filtered, compressed air over them. The samples were then analyzed by laser fluorination using a 50-watt CO_2 laser, BrF_5 reagent, and apparatus for gas purification and conversion of O_2 to CO_2 based on designs by *Sharp* [1990] and *Valley et al.* [1995]. Oxygen yields were 96 ± 3% (1σ), based

Table 1. Oxygen Isotope Compositions of Phenocrysts From Central American Arc Lavas

Country	Volcano	Sample	Mg#	$\delta^{18}O_{olivine}$	±1σ	$\delta^{18}O_{plagioclase}$	±1σ
Guatemala	Tecuamburro	Qam12	0.48	—	—	6.55	0.00
Guatemala	Tecuamburro	Qam13	0.47	—	—	6.36	0.00
Guatemala	Tecuamburro	Qam14	0.48	5.67	0.09	6.41	0.00
Guatemala	Tecuamburro	Qam15	0.53	5.57	0.02	6.34	0.02
Guatemala	Tecuamburro	T301	0.54	5.59	0.00	6.29	0.00
Guatemala	Tecuamburro	T302	0.59	5.51	0.04	6.21	0.09
Guatemala	Pacaya	GUP701	0.44	5.43	0.03	6.29	0.05
Guatemala	Pacaya	Pacaya 1985	0.47	5.34	0.08	6.20	0.03
El Salvador	Cerro Verde	CV1	0.52	5.60	0.04	6.40	0.00
El Salvador	Izalco	IZ101	0.52	5.43	0.01	6.34	0.04
El Salvador	Izalco	IZ103	0.51	5.49	0.01	6.21	0.07
El Salvador	Izalco	IZ104	0.50	5.44	0.05	6.31	0.02
El Salvador	Izalco	IZ108	0.51	5.45	0.02	6.25	0.03
El Salvador	Izalco	IZ 109	0.46	—	—	6.45	0.01
El Salvador	Izalco	IZ 112	0.52	5.41	0.04	6.15	0.03
El Salvador	Izalco	IZ 114	0.46	5.42	0.01	6.44	0.04
El Salvador	Izalco	IZ119	0.53	5.44	0.03	6.31	0.03
El Salvador	Izalco	IZ122	0.46	5.45	0.00	6.23	0.01
El Salvador	Apastapeque	AP-3	0.53	5.10	0.03	5.81	0.09
Honduras (bhf)	Yohoa	YO3	0.61	5.33	0.01	—	—
Honduras (bhf)	Yohoa	YO10	0.51	5.64	0.04	6.44	0.17
Nicaragua	Telica	TE3	0.54	—	—	5.51	—
Nicaragua	Telica	TE6	0.56	5.02	0.03	5.80	0.03
Nicaragua	Telica	TE112	0.42	5.07	0.01	5.63	0.07
Nicaragua	Telica	TE114	0.45	4.92	0.03	5.72	0.03
Nicaragua	Telica	TE119	0.47	4.82	0.01	5.65	0.04
Nicaragua	Telica	TE123	0.53	4.94	0.03	5.80	0.09
Nicaragua	Telica	TE124	0.55	4.84	0.06	5.75	0.03
Nicaragua	Cerro Negro	CN1	0.49	4.83	0.00	5.54	—
Nicaragua	Cerro Negro	CN2	0.47	4.90	0.01	5.59	0.01
Nicaragua	Cerro Negro	CN3	0.60	4.79	0.02	5.69	0.05
Nicaragua	Cerro Negro	CN5	0.64	4.88	0.01	5.57	0.03
Nicaragua	Cerro Negro	CN10	0.53	4.88	0.05	5.65	0.08
Nicaragua	Cerro Negro	CN11	0.51	4.78	0.00	5.55	0.02
Nicaragua	Cerro Negro	CN12	0.56	4.80	0.01	5.68	0.02
Nicaragua	Cerro Negro	1995 bomb	—	4.94	0.01	5.47	0.09
Nicaragua	San Cristobal	SC2	0.53	4.78	0.06	5.69	0.07
Nicaragua	Las Pilas	LP2	0.57	4.62	0.04	5.39	0.01
Nicaragua	Nejapa	NE3	0.54	4.92	0.01	5.55	0.11
Nicaragua	Nejapa	NE5	0.62	4.98	0.04	5.62	0.07
Nicaragua	Nejapa	NE6	0.63	5.23	0.01	5.79	0.14
Nicaragua	Nejapa	NE203	0.65	5.05	0.17	5.63	0.19
Nicaragua	Granada	GR5	0.60	5.07	0.08	5.59	0.01
Nicaragua	Granada	GR101	0.63	5.01	0.09	—	—
Nicaragua	Grenada	GM 92-3	0.59	4.97	0.00	5.75	0.07
Costa Rica	Tenorio	TE9	0.52	5.18	0.02	6.05	0.06
Costa Rica	Platanar	PP7	0.76	5.09	0.02	—	—
Costa Rica	Barba	B7	0.60	5.13	0.01	6.08	0.02
Costa Rica	Irazu	IZ-63A	0.62	5.28	0.02	5.98	0.02
Costa Rica	Turrialba	T24-2	0.62	5.10	0.02	—	—
Costa Rica	Turrialba	T91	0.62	5.04	0.01	—	—

on the typical major element compositions of phenocrysts in rocks of similar composition. Measurements of $\delta^{18}O$ were made on twelve different days. Two to five analyses of the SCO-1 olivine standard [*Eiler et al.*, 1995] and two to seven analyses of the UWG-2 garnet standard [*Valley et al.*, 1995] were made each day; reproducibility for repeat measurements of each standard on a given day averaged ±0.05‰ (1σ). The mean $\delta^{18}O$ values for standards were generally within 0.1‰ of their nominal values based on previous analyses [*Eiler et al.*, 1995, 1996a, 1996b, 1996c, 2000a, 2000b,

2000c; *Valley et al.*, 1995; *Cooper et al.*, 2004]. Differences in measurements from day to day were normalized by correcting all data for unknowns by a constant value equal to the average difference between measured and accepted values for all the measurements of standards on that day (the absolute value of this correction averaged 0.07‰). All unknown samples were analyzed two to nine (typically three) times, often distributed over several days, with an average reproducibility for a given sample of ±0.04‰ (1σ) after correction for day-to-day variations in measured values for standards.

3. Results

3.1. Isotopic Distributions Among Coexisting Minerals

[12] Phenocryst populations in arc lavas are often complex mixtures of crystals precipitated from multiple liquids [e.g., *Cooper and Reid*, 2003] and could include xenocrysts (i.e., crystals precipitated from liquids other than their host magma) with oxygen-isotope compositions that do not reflect those of their host magmas. We measured oxygen-isotope ratios of both olivine and plagioclase in most samples, with the expectation that rocks containing few or no xenocrysts would exhibit near-equilibrium plagioclase-olivine fractionations, whereas those containing abundant xenocrysts might exhibit disequilibrium plagioclase-olivine fractionations. Furthermore, because we analyzed most samples multiple times, we anticipated that rocks containing isotopically exotic xenocrysts might be revealed by poor reproducibility. Although it is possible that all measured grains of both olivine and plagioclase in any given sample could be xenocrysts that are in oxygen-isotope exchange equilibrium with one another but not with their host magma, we assume on the basis of previous studies of the oxygen-isotope geochemistry of phenocrysts and xenocrysts in basalts [*Garcia et al.*, 1998; *Maclennan et al.*, 2003; *Wang et al.*, 2003] that this would be an unusual circumstance.

[13] We observe intrasample reproducibility in most samples similar to our analytical precision (Table 1). Although the difference is small, the average reproducibility for olivine phenocrysts (±0.03‰, 1σ) is somewhat better than for plagioclase (±0.05‰, 1σ), perhaps indicating that plagioclase xenocrysts are more common than olivine xenocrysts in these lavas. Nevertheless, all but a handful of samples are homogeneous in $\delta^{18}O$
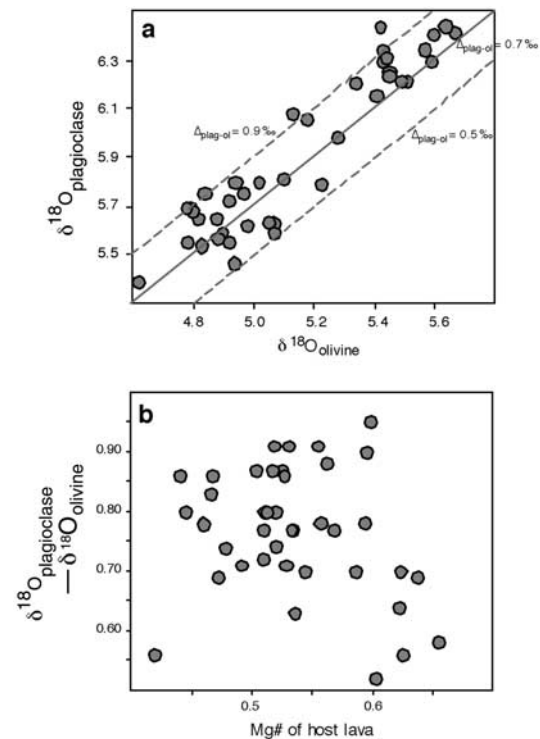

Figure 2. (a) Comparison of $\delta^{18}O$ values of coexisting plagioclase and olivine phenocrysts from lavas examined in this study. The diagonal gray lines mark the range of fractionations consistent with equilibrium at magmatic temperatures [*Chiba et al.*, 1989]. (b) Comparison of the plagioclase-olivine fractionation to the Mg# of the host lava. Values of Mg# were calculated as (mole fraction MgO)/(mole fraction MgO + 0.9x (mole fraction total iron as FeO) and are based on data for the same samples analyzed for $\delta^{18}O_{olivine}$, taken from the M. J. Carr database. Although the relationship between these two variables is scattered, most lavas having relatively low $\Delta_{plagioclase-olivine}$ values (0.7 or less) are relatively primitive (Mg# greater than ~0.58). This relationship is consistent with the decrease in plagioclase-olivine fractionation expected for the higher liquidus temperatures and more Ca-rich plagioclase compositions typical of high-Mg# lavas.

given the precision of our measurements. Measured plagioclase-olivine fractionations average 0.76 ± 0.11‰ (Table 1; Figures 2a and 2b), consistent with the range of ~0.6 to 1.1‰ expected for equilibrium between forsterite and An$_{50-100}$ plagioclase at temperatures of 1150–1350°C [*Chiba et al.*, 1989; *Eiler et al.*, 1995]. Moreover, plagioclase-olivine fractionations are correlated weakly with the Mg# of the host lava (Figure 2b), as expected on the basis of the more albitic plagioclases and lower temperatures characteristic of more differentiated magmas. These results suggest to us that isotopically exotic crystals, though possibly present

in some rocks, do not control the oxygen-isotope systematics of our sample suite.

3.2. Range and Geographic Distribution of Oxygen-Isotope Compositions

[14] Oxygen-isotope compositions of phenocrysts from Central American arc lavas vary systematically with distance along the strike of the volcanic front, with a minimum in Nicaraguan lavas (Figure 1f). Broadly similar-looking minima or maxima are also observed for other geochemical variables (Figures 1a–1c), suggesting to us that a common set of petrogenetic processes could be responsible for all of these trends. Note, however, that oxygen-isotope ratios of phenocrysts from lavas from the northwest end of the arc (Guatemala and El Salvador) are systematically higher than those from the southeast end of the arc (central Costa Rica); thus the geographic trend in $\delta^{18}O$ is asymmetric, like those for Ba/La ratios and perhaps also $Na_{6.0}$ values (Figures 1c and 1a), rather than symmetric, like that for U/Th ratios (Figure 1b).

[15] Values of $\delta^{18}O_{olivine}$ of 4.6–4.9‰ from the center of the arc (Nicaragua) are lower than values typical for arc-related basalts ($\delta^{18}O_{olivine} = 5.2 \pm 0.2$ [Eiler et al., 2000a; Eiler, 2001]), most mantle peridotites ($\delta^{18}O_{olivine} = 5.2 \pm 0.2$‰ [Mattey et al., 1994; Eiler, 2001]), and normal mid-ocean-ridge basalts (NMORB; $\delta^{18}O_{olivine} \approx 5.0$–5.2‰, based on measurements of glass [Eiler et al., 2000b; Cooper et al., 2004]). Basaltic lavas with $\delta^{18}O_{olivine}$ values as low as the Nicaraguan phenocrysts are only known to be abundant in Iceland [Gee et al., 1998; Eiler et al., 2000c] and Hawaii [Eiler et al., 1996b, 1996c; Wang et al., 2003]; they also occur, although less commonly, in other ocean-island volcanic centers (e.g., St. Helena and the Canary Islands [Eiler et al., 1996a; Thirlwall et al., 1997]). In contrast, phenocrysts from lavas from the northwestern margin of the arc (Guatemala and El Salvador; $\delta^{18}O_{olivine} = 5.10$–5.67; 5.46‰ average) and behind the volcanic front (Honduras; $\delta^{18}O_{olivine} = 5.33$ and 5.64) are higher in $\delta^{18}O$ than typical mantle peridotite and most basaltic lavas. These relatively high values are within the range common for "EM-2" type ocean island basalts (including those from French Polynesia and Samoa; $\delta^{18}O_{olivine} = 5.4$–6.1 [Eiler et al., 1996a]), Hawaiian lavas from Koolau and Lanai having relatively radiogenic Sr isotope ratios ($\delta^{18}O_{olivine} = 5.6$–6.0 [Eiler et al., 1996c]), and some subduction-related basalts from Vanuatu and the Taba-Lihir-Tanga-Feni arc

($\delta^{18}O_{olivine} = 5.5$–5.8 for boninites and low-Ti basalts and basaltic andesites [Eiler et al., 2000a]).

3.3. Comparisons of Oxygen Isotopes With Other Geochemical Properties

[16] Figure 3 compares $\delta^{18}O_{olivine}$ values with other geochemical variables previously measured for whole rock samples of the same specimens. Note that $Na_{6.0}$ values are based on regressions of compositions of multiple lavas (see Figure 1 caption), so each plotted point in Figure 3a is the average for all analyzed samples from a single volcano, whereas each point represents a single hand specimen in Figures 3b–3g. Variations in $\delta^{18}O_{olivine}$ correlate with most of the plotted geochemical parameters: $Na_{6.0}$ values correlate positively with $\delta^{18}O_{olivine}$, whereas Cu concentrations, Sr and Nd isotope ratios and U/Th and Ba/La abundance ratios correlate negatively with $\delta^{18}O_{olivine}$. These correlations further support our conclusion that $\delta^{18}O$ values of olivines generally reflect those of their host magmas; i.e., the concentrations and ratios plotted against $\delta^{18}O_{olivine}$ in Figure 3 are based on elements that are strongly concentrated in the groundmass, and thus they would not in general be expected to correlate with $\delta^{18}O_{olivine}$ unless the olivines were cogenetic with the groundmass. Note that the La/Sm ratio is uncorrelated with $\delta^{18}O_{olivine}$; it is shown to illustrate the unusual characteristics of some of the Costa Rican lavas (discussed below; see also Herrstrom et al. [1995]).

[17] Note that high $\delta^{18}O_{olivine}$ is associated with a relatively "depleted" (unradiogenic) Sr isotope composition on the one hand (Figure 3f) and a relatively "enriched" (also unradiogenic) Nd isotope composition on the other (Figure 3g). This reflects the unusual positive correlation between Sr and Nd isotope ratios exhibited by Central American lavas [Feigenson and Carr, 1986], which contrasts with the negatively sloped array typical of MORBs and most ocean-island basalts (Figure 4) [see also Hofmann, 1997]. This peculiarity has been previously interpreted to reflect mixing between an enriched mantle wedge having Sr and Nd isotope compositions plotting on the "mantle array" in Figure 4 (perhaps resembling enriched, so-called "E" MORBs) and a slab-derived component with higher $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ plotting above and to the right of the mantle array on Figure 4 [Feigenson and Carr, 1986; Carr et al., 1990, 2004]. Carr and his coworkers have hypothesized that this slab-derived component has
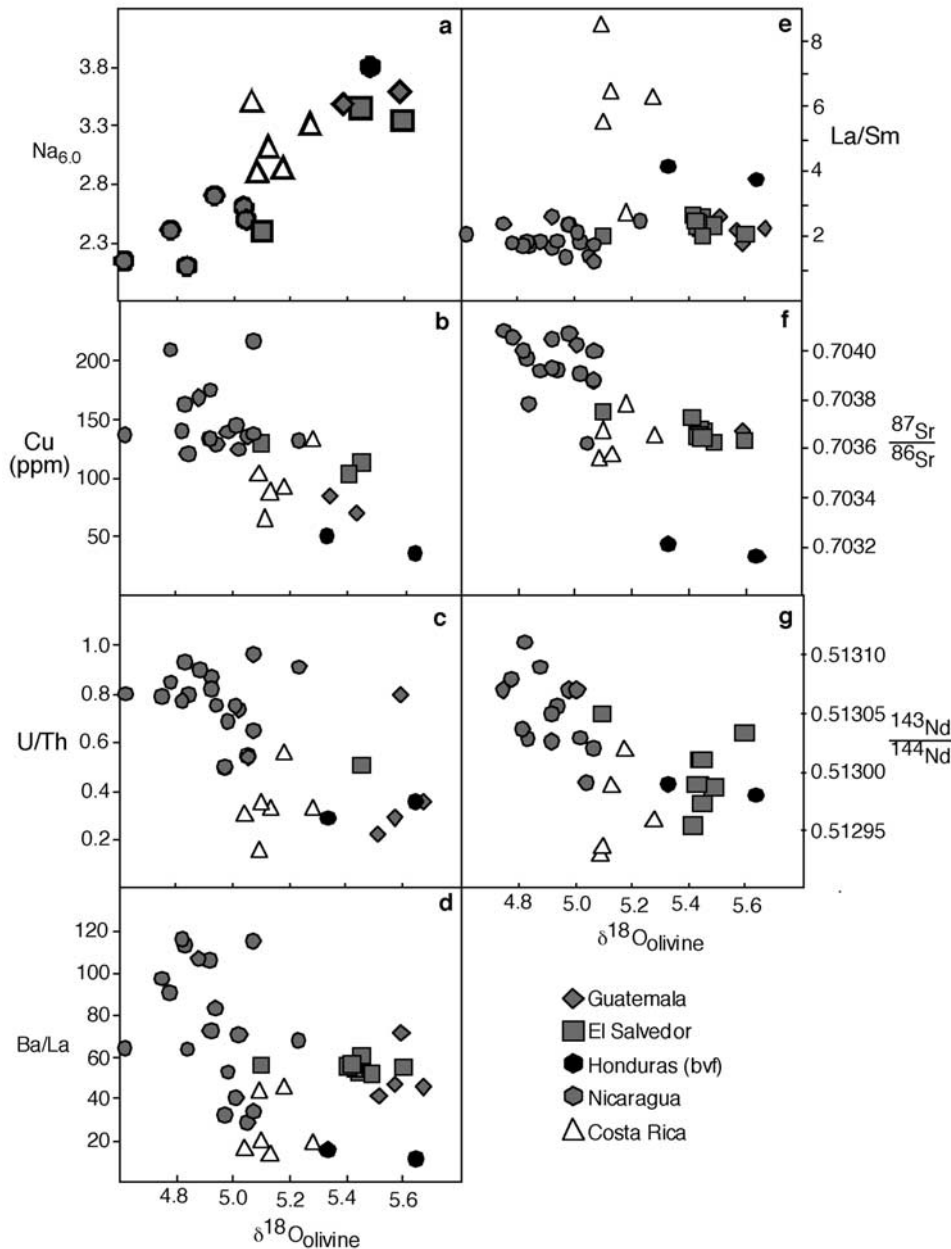
Figure 3. Correlations of $\delta^{18}O_{olivine}$ values measured in this study for Central American lavas (Table 1) with other geochemical parameters previously measured for these same samples and available through the M. J. Carr database. Figure 3a compares $Na_{6.0}$ values, calculated as described in the caption to Figure 1, to the average $\delta^{18}O_{olivine}$ value of all analyzed lavas from the same volcanic center.

relatively "depleted" (i.e., radiogenic) Nd isotope ratios because of the depleted nature of the Pacific mantle sources from which the Cocos plate was derived, but "enriched" Sr isotope ratios due to the addition of seawater Sr to the plate when it was hydrothermally altered before subduction.

[18] The trends in Figures 3a–3d, 3f, and 3g suggest that variations in $\delta^{18}O$ might be controlled by the same petrogenetic processes controlling

other geochemical indices previously used as the basis for models of Central American magmatism: Low-$\delta^{18}O$ values are associated with high inferred integrated degrees of mantle melting (i.e., Na-poor lavas), high abundances of some fluid-soluble elements (e.g., Ba and Cu; see *Stolper and Newman* [1994] and *Noll et al.* [1996] for previous studies of this often-overlooked element in arc lavas), high ratios of fluid-soluble to fluid-insoluble elements (i.e., Ba/La and U/Th), and Sr
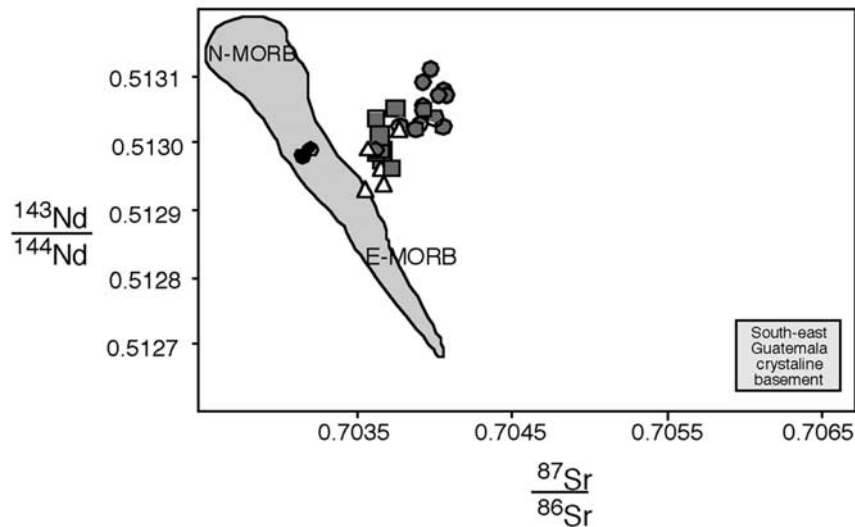
Figure 4. Plot of Sr versus Nd isotope compositions of the lavas we studied and comparison with the compositions of Atlantic and Pacific mid-ocean ridge basalts and basement gneisses from southeast Guatemala (based on data from the PetDB database maintained by the Lamont-Doherty Oceanographic Observatory, http://petdb.ldeo.columbia.edu/petdb/, and data reported by *Walker et al.* [1995]).

and Nd isotope compositions thought to be characteristic of weathered and/or hydrothermally altered rocks in the Cocos slab. In contrast, high $\delta^{18}O$ values are associated with lower inferred integrated degrees of melting and weaker slab signatures.

4. Discussion

4.1. Two-Component Models

[19] The geographic trend in $\delta^{18}O_{olivine}$ (Figure 1f) and correlations between $\delta^{18}O_{olivine}$ and other geochemical variables (Figure 3) suggest that oxygen-isotope data can be used to test or extend previous models for the petrogenesis of Central American arc lavas. The best-defined trends in Figure 3 are roughly linear and could be explained by petrogenetic models involving only two components, one relatively low in $\delta^{18}O$ and the other relatively high in $\delta^{18}O$. We consider two models that might explain these trends in terms of only two compositionally distinct end-members:

[20] 1. Higher $\delta^{18}O$ values occur on the northern and southern extremities of the arc where the crust is thick and lower $\delta^{18}O$ values occur near the middle of the arc where the crust is thin. The first possibility that we consider is that all mantle-derived magmas delivered to the arc are initially low in $\delta^{18}O$ but that contamination by crustal rocks in the overriding plates (North American crust in the extreme northwest end of the arc; Caribbean crust elsewhere) is responsible for higher $\delta^{18}O$

values, and that crustal contamination is more extensive where the crust is thicker. This hypothesis would imply that much of the geochemical variability previously interpreted in terms of mantle processes [e.g., *Carr et al.*, 1990; *Patino et al.*, 2000; *Plank et al.*, 2002] actually reflects systematic variations along the length of the arc in the degrees of crustal contamination.

[21] 2. Because the low-$\delta^{18}O$ extreme is associated with "slab-like" geochemical signatures and high inferred degrees of melting (and the high-$\delta^{18}O$ extreme with the opposite), the data might be explained by a two-component model where the two components are a high-$\delta^{18}O$ mantle wedge beneath Central America and a low-$\delta^{18}O$ slab-derived, water-rich component that induces melting of the mantle wedge. This is similar to the petrogenetic models of *Carr* [1984], *Carr et al.* [1990], *Patino et al.* [2000], and *Plank et al.* [2002]. If such a model can successfully account for the full array of geochemical data, the constraints placed on the oxygen-isotope ratios of the mantle and slab-derived components would allow evaluation of the plausibility of the model.

[22] The following paragraphs examine the consistency of these two models with the geochemical data.

4.1.1. Contamination by the Upper Plate?

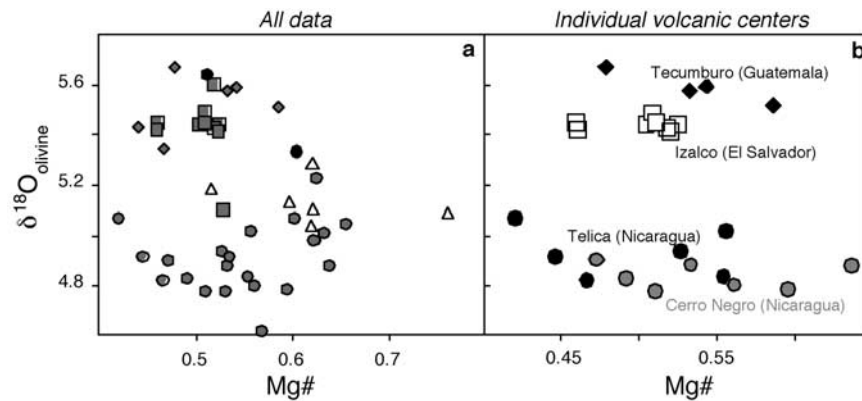[23] The simplest hypothesis of this kind would interpret lower $\delta^{18}O$ values in Nicaraguan lavas as

Figure 5. Comparison of $\delta^{18}O_{olivine}$ values for lavas examined in this study (Table 1) to the Mg# values of host lavas. Symbols are as in Figure 3.

relatively uncontaminated and higher $\delta^{18}O$ values in Guatemalan, El Salvadoran, Honduran, and Costa Rican lavas as more strongly contaminated. This hypothesis is difficult to reconcile with several geochemical observations:

[24] 1. *Walker et al.* [1995] and *Patino et al.* [2000] presented evidence that relatively radiogenic Sr and nonradiogenic Nd isotope ratios in lavas erupted behind the volcanic front ("bvf") in Guatemala reflect contamination by crystalline basement rocks of the continental North American plate. However, they did not find evidence for contamination in high-Mg# lavas in the volcanic front or in lavas erupted further to the southeast through the Caribbean plate (i.e., in samples comparable to those investigated here). Moreover, the quartzo-feldspathic gneisses identified by *Walker et al.* [1995] as the assimilants in Guatemalan bvf lavas are higher in $^{87}Sr/^{86}Sr$ and lower in $^{143}Nd/^{144}Nd$ than any Central American arc lavas and could not represent an end-member in the positively sloped Central American Sr-Nd isotope array (Figure 4). Oxygen isotopes compound this problem since, although the $\delta^{18}O$ values of these basement rocks are unknown, they consist of lithologies that are typically higher in $\delta^{18}O$ than the mantle (i.e., typically $\sim 8-14\text{‰}$ [*Eiler*, 2001; *Simon and Lecuyer*, 2005]), and therefore crustal contamination, at least in Guatemala, would be expected to produce a positive trend in Figure 3f rather than the negative trend we observe.

[25] 2. There is no correlation between $\delta^{18}O$ and Mg# in the lavas we studied (Table 1 and Figure 5a). Crustal contamination in variably differentiated magmatic suites generally increases with the extent of crystallization differentiation [e.g., *Taylor*, 1980; *DePaolo*, 1981; *Nicholson et al.*, 1991; *Eiler et al.*, 2000c], so low-Mg# lavas are

expected to be systematically higher in $\delta^{18}O$ than high-Mg# lavas if crustal contamination strongly influences their oxygen-isotope ratios, but no such relationship is observed. Similarly, suites of lavas from the same volcanic edifice spanning ranges in Mg# are nearly uniform in $\delta^{18}O$, regardless of the average $\delta^{18}O$ value of that suite or its geographic location along the length of the arc (Figure 5b). The increase in $\delta^{18}O$ of Tecuamburro lavas with decreasing Mg# is a possible exception, but even if so, this shift is small relative to the 1‰ range observed across our sample suite (note that this trend at Tecuamburron is also consistent with the effects of crystal fractionation alone [*Eiler*, 2001]).

[26] 3. In order to explain the low $\delta^{18}O$ values of the Nicaraguan samples, this hypothesis requires that the mantle wedge beneath the Central American arc is lower in $\delta^{18}O$ than the sources of normal MORBs. This is possible, but the scarcity of low $\delta^{18}O$ basalts elsewhere suggests this is unlikely.

[27] Although we cannot absolutely rule it out, we conclude that crustal contamination is an implausible explanation of the oxygen-isotope variations of relatively high-Mg# volcanic-front lavas in the Central American arc.

4.1.2. Melting Fluxed by a Single, Low-$\delta^{18}O$ Slab-Derived Component?

[28] As noted above, the geochemistry of Central American arc lavas has been previously interpreted in terms of a mantle wedge consisting of fertile peridotite that melts in response to influx of slab-derived aqueous fluids that are more abundant beneath the center of the arc than beneath its northern and southern ends [*Carr et al.*, 1990]. Following this reasoning, we could interpret our data as evidence that the mantle wedge is relatively
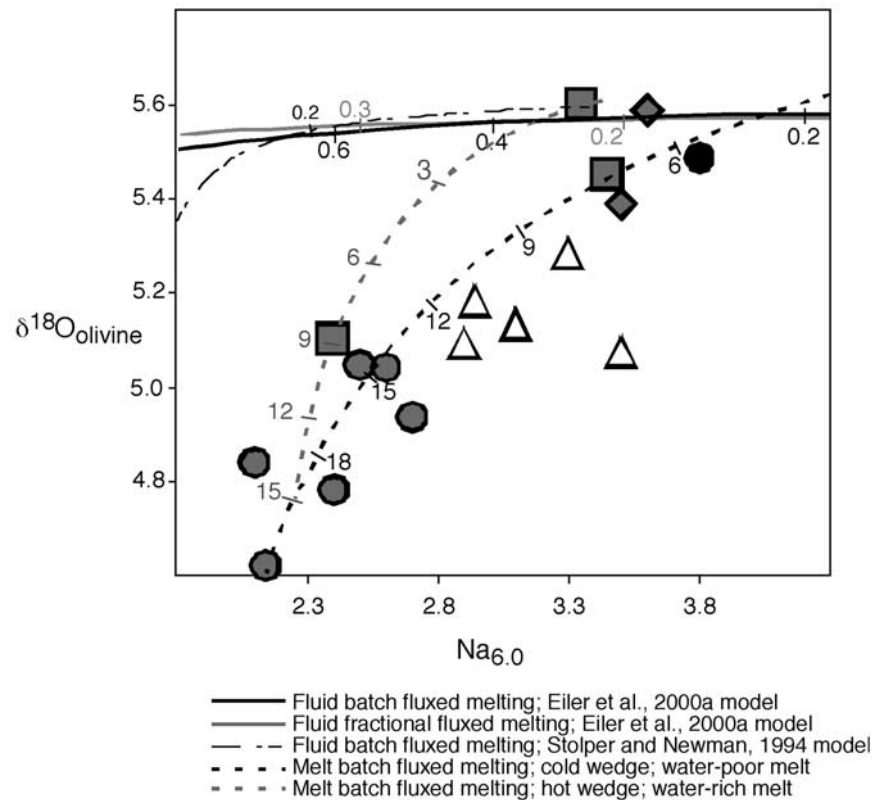
Figure 6. Correlation of average $\delta^{18}O_{olivine}$ values versus $Na_{6.0}$ values for suites of Central American arc lavas; each data point is the average for a single volcanic center (reproduced and transposed from Figure 3a). The curves are trends predicted by models of fluxed melting of fertile peridotite by low-$\delta^{18}O$ aqueous fluid (solid or thin, long-and-short dashed curves) or hydrous melt (dashed curves). See text and Appendix A for further details. Symbols are as in Figure 3.

high in $\delta^{18}O$ (like lavas from the northern end of the arc) and the slab-derived metasomatic agent is relatively low in $\delta^{18}O$ (like lavas from the center of the arc).

[29] Figure 6 compares the correlation we observe between $\delta^{18}O$ and $Na_{6.0}$ with that predicted for a representative fluxed melting model in which a high-$\delta^{18}O$ peridotite ($\delta^{18}O_{olivine} = 5.6‰$) melts in response to infiltration by low-$\delta^{18}O$ aqueous fluid ($\delta^{18}O = 0‰$). The solid black curve and the solid gray curve in Figure 6 represent the compositions of magmas produced by batch and fractional melting, respectively, assuming the low-$\delta^{18}O$ fluid contains 90 wt.% H_2O and 2 wt.% Na_2O, and a productivity of fluxed melting as defined by *Eiler et al.* [2000a] (see Appendix A for further details). For comparison, we also plot as a thin, long-and-short dashed black curve the compositions of magmas generated by batch melting, assuming a composition for the low-$\delta^{18}O$ fluid (44 wt% H_2O and 42.6 wt.% Na_2O) and a productivity of fluxed melting from *Stolper and Newman* [1994]. These

three models all predict that only small amounts of fluid (<wt. 1%) are required to produce the observed range of lava Na contents, but such small fluid fluxes can produce only ~0.1 to 0.2‰ differences between the $\delta^{18}O$ values of Na-rich and Na-poor lavas. This is inconsistent with our observations and suggests that Central American arc lavas cannot be the products of melting a high-$\delta^{18}O$, enriched mantle wedge in response to fluxing by low-$\delta^{18}O$ aqueous fluids, at least as envisioned by these relatively simple models.

[30] An alternative is that the slab-derived metasomatic agent driving melting in the mantle wedge is a hydrous melt rather than an aqueous fluid. In this case, large amounts of that slab melt might be required to drive high degrees of melting in the mantle wedge because the amount of melt generated by addition of hydrous components to peridotite is roughly proportional to the amount of water added, whatever its form [*Hirschmann et al.*, 1999; *Eiler et al.*, 2000a; *Gaetani and Grove*, 2004]. Previous studies [*Carr et al.*, 1990; *Patino*

et al., 2000; *Leeman et al.*, 1994] have shown that Central American arc lavas having unusually strong "slab" signatures (i.e., those from central Nicaragua) also have dominantly "fluid-like" trace element signatures (e.g., high Ba/La and U/Th), and lack clear evidence of "slab melt" signatures (e.g., high Th and La/Sm [*Elliott*, 2004, and references therein]), arguing against this hypothesis. These arguments are mitigated in the case of Nicaragua because sediments on the downgoing Cocos plate have unusually high Ba/La and U/Th ratios and unusually low Th concentrations [*Plank et al.*, 2002], and so partial melts of those sediments might have trace element compositions comparable to those usually associated with slab-derived fluids. Given this ambiguity in the trace element evidence, we have examined whether fluxing by slab-derived melts can explain the correlation of $\delta^{18}O$ with $Na_{6.0}$.

[31] The dashed curves in Figure 6 show the compositions predicted for magmas produced by batch melting of peridotite in response to addition of a hydrous melt. Two models of this kind are shown (see Appendix A for further details): (1) The black dashed curve illustrates a model assuming the productivity for fluxed melting given by *Eiler et al.* [2000a] (appropriate for a mantle wedge colder than its dry solidus), a mantle wedge $\delta^{18}O_{olivine}$ of 5.9‰, and fluxing by slab-derived melt containing 5 wt.% H_2O and 1.1 wt.% Na_2O and having a $\delta^{18}O$ value of 0‰. Other models with slightly different parameters are similar, but all that fit the overall trend of our data require large amounts (~10 wt.%) of a water- and sodium-poor (~5–10% and ~1–2%, respectively) slab melt. (2) The gray dashed curve illustrates an alternative model that assumes the wedge is hotter than its dry solidus (so the degree of melting for a given amount of water addition is higher), has a $\delta^{18}O_{olivine}$ of 5.6‰, and is infiltrated by slab melt having 15% H_2O, 5.58‰ Na_2O and a $\delta^{18}O$ of 0‰. Both of these slab-melt-fluxed models capture the key feature of the $Na_{6.0}$ versus $\delta^{18}O_{olivine}$ trend defined by Central American arc lavas (the significant decrease in both parameters from the edges to the center of the arc), whereas models in which the flux is envisioned to be a hydrous fluid do not do so.

[32] Although the models outlined above can fit the observed relationship between $\delta^{18}O$ and $Na_{6.0}$, we nevertheless regard them as implausible because the characteristics of the required end-members are inconsistent with known or expected properties of the mantle wedge and/or slab-derived metasomatic agents.

[33] 1. The lithologies at the top of the Cocos slab that one might expect to melt on subduction (i.e., metamorphosed hemipelagic sediments at the top of the plate [*Plank et al.*, 2002]) are expected to have bulk $\delta^{18}O$ values of 20–30‰ [*Kolodny and Epstein*, 1976; *Arthur et al.*, 1983]. Thus such a component would lead to *increases* rather than observed *decreases* in $\delta^{18}O$ with increasing slab inputs. Low-$\delta^{18}O$ slab melt could come from partial fusion of hydrothermally altered rocks within the slab interior [*Gregory and Taylor*, 1981; *Muehlenbachs*, 1986], but thermal models of subduction suggest deep interiors of slabs generally heat enough to de-water but not enough to melt [*Peacock*, 2004; *Kelemen et al.*, 2004a].

[34] 2. The unmodified mantle wedge required by this model must have a $\delta^{18}O_{olivine}$ comparable to the highest known for olivines from mantle peridotites and basalts [*Eiler*, 2001]. This is possible, but known high-$\delta^{18}O$ mantle-derived materials [*Eiler et al.*, 1996a, 1996b; *Eiler*, 2001] have exceptional properties (such as $^{87}Sr/^{86}Sr$ ratios ≥ 0.705) that would be inconsistent with the mantle wedge component inferred by the simple two-component model shown in Figure 6.

[35] 3. According to this model, a large amount (nearly 20 wt.%) of the low-$\delta^{18}O$ slab melt would have to have been added to the sources of Nicaraguan lavas, suggesting that they might have geochemical characteristics resembling other arc lavas that have been proposed to be derived largely or entirely from slab melts (e.g., "adakites" and high-Mg andesites [*Defant and Drummond*, 1990; *Kelemen et al.*, 2004b]). However, Nicaraguan lavas, in addition to having unusually low concentrations of most incompatible trace elements (e.g., ~50 ppm Zr and 5 ppm La) and trace element ratios usually regarded as indicative of fractionations between fluid and silicate minerals (e.g., U/Th ratios near 1 [*Johnson and Plank*, 1999; *Elliott*, 2004]), lack trace element characteristics previously suggested to be indicative of direct partial melts of the subducted slab. For example, their Th/La ratios are ~0.05–0.15, in contrast to expected partial melts of subducted sediment (~0.5–1.0 [*Johnson and Plank*, 1999; *Elliott*, 2004]), and their Sr/Y ratios are ~15–25, in contrast to expected partial melts of eclogitic sources (~500–1000 [*Kelemen et al.*, 2004b]).

[36] We conclude that while it is possible to construct simple melt-fluxed models that can explain our observations, the sets of geochemical characteristics of the end-members of successful

models of this kind are implausible. Given the underlying strength of evidence that oxygen-isotope variations of Central American basalts are related to their primary petrogenesis (Figures 1–3), we proceed by developing a model that is more complex (i.e., has more than two end-members), but also capable of explaining all the geochemical constraints satisfactorily.

4.2. Melting Fluxed by Mixtures of Two Slab Components

[37] To address the difficulties of the two-component mixing-melting models presented in Figure 6, we consider in this section a model involving the peridotitic mantle wedge and two slab-derived components, one higher and one lower in $\delta^{18}O$ than common mantle peridotites. This model has much in common with previous hypotheses [*Plank and Langmuir*, 1993; *Elliott et al.*, 1997; *Elliott*, 2004] that invoke both a sediment-derived melt (which we expect to be anomalously high in $\delta^{18}O$) and an aqueous fluid derived from dehydration metamorphism of rocks in the slab interior (some of which are expected to be anomalously low in $\delta^{18}O$). As we demonstrate below, this model can explain the geochemistry of Central American arc lavas because all such lavas with strong trace element signatures of slab-derived components (e.g., Ba/La $\geq \sim 40$) are *either* anomalously ^{18}O-rich *or* anomalously ^{18}O-poor. Conversely, the only major group of Central American lavas that are consistently "normal" in $\delta^{18}O$ (those from Costa Rica), consistently have trace element patterns indicative of small or negligible contributions from slab-derived components. These observations could be at least qualitatively explained if the mantle wedge under the Central American arc were normal in $\delta^{18}O$ (i.e., like the sources of most basalts) and variable proportions of two different slab-derived components (one high in $\delta^{18}O$ and the other low in $\delta^{18}O$) were added to it. Such a model is also consistent with the recent suggestion of *Cameron et al.* [2003] that volcanic-front lavas from Guatemala are derived from sources metasomatized by both sediment melt and fluid evolved from the slab interior. In this section, we examine this class of model quantitatively in light of our new oxygen-isotope data and previously published trace element and radiogenic-isotope data.

[38] As we did for the simpler two-component models, we examine this hypothesis using an approach similar to that presented by *Eiler et al.* [2000a]. They assumed a mineralogy and chemical composition for the mantle wedge, $\delta^{18}O$ values for both the mantle wedge and a slab-derived component, and a water content for the slab-derived component. Given these assumptions, and constraints on the melting properties of hydrous peridotite from experiments and the MELTS model, they then estimated the amount of slab-derived phase required to have been added to the sources of lavas from the Vanuatu arc in order to explain simultaneously their $\delta^{18}O$ values, TiO_2 contents, and Yb/Sc ratios and the $Cr/(Cr + Al)$ ratios of their spinel phenocrysts. They then used these results, combined with the known trace element chemistry of the lavas and the assumed trace element chemistry of their mantle wedge sources prior to metasomatism to solve for the trace element composition of the slab-derived component added to the source of each lava. We follow a similar approach here, but assume two slab-derived components and modify some of the assumed properties of the mantle wedge and slab-derived components to match better the particulars of the Central American arc; we also use a different algorithm to estimate the trace element compositions of slab-derived components based on those of the lavas.

4.2.1. Model Assumptions

[39] 1. The unmetasomatized mantle wedge beneath the Central American arc at the depth of melt segregation is assumed to be a spinel lherzolite (51.6 wt.% olivine; 28.7. wt.% orthopyroxene; 16.0 wt.% clinopyroxene; 3.7 wt.% spinel, as assumed in the model of *Eiler et al.* [2000a]). Our default assumption is that the minor and trace element composition of the mantle wedge is the same as the mantle wedge source given by *Eiler et al.* [2000a]; i.e., it has a $\delta^{18}O_{olivine}$ value of 5.0‰, and its Sr and Nd isotope ratios are within the range of normal Pacific and Atlantic MORBs [*Ito et al.*, 1987]. However, we also include in our modeling a second mantle wedge component in order to account for compositions of lavas from southeast of central Costa Rica, which are geochemically distinct from lavas elsewhere in the arc in ways that are best attributed to variability in the mantle wedge (e.g., as shown in Figure 3f they are higher in La/Sm; they also have distinctive Pb isotope compositions [*Herrstrom et al.*, 1995; *Carr et al.*, 2004]). *Herrstrom et al.* [1995] suggested that Costa Rican lavas are derived from a part of the mantle wedge resembling the sources of some ocean-island basalts (OIB). We thus include a mantle wedge component with such characteristics.

Table 2. Compositions of Model Components

	"MORB-Like" Mantle Wedge	"OIB-Like" Mantle Wedge	Low-δ^{18}O Slab Phase	High-δ^{18}O Slab Phase
Ba, ppm	0.317	33.93	2573	614
U, ppm	0.0042	0.09	2.60	0.28
Th, ppm	0.011	0.25	2.75	1.25
K_2O, wt.%	0.030	0.08	2.10	0.3
Nb, ppm	0.137	1.09	14.7	0.5
La, ppm	0.138	1.89	25.8	9.3
Pb, ppm	0.031	0.22	17.3	7.9
Ce, ppm	0.440	4.23	59.4	17.5
H_2O, wt.%	0.026	0.25	50.0	10.0
Nd, ppm	0.472	2.29	40.5	11.5
Sr, ppm	5.87	58.61	3071	921
Zr, ppm	5.45	13.44	215	25
Sm, ppm	0.20	0.49	9.7	1.6
Cu, ppm	4.80	5.67	1150	32
Na_2O, wt.%	0.20	0.24	8.0	2.1
TiO_2, wt.%	0.17	0.18	0.75	0.1
Yb, ppm	0.48	0.43	0.5	0.5
$\delta^{18}O_{olivine}$	5.0	5.1	0.0	25
$^{87}Sr/^{86}Sr$	0.70250	0.70368	0.7041	0.7040
$^{143}Nd/^{144}Nd$	0.51315	0.51294	0.5131	0.5128

The properties of the "OIB-like" mantle wedge component are based on the assumption that sample T24-2 from Turrialba (the best-characterized, high-La/Sm Costa Rican lava examined in this study) is a 5% batch partial melt of only that source (we further assume that this melting occurred in the spinel peridotite stability field, and we normalize both the model and lava compositions to 6% MgO by olivine addition or subtraction to account for differentiation of T24-2 before eruption). This lava has a $\delta^{18}O_{olivine}$ value of 5.1‰, and we assume this value is representative of this OIB-like source. The compositions of both the assumed MORB-like and OIB-like mantle wedge components are summarized in Table 2.

[40] 2. As described above, the key feature of these models is that the mantle wedge is assumed to be metasomatized by variable amounts of two slab-derived components: The first is meant to approximate a partial melt of sediments from the top of the slab; it has a $\delta^{18}O$ of +25‰ (similar to the expected weighted average for pelagic sediments [*Kolodny and Epstein*, 1976; *Arthur et al.*, 1983; *Plank et al.*, 2002]) and a water content of 10 wt.% (similar to inferred volatile contents of high-pressure partial melts of hemipelagic sediments [*Johnson and Plank*, 1999]). The second is meant to approximate an aqueous fluid derived from dehydration metamorphism of hydrothermally altered gabbros and/or serpentinites in the slab interior; it is assumed to have a $\delta^{18}O$ value of

0‰. This $\delta^{18}O$ value is at the lower end of the range for altered layer-3 gabbros and serpentinites in ophiolites [*Muehlenbachs*, 1986; *Shanks*, 2001] and similar to values expected for water in equilibrium at 400 to 500°C with silicate minerals having $\delta^{18}O$ values of +3‰ [*Chacko et al.*, 2001] (3‰ is similar to the average value for ocean lithosphere hydrothermally altered at high temperatures). We further assume this component has a water content of 50 wt.%, similar to estimates for slab-derived fluids by *Stolper and Newman* [1994] and *Grove et al.* [2002] and consistent with the high-pressure fluid-melt solvus of *Shen and Keppler* [1997].

[41] 3. Implementation of this model requires knowledge of the degree of melting of the mantle wedge as a function of its water content, including both the trace of water intrinsic to that mantle and water added to it as a result of metasomatism by slab-derived components. This relationship depends on P, T, and solid and fluid compositions, but we simply fit the average of the two functions presented by *Eiler et al.* [2000a] for partial melting of peridotite mixed with "hydrous melt" on one hand and "aqueous fluid" on the other. Although clearly an over-simplification, this allows the use of a single relationship to approximate the melting properties of peridotites mixed with different proportions of hydrous melt and solute-rich fluid (and is justified by the fact that the two functions presented by *Eiler et al.* [2000a] are so similar). The

average relationship was fit to the following polynomial: Melt fraction (F) = $20.3[H_2O] - 350[H_2O]^2$, where both melt fraction and water concentration are in weight fraction units (i.e., a melt fraction of 0.1 indicates 10% partial melting). Because this function dictates that any amount of water in the source leads to partial melting, our "MORB-like" mantle component will undergo 0.5% partial melting even in the absence of a slab-derived component, as would be expected if the mantle wedge is a few tens of degrees below its dry solidus. This function generates less melt for a given amount of water than calculated on the basis of data for Mariana trough lavas (F = 0.05 + 61[H_2O]; *Stolper and Newman*, 1994), but more closely resembles hydrous peridotite melting experiments conducted near the dry solidus [*Gaetani and Grove*, 2004].

[42] If the OIB-like mantle wedge component has a H_2O/Ce ratio within the range of mid-ocean-ridge and back-arc basin basalts (~200–600, on a weight fraction basis [*Stolper and Newman*, 1994; *Michael*, 1995], then the water content of that source would yield ~2–5% melting even without addition of slab-derived components based on the hydrous peridotite melting function adopted here. We assume this source contains 0.25 wt.% H_2O and so undergoes 5% partial melting, as was assumed when calculating the minor and trace element composition of that source.

[43] 4. The melting reaction was assumed to have the same stoichiometry as that used by *Eiler et al.* [2000a] for hydrous melting fluxed by aqueous fluid: $Fluid_{\sim 1}$ + $Clinopyroxene_{9.8}$ + $Orthopyroxene._{9.9}$ + $Spinel_{1.5}$ = $Melt_{14.6}$ + $Olivine_{7.6}$ (on a mass basis). All melting was modeled as a batch process, using the equations of *Shaw* [1970] and the distribution coefficients listed in Appendix A.

4.2.2. Compositions of the Slab-Derived Components

[44] We calculated the minor and trace element compositions of the two slab-derived components by assuming that only the high-$\delta^{18}O$ component metasomatized the sources of the five highest-$\delta^{18}O$ volcanic-front lavas from Tecuamburro and Cerro Verde, and only the low-$\delta^{18}O$ component metasomatized the sources of the five lowest $\delta^{18}O$ lavas from San Cristobal, Las Pilas, and Cerro Negro. This approach results in the smallest possible difference in composition between the high-$\delta^{18}O$ and low-$\delta^{18}O$ components (i.e.,

their compositions might be more different from one another than our approach suggests if, in reality, both are present in the sources of all studied lavas).

[45] For each sample in these two groups, we first normalized the concentrations of all incompatible minor and trace elements to account for differences in their extents of crystallization differentiation by adding or subtracting small increments of equilibrium olivine until the lava contained 6 wt.% MgO. These corrections were generally small (less than 10%, relative). We then averaged for each group the concentrations of each of the minor elements Na, K, and Ti, and the trace elements Ba, Sr, Pb, U, Th, Nb, Zr, La, Ce, Sm, Nd, Yb, and Cu, and the isotopic indices $\delta^{18}O_{olivine}$, $^{87}Sr/^{86}Sr$, and $^{143}Nd/^{144}Nd$. We refer to these fractionation-corrected, group averages as the "model high-$\delta^{18}O$ end-member lava" and the "model low-$\delta^{18}O$ end-member lava". Because none of the highest-$\delta^{18}O$ lavas were analyzed for Cu, we assume the model high-$\delta^{18}O$ lava contains 70 ppm Cu (a round number slightly lower than concentrations in other Guatemalan and Salvadoran lavas having $\delta^{18}O_{olivine}$ values of ~5.4).

[46] We then calculated by mass balance the amount of high-$\delta^{18}O$, slab-derived component that must be added to the peridotitic mantle wedge to match the $\delta^{18}O$ value of the model high-$\delta^{18}O$ end-member lava (2.5 wt.%), and similarly the amount of low-$\delta^{18}O$, slab-derived component required to explain the $\delta^{18}O$ value of the model low-$\delta^{18}O$ end-member lava (3.0 wt.%). On the basis of the assumed water content of each component and our melting function for hydrous peridotite (above), we then calculated the degree of batch melting required to generate each of the two model lavas. On the basis of these degrees of melting, the amount of low- or high-$\delta^{18}O$ slab-derived component in the sources of these end-member lavas, and the assumed composition of the MORB-like mantle wedge component, we then solved for the minor and trace element concentrations in the low- and high-$\delta^{18}O$ slab-derived components. These calculations assumed batch melting, the nonmodal peridotite melting reaction given above, and the mineral-melt distribution coefficients given in Appendix A. Finally, we solved for the Sr and Nd isotope composition of each slab-derived component required to match the isotopic compositions of the respective model end-member lavas to which they contributed. The compositions

of the high- and low-δ^{18}O slab derived components are listed in Table 2.

4.2.3. Comparison of Model End-Members to Materials and Model Components From Previous Studies

[47] The compositions of all mantle-wedge and slab-derived components used in this model are plotted in Figure 7, along with previous estimates of the compositions of slab-derived metasomatic agents [*Stolper and Newman*, 1994; *Eiler et al.*, 2000a; *Grove et al.*, 2002] and Cocos plate sediments [*Plank et al.*, 2002].

[48] The composition of the MORB-like mantle wedge (a horizontal line in this figure since it was used to normalize all other patterns) is similar in most respects to mantle wedge compositions assumed or calculated in models from *McCulloch and Gamble* [1991], *Stolper and Newman* [1994], and the "depleted source" of *Grove et al.* [2002]. The OIB-like mantle wedge is relatively incompatible element enriched, but has a pronounced negative K anomaly. A negative K anomaly is characteristic of the "HIMU" type of OIB [*Sun and McDonough*, 1989], and so our trace element model is consistent with the *Herrstrom et al.* [1995] suggestion that the enriched component beneath Costa Rica is a HIMU-like source.

[49] The Na$_2$O content of the model high-δ^{18}O slab-derived component (2.1 wt.%) is consistent with it being a high-degree partial melt of hemipelagic sediments, based on the compositions of Cocos plate sediments and previous sediment melting experiments [*Johnson and Plank*, 1999; *Plank et al.*, 2002]. Note that although we assumed this component was a hydrous melt and set its H$_2$O content (10 wt.%) accordingly, the Na$_2$O content was solved for, so this correspondence with a partial melt of sediment supports the internal consistency in the model. The Na$_2$O content of the model water-rich, low-δ^{18}O slab-derived component (8.0 wt.%), though much higher than that of the high-δ^{18}O component, is lower than the calculated water-rich components of *Stolper and Newman* [1994] (42.6 wt.%) and *Grove et al.* [2002] (26–32 wt.%), and higher than the water-rich component assumed by *Eiler et al.* [2000a] (2 wt.%).

[50] The model minor and trace element compositions of the high- and low-δ^{18}O slab-derived components have many similarities with each other. At the resolution of the logarithmic scale in Figure 7, the low-δ^{18}O component (i.e., the component as-
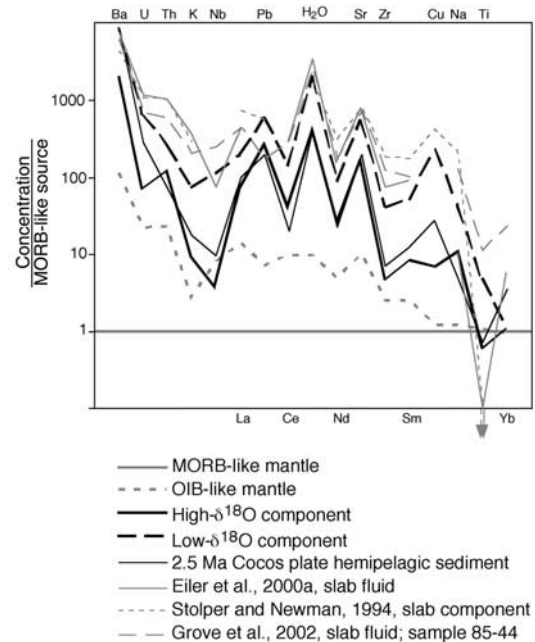

Figure 7. Abundances of selected minor and trace elements in model MORB-like and OIB-like mantle wedge components (heavy solid and dashed gray lines, respectively), the model high-δ^{18}O, water-poor component (heavy solid black line), the model low-δ^{18}O, water-rich component (heavy dashed black line), 2.5 Ma hemipelagic sediment on the Cocos plate (light solid black line; data from *Plank et al.* [2002]), the model slab-derived aqueous fluid from *Eiler et al.* [2000a] (thin solid gray line), model slab-derived component from *Stolper and Newman* [1994] (thin short-dashed gray line), and a representative model slab-derived component from *Grove et al.* [2002] (thin long-dotted gray line). All concentrations are normalized to those in our model MORB-like mantle wedge component (Table 2). Elements are plotted in their approximate order of increasing compatibility in residual solids during peridotite partial melting (see Appendix A), adjusted to be consistent with common convention (Nb was placed between K and La). For reference, labels for the lanthanide elements are on the bottom horizontal axis, and those for all other elements are on the top horizontal axis.

sumed to be a fluid rather than a melt) is similar to model slab-derived components inferred for the sources of lavas in the Mariana trough [*Stolper and Newman*, 1994], the Vanuatu arc [*Eiler et al.*, 2000a], and the Cascade arc [*Grove et al.*, 2002]: All are characterized by significant enrichments in Ba, Sr, H$_2$O, and Pb and depletions in high-field-strength elements such as Nb, Ti, and perhaps Zr relative to elements of similar compatibility during peridotite partial melting. Note that it is possible that these depletions in high-field-strength ele-

ments in fact reflect depletion of those elements in the mantle wedge prior to its melting beneath the arc [e.g., *Woodhead et al.*, 1993; *Stolper and Newman*, 1994], rather than properties imposed on undepleted sources by addition of the slab-derived component.

[51] Figure 7 shows that despite some similarities (e.g., the elevations in Ba, Pb and Sr relative to neighboring elements), the model high-δ^{18}O component is readily distinguishable in its trace and minor element abundance pattern from the model low-δ^{18}O component. For example, the low-δ^{18}O component is approximately six-times higher in Cu/Sm ratio, four-times higher in U/Th and K/Th ratios, and two-times higher in Ba/Th ratio than the high-δ^{18}O component (Table 2). These differences are broadly consistent with the low-δ^{18}O component being an aqueous fluid and the high-δ^{18}O component being a hydrous silicate melt [*Brenan et al.*, 1995; *Elliott et al.*, 1997; *Johnson and Plank*, 1999; *Elliott*, 2004], as we assumed when choosing their water concentrations. The trace element abundances of the model high-δ^{18}O component are particularly close to those of sediments being subducted on the Cocos plate [*Plank et al.*, 2002] (concentrations of all plotted elements are within 25% of each other, on average), strongly supporting our inference that this component represents a high-degree partial melt of such sediments. Moreover, the pattern of the model low-δ^{18}O component is also broadly similar to these sediments, consistent with their being the sources of much of the trace element inventory of this slab-derived component as well. The high concentrations of ^{10}Be (which must come from recently subducted sediment) in many Central American lavas [*Morris et al.*, 1990] support our suggestion that sediment is the source of much of the trace element inventory of slab-derived components, as does recent evidence that spatial and temporal variations in trace element compositions of Central American arc lavas mimic those in Cocos plate sediments [*Patino et al.*, 2000; *Plank et al.*, 2002]. It is, however, not so easy to reconcile the radiogenic-isotope composition of our slab-derived components with these sediments (see section 4.2.5).

4.2.4. Model Algorithm and Application to the Central American Arc

[52] To this point, although we have described how we used the compositions of extremes in the Central American sample suite to define chemical and isotopic characteristics of model slab-derived components in this system, we have not actually demonstrated that our model can successfully account for the compositional variations of other lavas from the Central American arc. In this section, we examine the degree to which our model can explain the geochemical properties of all Central American arc lavas examined in this study, and go on to examine the geographic distribution of model components implied by spatial trends in the compositions of those lavas (Figure 1).

[53] We first calculated an average, fractionation-normalized composition for each of the 16 volcanic centers in the volcanic front examined in this study. For relatively well-studied suites, this was done empirically by regressing the concentrations of all elements of interest as a function of wt.% MgO and calculating the value of that regression line at 6 wt.% MgO. Some suites of samples were not sufficiently well characterized to calculate meaningful regressions, so in those cases we corrected the compositions of each lava from that suite to 6 wt.% MgO by addition or subtraction of small increments of equilibrium olivine and then averaged the olivine-adjusted concentrations. Although this exercise results in internal consistency and was thus in our view worth doing, in fact these normalizations generally involved small changes and have little impact on our model fits.

[54] We then modeled each of the fractionation-normalized, suite-average compositions as a partial melt of a mixture of high- and low-δ^{18}O slab-derived components and a mantle source containing variable amounts of the MORB-like or OIB-like mantle components (Table 2). The best-fit amounts of these four components in the source of each suite-average were determined by initially defining there to be 0.1 wt.% of each slab-derived component in the source, and a ratio of MORB-like to OIB-like mantle components in that source needed to match the La/Sm ratio of the suite in question. We then iterated the abundances of each slab component and the OIB-like component (subject to the constraint that the amounts of the four components had to sum to 100%) to minimize the misfit between model and data. In each iteration, the degree of melting of the mixed source was set by its bulk water content (as described in section 4.2.1) and all calculations assumed batch melting, the melting-reaction stoichiometry given above, and the mineral-melt distribution coefficients given in Appendix A. A successful fit was taken as one that produced a model partial melt that matched the fractionation-normalized suite average simultaneously to within the following

tolerances: <0.1‰ in $\delta^{18}O$; <10^{-4} in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$; <10% in both the Na_2O concentration and La/Sm ratio; and the concentrations of other minor and trace elements shown in Figure 7 within <20%, on average. It was often possible to find fits to the suite averages that were factors of two or more closer matches in all these criteria, but there were also cases where we failed to find solutions within one or more of these limits. These exceptions are discussed below. Figures 8 and 9 compare the best-fit model compositions to the fractionation-normalized, suite-average compositions for all of the 16 volcanic-front suites examined in this study, including the calculated versus observed trends in plots of $\delta^{18}O_{olivine}$ versus $Na_{6.0}$ (Figure 8a) and $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ (Figure 8b), and the calculated versus observed trace element abundance patters of each suite (Figures 9a–9p). Figure 10 shows the best-fit proportions of the source components and the degree of partial melting for the 16 suits as a function of distance along the arc.

[55] The model we present succeeds at simultaneously explaining all the noteworthy features of geochemical variability of Central American arc lavas, including the minor and trace element abundances and the O, Sr, and Nd isotope compositions of basalts and basaltic andesites distributed along the full length of the arc. Note that the model is fit by varying only three independent variables (i.e., the abundances of three of the four source components, since their sum is fixed at 100%), yet succeeds in describing variations in many elemental abundances and isotope ratios among 16 different sample suites. Although this success is not surprising for the five volcanic centers that contain one or more the eleven samples used to constrain the properties of the high and low-$\delta^{18}O$ slab components and the OIB-like mantle source, there are 40 samples that were not included in these constraints, and 11 volcanic centers that contained none of the samples used to calculate model end-member lavas.

[56] Several aspects of the comparison between the model and suite average compositions are of particular interest:

[57] 1. Most Nicaraguan lavas are best fit by fluxed melting of a mantle wedge dominated by (>90%) the MORB-like peridotite source, driven by additions of ~1–4 wt.% of the water-rich, low-$\delta^{18}O$ slab-derived component and smaller amounts (~0–0.5 wt.%) of the water-poor, high-$\delta^{18}O$ slab-derived component.
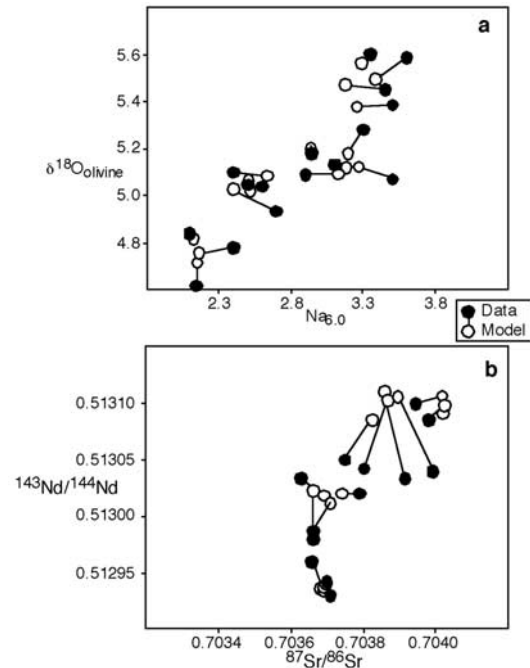

Figure 8. Comparison of the fractionation-corrected, suite-average Sr, Nd, and O isotope compositions and $Na_{6.0}$ values of Central American arc lavas (solid circles) with those fit by the model described in the text (open circles).

[58] 2. Most Guatemalan and El Salvadoran lavas are best fit by fluxing a mantle wedge also dominated by the MORB-like component, but containing, on average, slightly more enriched (OIB-like) component than that beneath Nicaragua, driven by addition of ~1.5–2.4 wt.% of the water-poor, high-$\delta^{18}O$ slab-derived component and traces (0–0.1 wt.%) of the water-rich, low-$\delta^{18}O$ slab-derived component. Samples from Apastapeque (Figure 9l) have $\delta^{18}O_{olivine}$ values near 5.1‰ and require a similar mantle wedge but fluxed by somewhat more of the low-$\delta^{18}O$ component and significantly less of the high-$\delta^{18}O$ component.

[59] 3. Costa Rican lavas from Platanar and volcanic centers southeast of it require partial melting of a mantle wedge dominated by (>98%) the OIB-like source, to which traces (~0–0.3 wt.%) of high- and/or low-$\delta^{18}O$ slab derived component were added.

[60] 4. Tenorio, in northwest Costa Rica, requires partial melting of a source made up mostly of MORB-like peridotite, but with a substantial (20%) contribution of OIB-like peridotite and significant amounts of the high-$\delta^{18}O$ (0.9 wt.%) and low-$\delta^{18}O$ (0.4 wt.%) slab-derived components. This volcanic center thus appears to require a
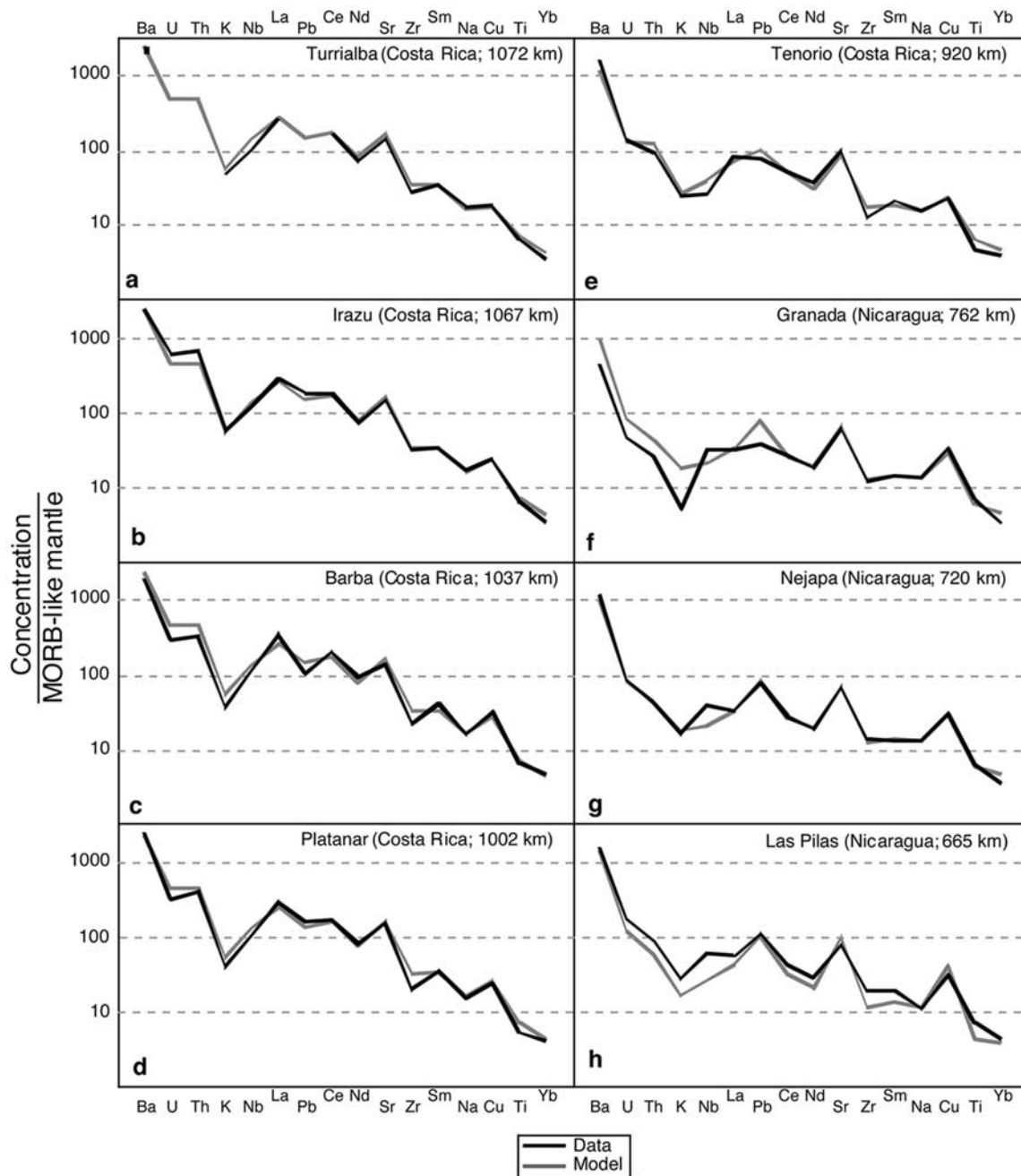
Figure 9. Comparison of the fractionation-corrected, suite-average trace element concentrations of Central American arc lavas (black lines) with those fit by the model described in the text (gray lines). All patterns are normalized to the MORB-mantle composition used in the modeling. Lines connect data and model-fit compositions for each suite. These fits are the same as those used to generate model points in Figure 8. Each panel also lists the volcanic edifice and nation where that suite comes from, and its distance along the arc from the Mexico-Guatemala border (to aid comparisons with Figures 1 and 10).

source transitional between the dominantly OIB-like mantle beneath Costa Rica and the dominantly MORB-like mantle beneath the rest of the arc, and between the abundant slab-derived components seen in the middle of the arc and the minimal slab-derived components characteristic of its southeast end.

[61] Our model implies that the amount of the low-$\delta^{18}O$, water-rich, slab-derived component is rela-
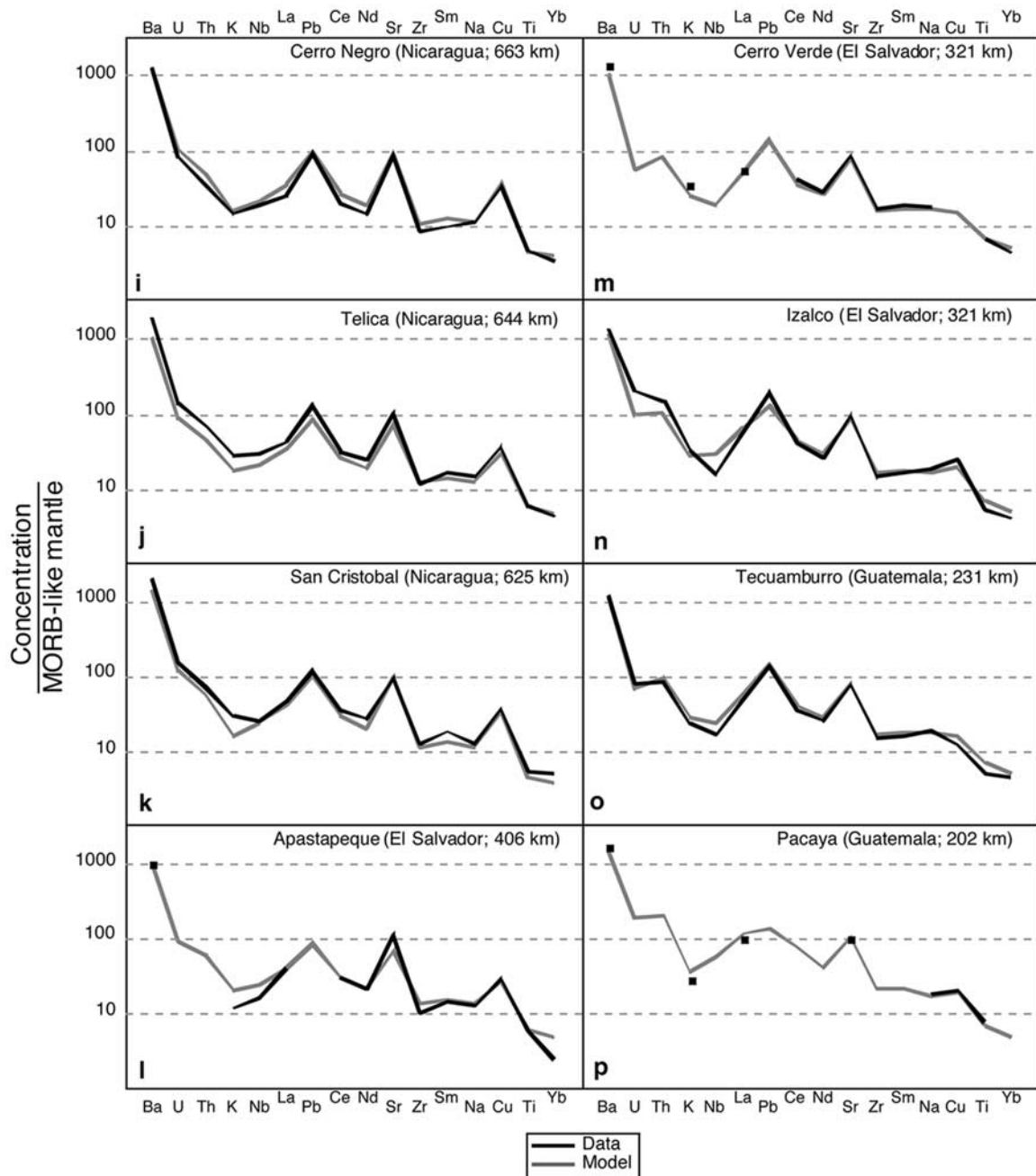
Figure 9. (continued)

tively high in the mantle wedge beneath northwestern Nicaragua and southeastern El Salvador and is low (essentially zero) at both ends of the arc (Figure 10a). In contrast, the amount of the high-δ^{18}O, water-poor, slab-derived component is low beneath the southeast end and center of the arc and high beneath the northwest end (Figure 10b). The OIB-like peridotite component overwhelmingly dominates the southeastern end of the arc (i.e., beneath Costa Rica) but is also present sporadically at abundances of up to ~30% throughout the arc.

This result is broadly consistent with a recent study of Pb isotope compositions of Central American arc lavas [*Feigenson et al.*, 2004]. Addition of water by the slab-derived components drives extents of melting beneath northwestern Nicaragua near or beyond the exhaustion of clinopyroxene in the residue (up to 25 to 27%), and the degree of melting decreases symmetrically about this maximum to minima of 5% beneath the northwest and southeast ends of the arc. The geographic distribution of melt fraction most closely resembles that for
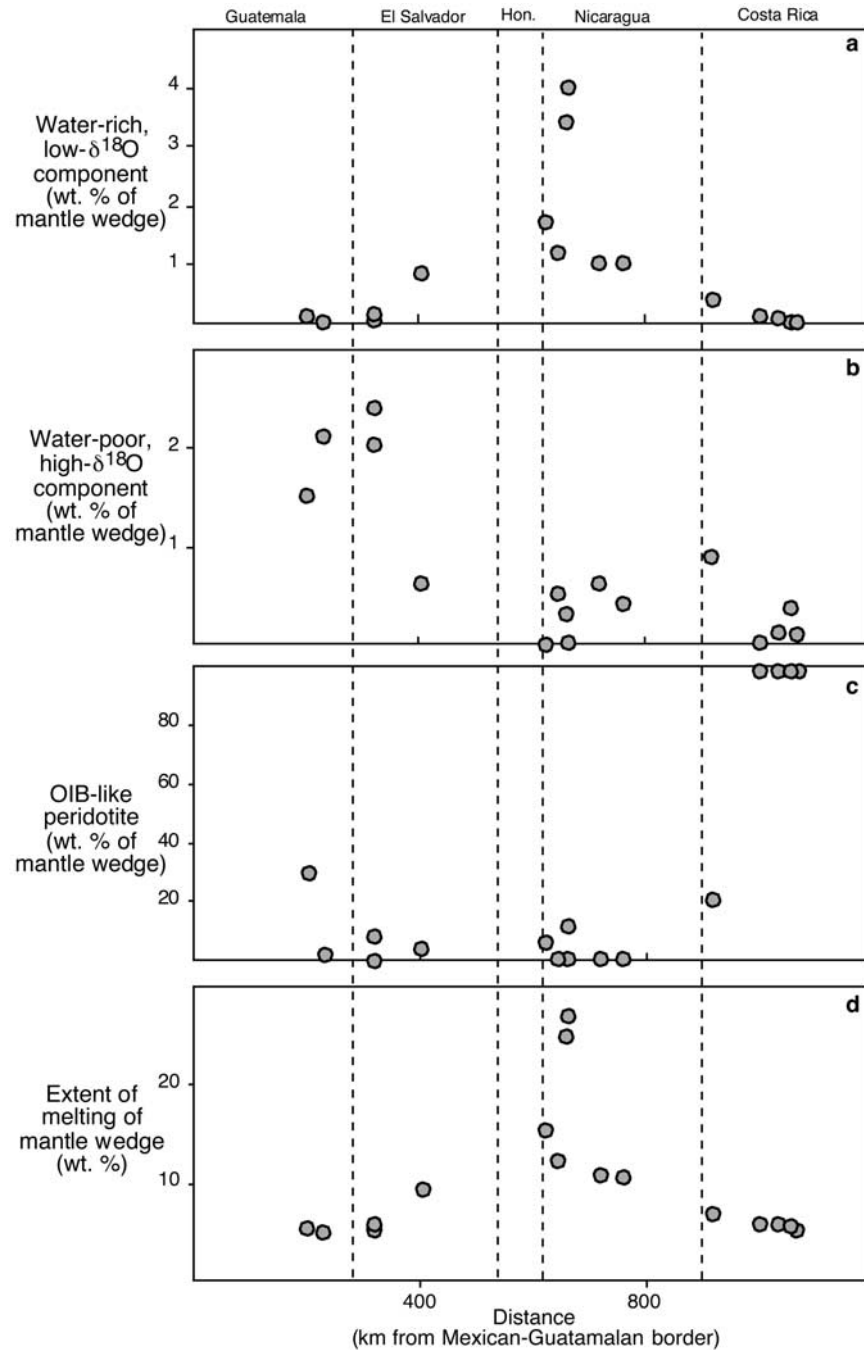
Figure 10. Geographic distribution of mantle-wedge and slab-derived components and degree of melting of the mantle wedge along the length of the Central American arc, based fits of the model described in the text to fractionation-corrected, suite-average compositions of volcanic centers examined in this study. One point is plotted for each volcanic edifice sampled in this study. These are the fitted parameters leading to the model solutions plotted in Figures 8 and 9.

the abundance of low-$\delta^{18}O$ slab component; i.e., in the context of our model, release of aqueous fluid from the slab interior is the principal control on the degree of melting of the mantle wedge throughout the arc.

[62] Previous studies of the U-series isotope geochemistry of Central American arc lavas have concluded that slab-derived components introduce significant quantities of Th and possibly Pa into the mantle wedge, and that the mantle sources of

Central American arc lavas experience protracted (up to several million years) multistage addition of slab-derived components [*Reagan et al.*, 1994; *Thomas et al.*, 2002]. It is tempting to try to associate each of the slab-derived components in our model with distinct metasomatic events in the mantle wedge, much as *Elliott et al.* [1997] hypothesized a long temporal gap between early slab-derived melt addition and late slab-derived fluid addition to the mantle wedge beneath the Mariana arc. However, both of our slab-derived components are capable of transporting significant U and Th, and both are elevated in Ba/Th ratio, an index Thomas et al. show is correlated with recent U addition to the mantle wedge (though our slab-derived, low-δ^{18}O fluid component is clearly more extreme in this ratio than our slab-derived, high-δ^{18}O melt component). For these reasons, we do not believe we can concretely tie our model to previous explanations of the U-series isotope geochemistry of the Central American arc. We suggest an important goal of future research should be to characterize the U-series isotope geochemistry of a subset of the samples used to construct our model, so that its relatively detailed treatment of the number, identity, and sources of slab-derived components can be linked to our current understanding of the timing of mantle wedge metasomatism.

4.2.5. Problems

[63] The model we present is generally successful at simultaneously explaining a wide range of geochemical properties of Central American arc lavas. Nevertheless, it has several weaknesses, which we note here.

[64] 1. Central American arc lavas are more variable in Ba/La and U/Th ratios than can be explained by our model. It is known, however, both for arcs generally and specifically for the Central American arc, that subducted sediments and rocks vary significantly in trace element composition over short length scales [*Staudigel et al.*, 1995; *Plank et al.*, 2002]. It is thus possible that the unexplained variance reflects the fact that our model, with its assumption that the two slab-derived components are constant in composition, is overly simplistic.

[65] 2. Three suites of lavas are well-fit overall by our model (i.e., with respect to Na$_{6.0}$, δ^{18}O, La/Sm, ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd), but have relatively large errors in some of their fitted trace element abundances. Granada (Nicaragua; Figure 9f) lavas have high U/Th ratios (0.7) and ^{87}Sr/^{86}Sr ratios

(0.7039), implying a source strongly influenced by the low-δ^{18}O, water-rich, slab-derived component, but are not proportionately high in Ba/La ratio (33) and have low Ba and U concentrations ($\sim$140 and 0.2 ppm, respectively). These features cannot be well explained by our model without changing the concentrations of trace elements in one or more of the model components. Similarly, Telica and San Cristobal (Nicaragua) are well fit for all properties but the absolute concentrations of highly incompatible trace elements, which are systematically low by $\sim$30% for any model solution that is acceptable in other respects. This could be explained if these suites were generated by slightly lower degrees of melting than implied by our model, perhaps related to variations in the temperature of the mantle wedge and/or water content of the mantle and slab-derived components.

[66] Overall, we regard the first two of these problems as minor relative to the overall success of the model at capturing the chemical and isotopic variability of the Central American arc lavas. They might reflect any of a number of "real world" complexities that our model does not try to address, such as variability in the characteristics of the source components (which surely must exist), in melting processes and parameters (fractional versus batch fusion; source temperature, and so forth), the freshness of the samples or oversimplifications in our method of normalizing model and measured magma compositions to 6.0 wt.% MgO (e.g., if lavas vary substantially in primary MgO content and/or in the MgO content at which they become multiply saturated).

[67] 3. Our model cannot explain the geochemistry of lavas from behind the volcanic front (the Yohoa volcanic center in Honduras). These lavas have δ^{18}O values, Na$_{6.0}$ and Cu contents, Nd isotope ratios, and U/Th ratios that are consistent with fluxing a "MORB-like" mantle wedge by $\sim$1−2 wt.% of the high-δ^{18}O slab-derived component (i.e., they plot near high-δ^{18}O Guatemalan and El Salvadoran lavas in Figures 3a, 3c, 3b, and 3g). However, their Ba/La and ^{87}Sr/^{86}Sr ratios are lower than those of high-δ^{18}O volcanic-front lavas (Figures 3f and 3d). The Yohoa "bvf" lavas have been previously interpreted as relatively low-degree partial melts of the mantle wedge, unmodified by slab-derived components. This would be an acceptable interpretation in the context of the simpler models described above and plotted in Figure 6, in which we assumed the mantle wedge is ^{18}O-rich and modified by a single, ^{18}O-poor slab-derived component. However, we

found those two-component models lacking for reasons detailed above. Alternatively, it is possible that the Yohoa lavas sample a high-$\delta^{18}O$, slab-derived component generally resembling that sampled by the volcanic front, but containing lower concentrations of fluid-soluble elements (Ba and Sr). Such a component might be added to the back-arc mantle by partial melting of deeply subducted sediment that had already had its fluid-soluble elements stripped out by dehydration metamorphism [*Cousens et al.*, 1994; *Hochstaedter et al.*, 2001; K. A. Kelley et al., Subduction cycling of U, Th and Pb, submitted to *Nature*, 2004]. This amounts to special pleading based on a limited number of samples but could explain their anomalously high $\delta^{18}O$ values and some other properties in the context of our model for volcanic front lavas.

[68] 4. Finally, although we can successfully account for many aspects of the minor and trace element abundances and O, Sr, and Nd isotopic ratios of Central American lavas in terms of a model involving two distinct slab-derived components, these components do not correspond in all known properties to any single subducted component. In particular, the $^{87}Sr/^{86}Sr$ ratios of both model slab-derived components (0.7040 and 0.7041) are far lower than those of Cocos plate sediments (0.7085 [*Plank et al.*, 2002]), and the $^{143}Nd/^{144}Nd$ ratios of these components (0.5128 and 0.5131) are far higher than these sediments (0.51265 [*Patino et al.*, 2000]), despite the fact that these components strongly resemble subducted sediment in many trace element abundances (Figure 7). This is a fundamental problem in understanding subducted contributions to Central American arc lavas [e.g., *Feigenson and Carr*, 1986]; i.e., it has been previously recognized and is not simply an artifact of our model. For example, Nicaraguan lavas contain ^{10}Be that is thought to have come from subducted pelagic sediments [e.g., *Reagan et al.*, 1994], and have trace element abundances requiring inputs of slab-derived Sr, yet have Sr isotope ratios far lower than those sediments. Previous attempts to resolve this conundrum have suggested that the Sr and Nd in the slab-derived component sampled in greatest abundance by Nicaraguan lavas (i.e., our low-$\delta^{18}O$, water-rich component) come principally from hydrothermally altered rocks in the basaltic crust underlying subducted sediments [*Feigenson et al.*, 1986; *Patino et al.*, 2000]. This is consistent with our suggestion that the low-$\delta^{18}O$ component is aqueous fluid released from hydrothermally altered rocks in the

slab interior. However, it requires that the resemblance in Figure 7 between the model slab-derived components from this study and Cocos plate sediments is fortuitous, at least for Sr and Nd. One way to reconcile these observations is that aqueous fluid is generated by dehydration of rocks within the slab interior, and inherits most or all of its Sr and Nd (and perhaps other elements) from there, but scavenges U, and perhaps other elements (e.g., ^{10}Be), from sediments as it moves upward through the slab. Similar processes might explain why the high-$\delta^{18}O$ component closely resembles Cocos plate sediments in many respects (Figure 7), but does not match them in Sr and Nd isotope ratio. Nevertheless, the combined Sr isotope and trace element composition of slab components in Central American arc lavas remains enigmatic.

5. Summary and Conclusions

[69] The major findings of this study can be summarized as follows:

[70] 1. Basalts and basaltic andesites from the Central American arc include the lowest $\delta^{18}O$ lavas know in recent arcs, as well as some of the highest. These compositions appear to be features of primary magmas, and not the result of assimilation during magmatic differentiation.

[71] 2. Oxygen-isotope compositions of Central American arc lavas vary systematically along the strike of the arc, from a maximum at the northwest end (Guatemala) to a minimum in the center (Nicaragua), to intermediate values at the southeast end (Costa Rica). This trend broadly resembles those previously know for major and trace element concentrations, slab dip and crustal thickness.

[72] 3. Many aspects of the coupled covariations in oxygen-isotope ratios and other geochemical characteristics of Central American arc lavas can be understood as a result of partial melting of a peridotitic mantle wedge that is "normal" in $\delta^{18}O$ in response to additions of two slab-derived, water-bearing components, one of which is relatively high in $\delta^{18}O$ and the other of which is relatively low in $\delta^{18}O$.

[73] 4. We interpret the high-$\delta^{18}O$, slab-derived component to be a partial melt of subducting sediment, and find that it is most abundant in the mantle wedge beneath the northwestern end of the arc. The trace element composition of this component, inferred from models of fluxed melting of the peridotitic mantle wedge, closely

resembles that of pelagic sediments subducting on the Cocos plate.

[74] 5. We interpret the low-δ^{18}O, slab-derived component to be a water-rich (i.e., aqueous) fluid that was released from hydrothermally altered rocks deep in the slab interior (e.g., serpentinites or altered gabbros). The trace element composition of this component has features in common with both the high-δ^{18}O component and Cocos-plate sediments, but is enriched relative to both in ratios of fluid-soluble to fluid-insoluble elements (e.g., Ba/La, Ba/Th, and U/Th). This component is most abundant beneath the center of the arc, and its addition to the mantle wedge is the most important factor controlling the degree of melting of the mantle wedge along the full length of the arc.

[75] These results generally support and expand upon the fluxed melting model of *Carr et al.* [1990] but are not straightforward consequences of the decompression-melting model of *Plank and Langmuir* [1988]. Nevertheless, our results could be consistent with the chemical and energy balance of partial melting in the mantle wedge being significantly influenced both by decompression melting and by open system fluxing by water-rich phases [*Hirschmann et al.*, 1999; *Gaetani and Grove*, 2004]. If so, any such model must deal with the facts that relatively large amounts of slab-derived components (up to ~4 wt.%) appear to be required to explain the oxygen-isotope variations we observe, yet such large amounts of slab components, if water-rich as we infer, would be expected to result in very high degrees of melting (≫25%) of a mantle that is upwelling at a potential temperature well above the dry solidus [*Gaetani and Grove*, 2004]. Such high degrees of melting might not be plausible for the sources of Central American arc lavas; for instance, baring some special circumstance, they would generate lavas with lower heavy-rare earth abundances than are observed in even the lowest-δ^{18}O Nicaraguan lavas. For reference, the melting properties we assumed were originally calculated assuming the mantle wedge is static and 50°C below its dry solidus [*Eiler et al.*, 2000a].

[76] Previous interpretations of the geographic gradients in Ba/La and U/Th ratios in Central American arc lavas (Figures 1b and 1c) have generally suggested that El Salvadoran and Guatemalan volcanic front lavas (the northern end of the arc) sample sources that contain less of the same slab-derived component that dominates trace element compositions of Nicaraguan lavas (the center of the

arc [e.g., *Plank et al.*, 2002; *Carr et al.*, 2004]. We suggest that while this conclusion is partly true (i.e., there is, according to our model, less of the water-rich, low-δ^{18}O, high-U/Th component under the northwest end of the arc), it is incomplete. Geochemical differences between the northwest end and center of the arc are also due to the presence of a greater abundance of a water-poor, high-δ^{18}O slab-derived component in the sources of Guatemalan and El Salvadoran lavas.

[77] One of the surprising results of this study is the low (<5 per mil) δ^{18}O values of lavas from the center of the Central American arc, which we have interpreted to indicate that one of the slab-derived components released from the Cocos slab beneath Central American (i.e., the water-rich metasomatic phase that dominates the slab-derived flux in the central part of the arc) has a δ^{18}O value significantly less than that of typical mantle peridotites. Fluids and melts extracted from subducted lithosphere at convergent margins are usually hypothesized to come from metabasalts and metasediments in the upper ~1–2 km of the slab because this part is water-rich, heats rapidly during subduction, and dominates some distinctive trace element signatures of arc-related magmas. However, such upper-crustal materials are typically higher in δ^{18}O than mantle peridotites. A low-δ^{18}O, slab-derived component must instead come from basalts, diabases, gabbros, and/or serpentinites that underwent high-temperature hydrothermal alteration deep within the slab before its subduction.

[78] Of the various low-δ^{18}O lithologies that might be the source of a water-rich, low-δ^{18}O metasomatic phase, serpentinites are attractive candidates because they are exceptionally water rich and dehydrate at pressures and temperatures similar to those expected for subducted slabs beneath volcanic fronts [*Schmit and Poli*, 1998; *Rupke et al.*, 2004]. A role for serpentinites is consistent with evidence that the Cocos plate offshore of Nicaragua is deeply faulted and rich in serpentinite [*Ranero et al.*, 2003], with the observation that the Cocos slab beneath Nicaragua has seismic properties consistent with a high abundance of serpentine [*Abers et al.*, 2003], and with heat flow evidence that the Cocos slab offshore of Nicaragua has undergone an unusually large amount of hydrothermal circulation [*Fisher et al.*, 2003].

[79] The inferred variations in the amount of the low-δ^{18}O, water-rich component in the mantle wedge (i.e., with a maximum in the center of the arc; Figure 10a) might well reflect the "focusing"

effect of slab dip, as previously suggested by *Carr et al.* [1990] (see section 1). Alternatively, this distribution could be a consequence of spatial variations in the composition of the subducting Cocos slab. As mentioned above, the Cocos plate offshore of Nicaragua is unusually rich in deeply penetrating normal faults as a consequence of the plate flexure in response to steep subduction [*Ranero et al.*, 2003]. This faulting could be responsible for more intense hydration of the slab beneath the center of the arc and thus for release of relatively large amounts of low-δ^{18}O fluid when the slab dehydrates beneath the volcanic front.

[80] The negligible inferred amounts of high-δ^{18}O, water-poor component beneath central Costa Rica may simply reflect the relatively low subduction fluxes of hemipelagic sediment beneath this part of the arc, as evidenced by the low concentration of ^{10}Be in central Costa Rican lavas [*Carr et al.*, 2004]. Our suggestion that fluxes of sediment melt through the mantle wedge are highest beneath Guatemala is consistent with previous interpretations of relatively high δ^{15}N values of volatiles from Guatemalan volcanoes [*Fischer et al.*, 2002] and with identification of sediment melt as the major slab constituent added to the sources of some Guatemalan lavas [*Cameron et al.*, 2003].

Appendix A

[81] Unless otherwise stated, all partial melting calculations presented in this paper assume that melting is a nonmodal batch process, governed by the following mass balance equation for each element:

$$C_l = C_s/[(1 - F) \times D + F], \qquad (A1)$$

where C_l is the concentration of the element of interest in the liquid, C_s is the concentration in the source prior to partial melting, F is the weight fraction of partial melt, and D is the distribution coefficient, equal to C_r/C_l, where C_r is the concentration in the residue of partial melting. For models in which the degree of melting was controlled by fluxing with a water-bearing metasomatic agent, F was estimated as the average of the "fluid-fluxed" and "melt-fluxed" model curves from Figure 5b of *Eiler et al.* [2000a]. This hydrous melting model can be approximated by the polynomial, $F = 20.3[H_2O] - 350[H_2O]^2$, where $[H_2O]$ is the weight fraction of H_2O in the source, including that added by metasomatic agent(s). In all other cases, F was assumed as described in the

Table A1. Mineral-Melt Distribution Coefficients

	Olivine	Orthopyroxene	Clinopyroxene	Spinel
Ba	0.0003	0.0001	0.00068	0.0005
U	0.00002	0.0002	0.0038	0.01
Th	0.00005	0.0001	0.013	0.01
K	0.00005	0.0001	0.0072	0.001
Nb	0.00004	0.002	0.0077	0.4
La	0.00003	0.00005	0.054	0.003
Pb	0.008	0.008	0.008	0.008
Ce	0.0001	0.00015	0.09	0.003
H_2O	0.0001	0.00015	0.09	0.003
Nd	0.0004	0.0005	0.15	0.005
Sr	0.0015	0.0005	0.13	0.1
Zr	0.0007	0.014	0.123	0.4
Sm	0.001	0.0015	0.25	0.0075
Cu	0.04	0.04	0.04	0.04
Na	0.001	0.0015	0.25	0.0075
Ti	0.032	0.215	0.358	0.167
Yb	0.035	0.214	0.91	0.007

text. All partial melting calculations used values of D equal to the weighted average of mineral/melt distribution coefficients for minerals in the residue of partial melting of spinel lherzolite. Table A1 lists the mineral/melt distribution coefficients used in this study, which are the same as those used for similar purposes by *Eiler et al.* [2000a] and are derived from experimental and empirical calibrations cited in that paper. The mineralogy of the source prior to melting was assumed to be 51.6 wt.% olivine, 28.7. wt.% orthopyroxene, 16.0 wt.% clinopyroxene and 3.7 wt.% spinel. The mineralogy of the residues of partial melting were calculated as a function of F, assuming a stoichiometry for the partial melting reaction the same as that derived by *Eiler et al.* [2000a] for fluid-fluxed melting: $Fluid_{\sim1}$ + $Clinopyroxene_{9.8}$ + $Orthopyroxene._{9.9}$ + $Spinel_{1.5}$ = $Melt_{14.6}$ + $Olivine_{7.6}$ (on a mass basis). The concentration of the element of interest in the lava (C_l) was either the dependent variable of the calculation (e.g., for models presented in Figure 6), or was based on the measured compositions of lavas. Where measured lava compositions were normalized for crystallization differentiation, this was done either through empirical correlations with MgO, as described in the text, or by addition or subtraction of "equilibrium olivine"; that is, starting with the measured lava composition, a small increment of olivine in Fe/Mg exchange equilibrium with that lava was either added or subtracted, the resulting liquid's composition was recalculated, and the process repeated until the desired MgO content of the liquid was reached. Unless otherwise stated, both methods corrected lava compositions to MgO contents of 6.0 wt.%.

Compositions of sources (C_s) were either assumed, or calculated as mixtures of assumed mantle and slab-derived end-members (see the text). The fractional melting model shown as a gray solid curve in Figure 6 was made as for the batch partial melting calculations, except F was incrementally increased from 0 in small, discrete steps of 0.0005, the melt removed, and the residue of partial melting defined to the be the source for the next increment of melting.

Acknowledgments

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