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Incompatible element and isotopic evidence for tectonic control of source mixing and melt extraction along the Central American arc

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Abstract. The Sr and Nd isotopic ratios of Central American volcanics can be described by the mixing of four components, marine sediment from DSDP Site 495, MORB-source mantle (DM), EMORB-source mantle (EM), and continental crust. Most of the isotopic data define a trend between EM and a modified mantle (MM) formed as a mixture of DM and less than 0.5% marine sediment, or fluid derived there from. The MM to EM trend is equally apparent in the incompatible-element data and is most clearly seen in a Ba/La versus La/Yb plot. A hyperbolic trend connects high Ba/La and low La/Yb at the MM end of the trend to low Ba/La and high La/Yb at the EM end. Smooth regional variations in incompatible-element and isotopic ratios correlate with the dip of the subducted slab beneath the volcanic front and the volume of lava erupted during the last 100,000 years (volcanic flux). Steep dip and low flux characterize the MM end-member and shallow dip and high flux characterize the EM end-member. The simplest model to explain the linked tectonic and geochemical data involves melting in the wedge by two distinct mechanisms, followed by mixing between the two magmas. In one case, EM magma is generated by decompression of EM plus DM asthenosphere, which is drawn in and up toward the wedge corner. EM mantle is preferentially melted to small degrees because of the presence of low melting components. The second melt is formed by release of fluid from the subducted slab beneath the volcanic front to form MM magma. Mixing between EM and MM magmas is controlled by subduction angle, which facilitates delivery of EM magma to the volcanic front at low-dip angles and impedes it at steep-dip angles.

Introduction

Our purpose is to define the sources that contribute to Central American magmatism, describe regional variations in the relative contributions from these sources, and attempt to relate the regional differences to tectonic parameters. The primary data set consists of 54 pairs of Sr and Nd isotopic ratios, 23 of which have been previously published, and new rare earth element (REE) and trace element data for 125 rocks. The samples are primarily basaltic rocks that span the geographical and geochemical variation found in Quaternary lavas in Central America.

Central America has unique characteristics that make it a useful place for source characterization. Initial isotopic work revealed an unusual positive correlation between Sr and Nd isotopic ratios (Feigenson and Carr 1986). The upper end of the array has MORB-like Nd isotopic ratios and elevated Sr isotopic ratios. Several of these samples have some of the highest ^{10}Be contents found at convergent margins (Brown et al. 1982). Another unusual feature is the presence along the volcanic front of tholeiitic and alkaline basalts that lack the usual characteristics of arc basalts (Walker 1989; Reagan and Gill 1989). Several of these samples contain virtually no ^{10}Be (Morris and Tera 1989). These studies suggest

Table 1. Characteristics of volcanic segments

Name	Arc-trench gap (km)	Dip below front (degrees)	Length (km)	Volume (km^3)	Flux[a]	Crustal thickness (km)
West Gua	190	40	45	55	ND	48
Cent Gua	190	40	145	660	4.6	45
East Gua	180	ND	90	24	ND	40
El Salvador	180	55	240	1000	4.2	32–38
West Nic	180	65	175	270	1.5	32
East Nic	180	75	120	226	1.9	32
No CR	165	65	130	495	3.8	32–40
Cent CR	165	35	115	1645	14.3	40

[a] Flux is volume/length/10^5 yr

Abbreviations: Gua, Guatemala; Nic, Nicaragua; CR, Costa Rica; West, Western; East, Eastern; No, Northern; Cent, Central

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Table 2. Representative analyses

	1	2	3	4	5	6	7
SiO_2	51.40	52.60	50.80	48.80	48.60	48.10	46.90
TiO_2	1.15	0.80	0.77	0.74	1.26	1.15	0.55
Al_2O_3	19.85	17.70	19.50	20.40	16.40	16.10	15.90
FeO	8.90	9.80	9.70	9.10	11.20	10.40	10.03
MnO	0.16	0.18	0.18	0.19	0.18	0.17	0.18
MgO	3.50	4.47	4.73	4.15	6.96	7.97	8.72
CaO	9.89	9.90	11.50	11.80	12.10	12.40	14.40
Na_2O	3.57	2.77	2.20	2.36	2.40	2.19	1.46
K_2O	0.84	1.34	0.46	0.59	0.14	0.10	0.30
P_2O_5	0.27	0.18	0.12	0.14	0.12	0.12	0.11
H_2O	0.34	0.20	0.25	0.35	0.19	0.18	0.50
Total	99.87	99.94	100.21	98.62	99.55	98.88	99.05
Rb	15	29	8	10	5	4	6
Ba	442	818	407	470	117	117	212
Sr	623	469	481	512	283	305	472
V	267	302	332	343	307	290	336
Cr	23	15	21	15	167	333	173
Ni	16	16	18	19	74	95	53
Zr	97	93	48	60	72	71	45
Sc	25	29	32	29	38	41	50
Cu	83	179	163	163	169	138	146
Nb	3.8	2.4	2.4	2.7	3.9	4.5	2.7
Be	0.87	0.83	0.72	0.90	0.60	0.67	0.50
La	10.1	7.0	3.6	6.0	2.8	3.4	5.2
Ce	24.8	17.7	9.1	13.7	9.4	10.1	11.8
Nd	15.5	12.0	7.1	9.4	8.6	8.0	7.8
Sm	3.60	2.64	1.95	2.46	2.58	2.76	2.46
Eu	1.23	0.92	0.77	0.86	1.01	0.98	0.74
Gd	4.16	3.83	2.53	2.59	3.70	3.56	2.64
Dy	3.91	3.73	2.95	2.92	3.92	3.40	2.85
Er	2.17	2.41	1.73	1.52	2.04	2.08	1.39
Yb	1.77	2.41	1.62	1.39	1.48	1.58	1.18
Y	21.7	24.1	16.6	16.4	21.1	19.9	14.9
$^{87}Sr/^{86}Sr$	0.70389	0.70402	0.70397	0.70406	0.70384	0.70388	0.70402
$^{143}Nd/^{144}Nd$	0.51293	0.51309	0.51311	0.51305	0.51301	0.51302	0.51307

1 E1	Pacaya volcano, Guatemala
2 TE1	Telica volcano, Nicaragua
3 CN1	Cerro Negro volcano, Nicaragua
4 AP5	Apoyo volcano, Nicaragua, low-ti basalt
5 GR3	Granada lava, Nicaragua, high-Ti basalt
6 GR5	Granada lava, Nicaragua, high Ti basalt
7 GR101	Granada scoria, Nicaragua, low-Ti basalt

that Central American basalts can provide insight both on melting processes strongly affected by the addition of slab-derived fluid and on melting processes with minimal contribution from the subducted lithosphere.

Analytical models of fluid flow in the asthenospheric wedge (Spiegelman and McKenzie 1987) predict that the dip of the subducted slab beneath the volcanic front is an important parameter in determining melt migration paths. In Costa Rica the shape of the inclined seismic zone is best defined by micro-earthquake locations. Over the rest of the margin, teleseismic data, relocated using Joint Hypocenter Determination (JHD) by Dewey and Algermissen (1974) and Carr (1976), provide the best estimate of the shape of the inclined seismic zone. Carr (1984) used these data to estimate the dip of the slab immediately beneath the volcanic front. We include these estimates, modified on the basis of new data from Costa Rica (Guendal 1986), in Table 1. The variation in dip angle is from 35°–75°, a large range for a single arc.

Most previous interpretations of regional geochemical variations along Central America have been based primarily on major element data (e.g., Kussmaul et al. 1982; Carr 1984; Plank and Langmuir 1988). Carr (1984) and Grant et al. (1984) argued that magma stagnation occurs at the base of the crust and that the empirical correlations between geochemical parameters and crustal thickness were caused by density filtering coupled with AFC (assimilation – fractional crystallization) processes at different pressures. Plank and Langmuir (1988) related normalized CaO and Na_2O contents to the extent of partial melting, which was controlled by crustal thickness. By focussing on the most mafic samples available

Table 2 (continued)

	8	9	10	11	12	13	14
SiO_2	49.76	47.11	50.69	45.33	49.90	58.60	7.11
TiO_2	0.85	1.58	1.14	1.69	1.36	0.48	0.00
Al_2O_3	18.80	14.99	15.84	14.16	16.50	11.00	0.20
FeO	9.26	9.75	8.23	9.60	8.96	4.87	0.74
MnO	0.16	0.17	0.14	0.16	0.16	0.18	0.18
MgO	4.58	10.21	8.41	12.30	7.68	2.11	0.37
CaO	9.15	11.47	8.95	8.66	9.80	2.80	51.40
Na_2O	2.83	2.23	2.81	2.09	3.23	2.01	0.13
K_2O	2.81	1.32	1.65	1.19	0.57	1.70	0.08
P_2O_5	0.58	0.52	0.47	0.68	0.24	0.11	0.09
H_2O	0.32	0.23	0.30	2.60	0.43	nd	nd
Total	99.10	99.58	98.63	98.45	99.17		
Rb	51	35	38	22	7	31	13
Ba	1944	646	773	706	179	3717	1800
Sr	1582	817	843	1141	482	320	1561
V	299	266	237	218	241	124	27
Cr	7	479	342	480	147	50	17
Ni	16	208	170	331	72	156	13
Zr	170	180	176	167	131	86	10
Sc	24	32	28	24	31	16	5
Cu	174	117	123	90	71	134	38
Nb	18.4	18.8	18.4	22.2	5.3	9.5	14.3
Be	2.00	1.38	1.38	1.48	1.24	0.24	0.39
La	103.0	59.9	44.4	42.2	8.5	16.1	9.1
Ce	186.9	118.9	90.0	82.5	24.1	25.0	3.3
Nd	82.5	57.5	39.0	44.0	15.0	14.1	6.1
Sm	14.20	10.80	7.89	8.04	4.03	2.80	1.51
Eu	3.70	2.90	2.08	2.24	1.27	0.86	0.27
Gd	10.30	8.60	6.68	6.41	4.30	3.32	1.39
Dy	6.30	6.10	4.82	5.02	4.68	3.62	2.38
Er	3.20	3.20	2.14	2.11	2.46	2.62	1.46
Yb	2.70	2.70	1.59	1.64	1.80	2.32	1.25
Y	33.5	32.3	23.2	25.9	25.1	23.6	11.9
$^{87}Sr/^{86}Sr$	0.70375	0.70376	ND	ND	0.70321	0.70763	0.70854
$^{143}Nd/^{144}Nd$	0.51291	0.51294	ND	ND	0.51299	0.51274	0.51240

8 PP11	Platanar volcano, Costa Rica, alkaline basalt
9 PP8	Platanar volcano, Costa Rica, alkaline basalt
10 D7	Irazu volcano, Costa Rica
11 PAC1	Guayacan lava, Costa Rica, alkaline basalt
12 GUC303	Cuilapa lava, Guatemala, BVF basalt
13 9-5-42	hemipelagic sediment, DSDP Hole 495
14 33-5-41	carbonate sediment, DSDP Hole 495

Sr isotopic ratios are normalized to $^{86}Sr/^{88}Sr$ of 0.1194 and are reported as measured. NBS SRM 987 is measured at $^{87}Sr/^{86}Sr = 0.710248$. Nd isotopic ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$, and reported as measured. La Jolla Std Nd is measured at $^{143}Nd/^{144}Nd = 0.511852$. Internal precision is better than ± 0.000010 for Sr and ± 0.000020 for Nd (two sigma); external precision (from replicate analyses of standards) is estimated at ± 0.000030 for both isotopes

and by using isotopic ratios and ratios of incompatible elements, we are attempting to see through the effects of near surface AFC processes.

Data

Major elements for most samples were determined by dc-plasma atomic emission spectroscopy (DCP-AES) following Feigenson and Carr (1985). The majority of Guatemalan samples were analyzed by X-ray fluorescence at Michigan Technological University and reported in CENTAM by Carr and Rose (1987). Major elements for three Nicaraguan samples are from McBirney and Williams (1965). All trace element and REE measurements were made by DCP-AES following Feigenson and Carr (1985). New isotopic ratios were obtained from the mass spectrometry facility at Rutgers University.

Sampling

We selected 125 lavas and tephras including the most mafic samples from each volcanic center and several documented lavas that had been selected previously for ^{10}Be analysis. We included nine silicic samples ($SiO_2 > 62$ wt%) from Guatemala. In addition, we analyzed six inclusions of various types and eight marine sediments provided by T.N. Donnelly from DSDP Hole 495, offshore of

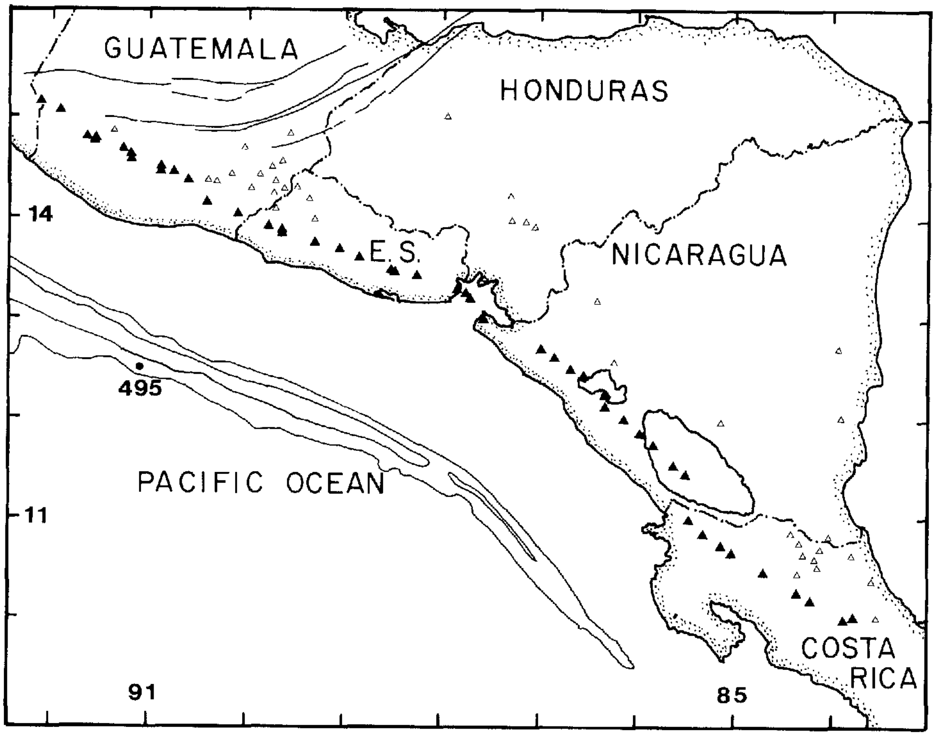


Fig. 1. Locations of Central American Volcanoes. *Solid triangles*, Volcanoes on the volcanic front; *open triangles*, behind-the-front volcanoes. Strike-slip faults marking the Caribbean-North America plate boundary shown as lines crossing central Guatemala. Site of DSDP Hole 495 is marked. *E.S.*, El Salvador. Contours mark position of Middle America Trench

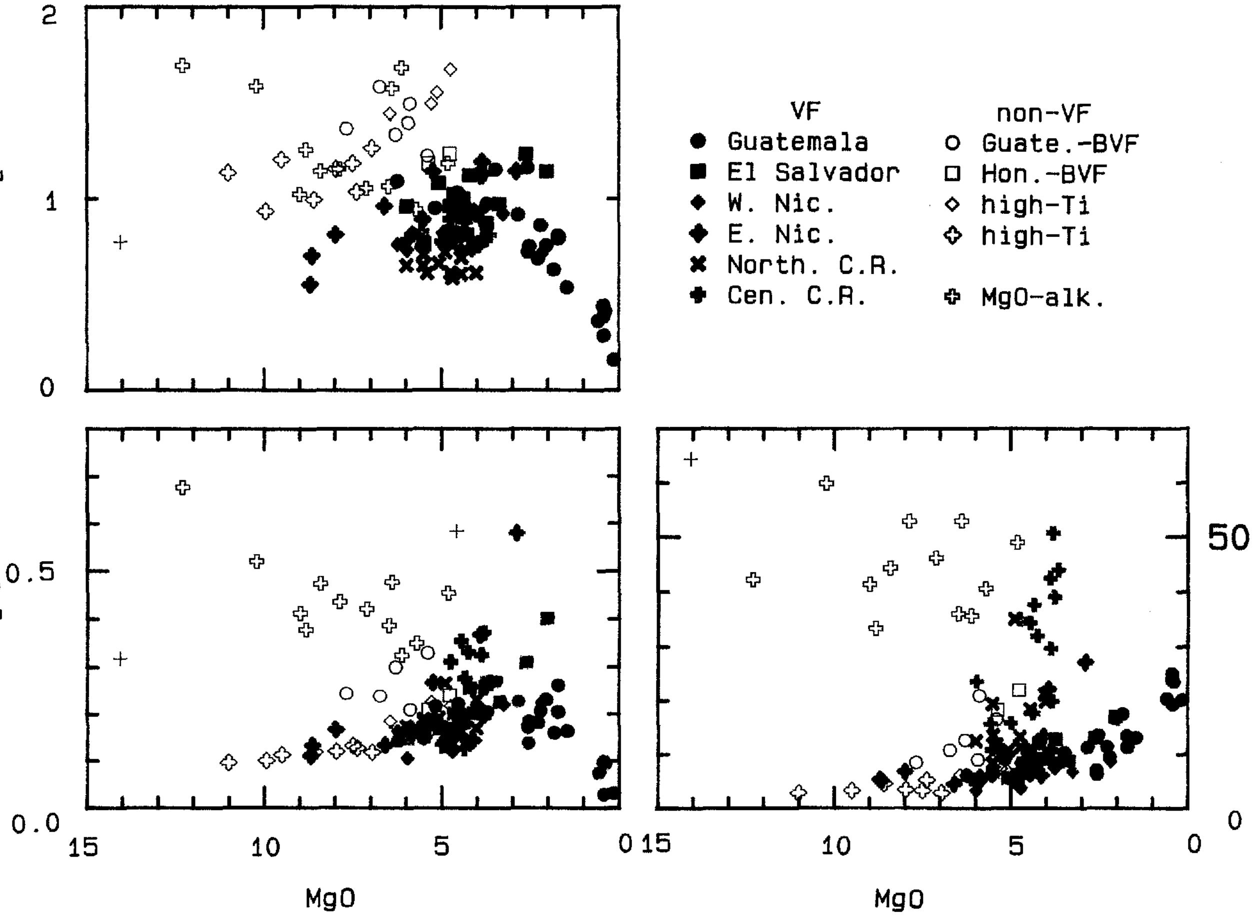


Fig. 2. Discrimination diagrams. High-Ti lavas of western and eastern Nicaragua identified in TiO_2 plot. Magnesian and alkaline lavas of central Costa Rica identified as *open crosses* in P_2O_5 and La plots

Guatemala. The complete data set is available from the authors. Representative analyses are shown in Table 2.

The primary tectonic subdivision of Central American volcanoes separates the volcanic front (VF), which comprises narrow lines of central-vent volcanic complexes, from the behind-the-front (BVF) regions of cinder cones and shields (Fig. 1). Most samples (83) are subalkaline, basaltic to andesitic lavas from the VF. The fields of monogenetic cones and shields behind the VF are represented by eight high-Ti, subalkaline basalts from southeast Guatemala and Honduras, and five generally magnesian and alkaline samples from Costa Rica. The Costa Rican samples include four lavas and scorias from the cones immediately behind Platanar volcano, and one lava of Tertiary age from the alkaline volcanics of Guayacan (Tournon 1973). The BVF samples from Costa Rica are not geochemically distinguishable from nine other magnesian and K-, Rb-, P-, Ba-, Sr-, and light REE (LREE)-rich lavas that erupted from central vents along the VF in central Costa Rica and therefore are considered jointly with them.

Because there are pronounced regional variations in the geochemical data, we use the volcanic segments, defined by Stoiber and Carr (1973), to separate the VF samples into the tectonic/geographic groups defined in Fig. 2.

Unusual samples occur on the VF in Nicaragua and central Costa Rica. The abnormal Nicaraguan samples, described by Walker (1984) and Walker et al. (1990), generally have high MgO, TiO_2, and Nb and low K, Ba, and LREEs. In Fig. 2 we discriminate 11 Nicaraguan samples as high in TiO_2. The unusual central Costa Rican samples are magnesian and rich in incompatible elements, especially La. We discriminate 14 of these samples on the basis of MgO and P_2O_5 values. Some have high TiO_2 contents and some do not. Two samples (PP7, PP11) from vents on the north flank of Platanar volcano in central Costa Rica, have extreme concentrations of Ba and Sr and are plotted as crosses.

In all plots of geochemical data filled symbols denote the calcalkaline samples from the VF. Samples that are geographically and/or geochemically different from the VF are marked with open symbols. These non-VF samples generally have lower Ba/La ratios than adjacent VF samples (Fig. 4a).

Results

Sr and Nd isotopic ratios

The Sr and Nd isotopic data for Central America (Fig. 3) define three roughly linear arrays, two of which are confined to Guatemala. With the exception of Guatemala, the Central American data define an unusual positive correlation between Sr and Nd isotopic ratios (Feigenson and Carr 1986). This dominant trend reaches maximum Sr and Nd isotopic ratios in western Nicaragua. The lower end of this trend is in central Costa Rica and has isotopic ratios on the mantle array, similar to those found in Hawaiian tholeiites and similar to the P-type MORB field of Le Roex et al. (1983). The samples that are distinct from the VF (open symbols in Fig. 3) consistently are shifted toward lower Sr isotopic ratios than the VF samples to which they are geographically adjacent.

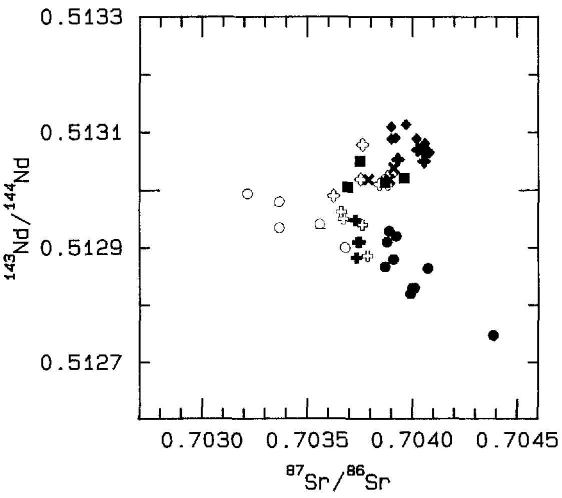


Fig. 3. Sr and Nd isotopic ratios for Central America. Symbols as Fig. 2

The Guatemalan data are divided by tectonic position into a VF group and a BVF group from the monogenetic basaltic cones of southeast Guatemala (Walker 1981). The VF data extend down the mantle array toward the fields defined by the VFs of Mexico and South America. The Guatemalan VF rests on thick continental crust and, in westernmost Guatemala, Paleozoic rocks crop out along the strike of the VF. The BVF data trend up the mantle array toward the field of N-MORB or depleted mantle. The monogenetic volcanism in this region extends more than 100 km behind the VF and is associated with normal faulting and crustal thinning.

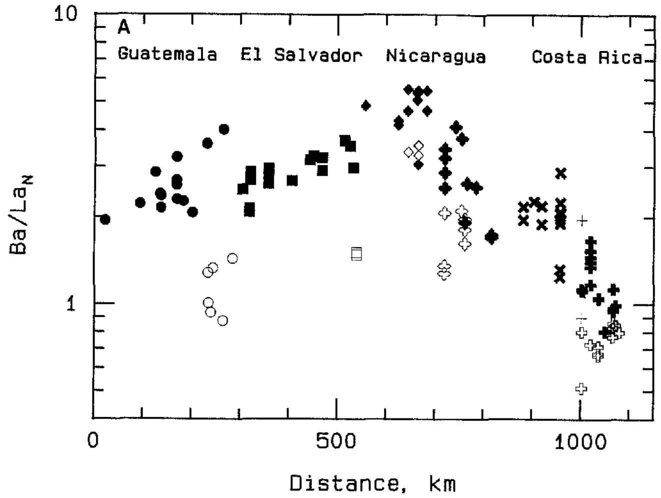
Incompatible element ratios

The largest variations in incompatible-element ratios are found in Ba/La and La/Yb. Most elements that are less incompatible in typical mantle mineralogies than La (e.g., P, Zr, Sm) have regional variations in element/Yb ratios similar to La/Yb but with less range. Similarly, the Ba/La ratio has the maximum variation among ratios of the more incompatible elements, such as K/La and Rb/La. In plots of ratios versus MgO and SiO_2, only Sr in intermediate and silicic rocks and P in silicic rocks showed effects of fractionation. The Nb contents, Nb/La ratios and other ratios involving Nb do not have smooth regional variations like those shown in Fig. 4 (Bennett et al. 1989) and will not be considered here.

The Ba/La_N (where N denotes chondrite-normalized) ratios for VF samples (solid symbols in Fig. 4a) reach a minimum of about 1 in central Costa Rica. The Ba/La_N ratios increase to the northwest to a maximum of about 5.5 in western Nicaragua. Then Ba/La_N decreases to a secondary low of 2–3 in western Guatemala. For the entire VF the Ba/La variation is about 6-fold, whereas within any sub-region (shown by symbol type, Fig. 4) the variation is only about 2-fold. The non-VF samples have Ba/La_N ratios lower than adjacent VF samples, generally near 1.

The regional variation in La/Yb_N is almost a mirror image of Ba/La_N (compare Fig. 4a, b.) One difference is that the range in La/Yb_N ratios is larger, about 10-fold. A second difference is that the non-VF samples (open symbols, Fig. 4) are not systematically different from the VF samples.

The Ba/La ratio was suggested by Kay (1980) as a measure of the influence of the subducted slab,



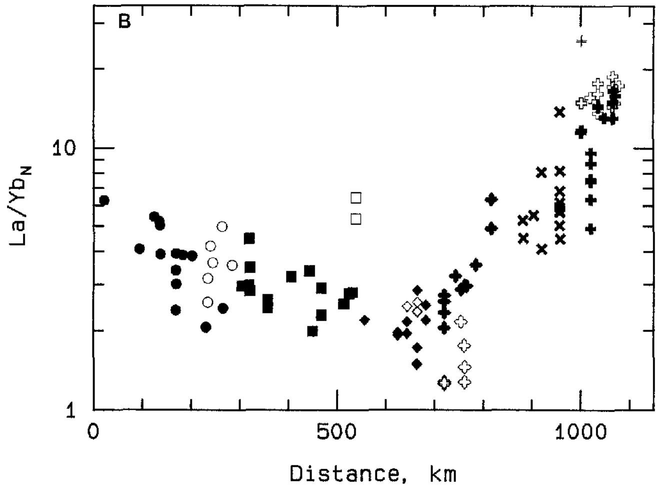


Fig. 4. Regional variation in incompatible-element ratios. Chondrite normalization factors from Nakamura (1974) and Thompson et al. (1984) for Ba. Symbols as Fig. 2. Samples with $SiO_2 > 60$ wt% not plotted

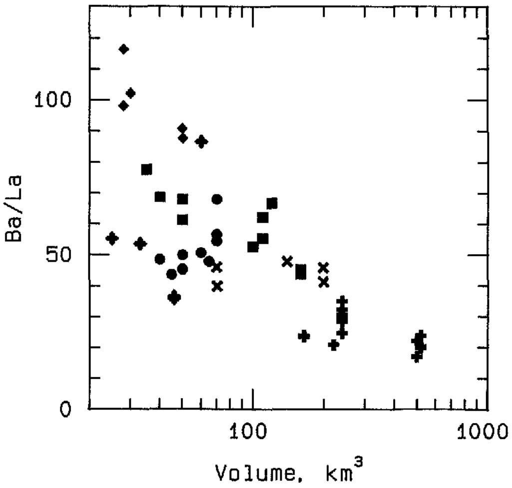


Fig. 5. Decrease in Ba/La with volcano size. Symbols as Fig. 2. Samples with $SiO_2 > 60$ wt% not plotted

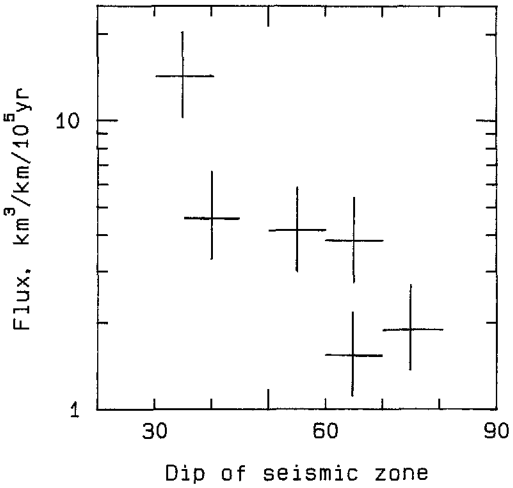


Fig. 6. Increase in volcanic flux with decrease in dip of seismic zone. *Error bar* for flux represents a factor of 2. *Bar* for dip represents 10°

especially subducted sediment. Because Ba is often high in marine sediments, the simplest explanation of changes in Ba/La would be change in Ba. Morris and Hart (1983) evaluated the worldwide data set and suggested that variation in Ba/La resulted more from changes in La contents than from changes in Ba. Central American data strongly support this. The regional change in Ba/La ratio is almost the inverse of La/Yb. Contents of Yb vary little along the arc and Ba/Yb varies only by a factor of two along the length of the arc.

Relation to geological and tectonic parameters

We systematically looked for volcanological and tectonic parameters that might show the same pattern of variation as the geochemical ratios, Ba/La_N and La/Yb_N. Previous studies indicate that crustal thickness and size of volcano are important parameters in Central America. Regional variation in crustal thickness correlates with major element contents (Carr 1984; Plank and Langmuir 1988). Crustal thickness is at a minimum in Nicaragua, a maximum in Guatemala and has an intermediate value in Costa Rica. This is somewhat similar to the variation in La/Yb except that this ratio has a very large maximum in Costa Rica and an intermediate value in Guatemala. This mismatch suggests that the crust is not directly related to the variation in ratios of the incompatible elements.

Carr (1984) showed that the spacing between volcanic centers increases with their volumes. Furthermore, incompatible element contents, normalized for fractionation, also increase with volcano size. Ba/La ratios from the larger volcanoes decrease with size of volcano (Fig. 5) and La/Yb ratios increase.

The volcanic segments in Central America have produced strongly contrasting volumes of volcanic products (Stoiber and Carr 1973). Following Wadge (1984) and our own estimates, we calculated volcanic flux over the last 100,000 years. We obtained an average flux for the

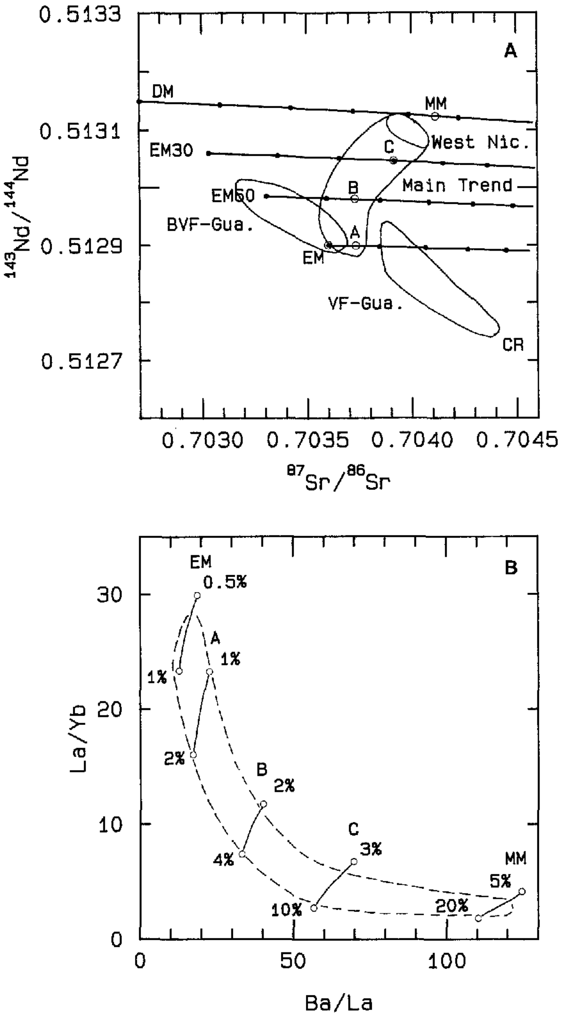


Fig. 7a, b. Mixing models for isotopic and incompatible element ratios. **a** DM, Depleted mantle; EM "enriched" mantle. Mixing between EM and DM shown with two intermediate mixes: EM30 and EM60. These clean mantle sources are modified by addition of IRS fluid derived from marine sediment. *Ticks* mark 0.1% increments of IRS fluid. The main trend of isotopic data, *Main Trend* field, is covered by EM and four metasomatized sources, A, B, C and MM. *BVF-Gua* is field of BVF lava from Guatemala. *VF-Gua* is field of VF lavas from Guatemala that trend toward schematic lower crust point CR. **b** The field includes volcanic front samples and magnesian and alkaline lavas of central Costa Rica. *Lines* marked *EM*, *A*, *B*, *C*, and *MM* show expected incompatible-element ratios for batch partial-melting of the mantle sources defined in **a**. Melt percentages are marked

Table 3. Assumptions for models

	Ba	Sr	La	Nd	Yb	87/86	143/144
DM	1.2	13.2	0.31	0.86	0.4	0.70270	0.51315
EM	4.77	17.9	0.66	1.11	0.3	0.70360	0.51290
MM	39.0	17.5	0.37	0.87	0.41	0.70399	0.51312
Sediment	3200.0	960.0	14.0	12.0	1.9	0.70839	0.51263
IRS	7500.0	960.0	14.0	12.0	1.9	0.70839	0.51263
D	0.0005	–	0.01	–	0.2		

Sediment, Weighted mean from DSDP site 495;
IRS, sediment with Ba content adjusted by about 2.3 × ;
D, bulk distribution coefficient

larger segments of the arc by summing the volumes of each volcanic center and dividing by the length of the segment (Table 1). The tectonic parameter that best correlates with flux is the dip of the seismic zone. As the dip of the seismic zone shallows, the volcanic flux increases (Fig. 6).

Discussion

Sources present

The Sr and Nd isotopic ratios of Central American lavas suggest complex interactions between several sources. In Fig. 7a we show four fields for Central American data and several potential mantle sources, including: (1) DM (depleted mantle or N-MORB source); (2) EM (enriched mantle or E-type MORB source); (3) MM (mantle modified by plate convergence); (4) CR, which points in the direction of continental crust. The trace element contents of DM and EM (Table 3) are from Wood (1979); isotopic ratios are after Le Roex et al. (1983).

Two lines of evidence suggest the presence of a DM source in Central America. Firstly, the BVF lavas from Guatemala extend up the mantle array toward DM. Secondly, the data from western Nicaragua define a subarray (Fig. 7a) that is nearly coincident with, and subparallel to, the mixing line between DM and average marine sediments cored in DSDP hole 495. We use the western Nicaragua data to identify MM, a modified mantle source, created from DM by the addition of 0.45% sediment-derived fluid.

The marine sediments consist of about 240 m of carbonate overlain by 180 m of hemipelagic mud (von Huene et al. 1980). Ratios of Sr/Nd are about 20 for the hemipelagic sediments and from 100–250 for the carbonates. Mixing a small amount of well-mixed sediment into DM causes a large increase in Sr isotopic ratio and virtually no change in Nd isotopic ratio. This sediment is ideal for creating a source that is shifted well above the oceanic mantle Sr/Nd array. The Ba contents of the sediments are very high (1800–8100 ppm), which led Nystrom et al. (1988) to suggest that the high Ba contents of Nicaraguan volcanoes came from subduction of this sediment.

The western Nicaragua array seems to represent a clear slab signature. Several of these samples have some of the highest ^{10}Be contents found at convergent margins (Brown et al. 1982), which further indicates the presence of subducted sediment. The sediments cored from the Cocos plate have ideal Sr, Nd, Ba, La, and Yb contents to create a clearly distinct MM field in both isotopic and incompatible-element composition.

Simple models of two-component mixing do not fit the Central American data. Melting of slab-modified mantle (MM) followed by assimilation of DM during rise to the arc may be appropriate at some arcs, but in Central America there is clearly no mixing line between MM and DM. We previously suggested two-component mixing between MM and lower crust to explain the positive correlation between Sr and Nd isotopic ratios found in El Salvador, Nicaragua, and Costa Rica. However, subsequent analyses of schistose inclusions found in Guatemalan and Nicaraguan lavas did not disclose any data that lie at the lower end of this array. Furthermore, new Costa Rican data included samples at the bottom of this array with MgO contents of 8–10 wt%, indicating that their isotopic ratios are clearly not the result of extensive AFC modification. New samples from western Guatemala create an array pointing toward the high Sr and low Nd isotopic ratios found in Mexican- and South American-arc lavas. The new Guatemalan data indicate a crustal component but one different from that needed to form the El Salvador-Nicaragua-Costa Rica array. Processes of AFC clearly occur all along the arc (Carr 1984). Outside of western and central Guatemala, however, the crust is sufficiently thin, or the assimilant sufficiently young, that the Sr and Nd isotopic systematics of mantle processes are still visible and not overwhelmed as they are at continental margins such as central Chile (Hildreth and Moorbath 1988).

We can reproduce the Central American data by mixing DM, MM and CR in carefully selected proportions. The BVF and VF data for Guatemala could represent mixing between DM and CR. However, the data from the rest of Central America do not radiate out from MM toward various points along the DM–CR line. Instead, they point toward EM. Furthermore, the samples nearest EM have high enough MgO, Ni and Cr contents to be considered as only slightly modified mantle melts. We conclude that EM-type mantle is present beneath Central America and that it is part of two separate two-component mixes, MM to EM (for most of the arc) and EM to DM (for the BVF lavas of southeast Guatemala). The Guatemalan VF array surely requires a crustal component, as well as EM and possibly MM, but we have not yet identified the specific crustal component and so we will not consider these data further.

We conclude that four sources are present beneath Central America. DM and EM are common mantle constituents that we use without modification to interpret the Central American data. MM is specially derived for Central America using the adjacent marine sediments and DM. Our crustal component is not yet directly identified, but is likely to be similar to analogous components determined for Mexico and South America.

Assumptions for melting and melt extraction models

The main group of samples that has to be explained is from the VF between El Salvador and Costa Rica. Isotopic ratios of Sr and Nd for this group define an array with a positive slope that extends between EM and MM. Incompatible trace elements define a similar array in Ba/La versus La/Yb (Fig. 7b). The geochemical data are closely linked to geography. The end of the array closest to MM has maximum Ba/La and occurs in western Nicaragua. The end of the array nearest to EM has maximum La/Yb and occurs in central Costa Rica. Between these end-members there are systematic variations in volcano size and dip of the seismic zone. The volcanoes in western Nicaragua have the strongest slab component (e.g., highest Ba/La) but they are small and sit above a segment of subducted slab that has a steep dip. At the other end of the continum are the volcanoes of central Costa Rica that have the lowest slab component, but huge volumes and sit above a segment of the subducted slab that has a relatively shallow dip.

We suggest two melt generation models that can link the geochemical, volcanological and tectonic parameters that appear to be associated in Central America. For both models we assume the asthenosphere is dominantly DM with small amounts of EM randomly dispersed within it (Morris and Hart 1983). MM is generated in the asthenosphere by an incompatile, radiogenic, silicic (IRS) fluid released from the subducted slab by pressure-induced breakdown of hydrous minerals over a limited depth range, such as 90–120 km (Gill 1981; Reagan and Gill 1989). The amount of IRS fluid per unit length of arc is assumed constant all along the arc. Tatsumi et al. (1986) showed that in IRS fluids Ba/La and Ba/Sr increase by a factor of about 1.5. For our modeling we increased the Ba content by a factor of about 2.3 from that observed in the mean sediment (Table 3).

Melt extraction

Melt extraction is assumed to follow approximately the model of Spiegelman and McKenzie (1987). This model predicts that flux of volcanic products will be negatively correlated to the dip of the subducted slab, which does occur in Central America (Fig. 6). However, some predictions and assumptions are contradicted by Central American data. The non-volcanic zone between the VF and back-arc volcanism is predicted to widen as the dip of the slab decreases. However, the opposite occurs in Central America: the non-volcanic zone is widest in Nicaragua and El Salvador, and least in central Costa Rica where the back-arc volcanism actually reaches the VF (Fig. 1).

In the analytical melt-extraction model, the VF is located above the asthenospheric wedge corner where the subducting plate and the upper plate meet. This specifies that lithospheric thickness is given by the depth to the seismic zone beneath the VF. However, this leads to some unrealistic predictions of lithospheric thickness in Central America. Specifically, Nicaragua, which has a younger and thinner crust than Guatemala, has a depth to the seismic zone of about 150 km, whereas Guatemala has a depth to the seismic zone of only about 90 km. The model might be improved with an additional pressure term to account for the stress developed in the swallow-thrust region. Most volcanic activity occurs in the few years or decades following major thrust earthquakes (Carr 1977), which suggests that the VF begins at the distance from the trench where the upper plate is no longer under compression from the subduction zone. In this case the VF need not directly overlie the wedge corner and flow lines for melt migration in the wedge might be more variable than those defined by Spiegelman and McKenzie (1987).

Variable source contribution with degree of melting

This model consists of a single melting process that is varied by changes in subduction geometry. IRS fluid egresses from the subducted slab over a limited depth range and the dip angle of the slab controls the volume of asthenospheric wedge that is fluxed by this fluid. A steep dip, as is present in western Nicaragua, delivers the IRS fluid to a small volume of asthenosphere that melts to a high degree. Extensive melting gives a low La/Yb ratio. Isotopic ratios are at MM because most of the melting is of DM mantle. The small amount of EM mantle present also melts but its isotopic signature is swamped by the larger contribution from DM.

A shallow dip, as is present in central Costa Rica, delivers IRS fluid to a much larger volume, one that extends beneath and behind the volcanic front. Throughout this volume a small degree of melting occurs because the IRS fluid is being most effectively utilized. Most of the mantle that melts will be the low melting fraction EM. Ratios of La/Yb will be high because most of what melts is EM and the degree of melting is low.

The shallowly dipping case represents efficient spreading of IRS fluid and a maximum total of melt generation. In the steeply dipping case the total volume of melt produced will be less if each additional unit of IRS fluid, delivered to the small mantle volume, generates progressively smaller increments of melt. The Ba/La ratios will be higher in the steeply dipping case because of the extremely high Ba/La ratio of the IRS fluid.

The array of magmas intermediate between the end-members can be generated by an elaborate linkage. Dip angle controls delivery of IRS fluid, which controls degree of melting, which then controls the ratio of EM to DM mantle that is melted. A model of this type that reproduces the isotopic data is presented in Fig. 7a. Mixing between DM and EM is shown by the end-members and two intermediate mixes EM30 and EM60. Mixing lines between IRS fluid and these four points are drawn with ticks marking each 0.1% fluid. Five mixed sources span the range of isotopic variation: EM and A for central Costa Rica, B for northern Costa Rica, C for El Salvador and MM for western Nicaragua.

Using the mixed sources and the Ba/La versus La/Yb array we estimate degrees of melting appropriate for each part of the arc (Fig. 7b), assuming batch melting and bulk partition coefficients in the range expected for garnet lherzolite (Table 3). The melting estimates qualitatively show regional differences but are preliminary because they are highly dependent on assumed bulk distribution coefficients and are based on batch melting, which may be inappropriate for high-percent melts. Future work will include inversion of alkaline suites to obtain realistic bulk distribution coefficients and mantle compositions.

Nye and Reid (1986) presented a model of variable interaction of two mantle sources and metasomatic fluids to explain magmas from Okmok volcano in the Aleutian arc. Our model is more elaborate because we are attempting to explain pronounced regional variations in both tectonic and geochemical parameters. The resulting model is a complex, delicate balance. Furthermore, the BVF lavas of Guatemala and the high-Ti lavas of Nicaragua are not readily explained by this model.

Magma mixing

This model has two separate melting processes and creates the regional variation in arc lavas by mixing them in different proportions controlled by subduction geometry. The structure of the mantle beneath the arc (Fig. 8a) is taken from Tatsumi et al. (1983) and the zone of partial melt is after Kushiro (1987). Our model differs from theirs by separating melt from a compacting layer (Spiegelman and McKenzie 1987), rather than calling upon rise of partially molten diapirs. The first melt (em in Fig. 8) occurs by decompression as asthenosphere is drawn inward and upward to the wedge corner. It occurs well behind the VF and produces magmas that

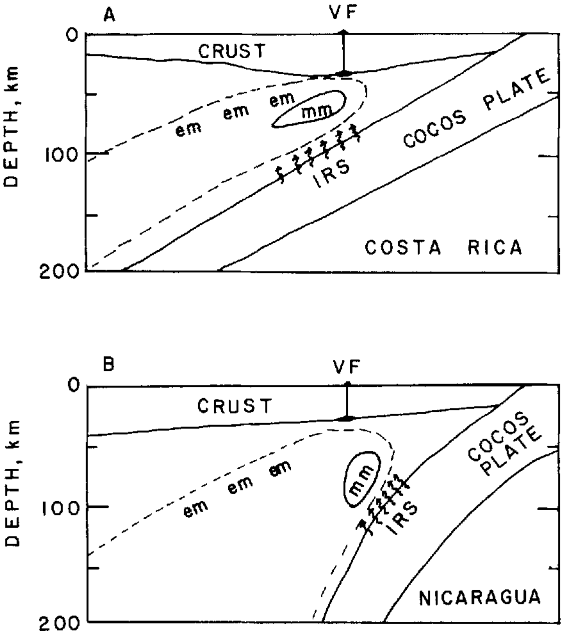


Fig. 8A, B. Cartoon showing two stages of melt generation. **A** Shallow-dipping slab, as for central Costa Rica and similar to Japan arc (Tatsumi et al. 1983; Kushiro 1987). *Dashed line* is outside limit of low-degree (<2%) melt region identified on petrological and seismological grounds in Japan. It approximately corresponds to 1100° C isotherm and its shape is similar to calculated flow lines for counterflowing asthenosphere. Melts (*em*) of low melting component, EM, are likely generated and extracted on the upwelling limb of the counterflow. *Solid line* marks zone of higher-degree melting (>2%) where IRS fluids have penetrated into asthenosphere where its temperature approaches the dry solidus (about 1400° C). MM mantle melts (*mm*) are generated here. **B** Schematic model for steeply dipping slab, as in western Nicaragua. The fields are as **A** but have shifted because of change in dip angle. The main difference is that MM melt region (*mm*) is shifted trenchward of the volcanic front and away from EM melts (*em*). This may explain the lack of EM component in western Nicaraguan lavas may have a small component of fluid derived from the subducted slab or which may be completely free of it, as is found behind the Japan arc (Nakamura et al. 1989). Typically, small-degree melts (0.5%–2%) are formed from incompatible-element-rich mantle, EM or A (Fig. 7b). Mildly alkaline lavas with EM isotopic signature are the result, and the BVF lavas of central Costa Rica are examples (e.g., PP8, D7 or PAC1, Table 2). Small-degree melts of this type have been proposed as the origin of the fractionated distribution of rare earths found in continents (O'Nions and McKenzie 1988). In areas with higher degrees of melting there should be a progressive increase in DM isotopic signature after the low melting EM component is expended. Less alkaline lavas with an EM to DM isotopic mixing trend should result and this is exactly what is present in the BVF lavas of southeast Guatemala.

The residue of melt extraction from EM will be isotopically unchanged, but similar in trace element content to DM. Asthenospheric flow toward and around the wedge corner will eventually deliver this mantle to the zone where IRS fluid is released from the subducted slab and causes melting (mm in Fig. 8). The dominant mantle source, DM, is fluxed by IRS fluid and MM mantle results. Melting this source to a high degree (5%–20%) generates the western Nicaragua basalts (Fig. 7b) of which CN1 and TE1 (Table 2) are good, though somewhat fractionated, examples.

Theoretical melt extraction paths (Spiegleman and McKenzie 1987) allow magmas from both melting processes to accumulate and mix beneath the volcanic front. Reagan and Gill (1989) have termed this "mantle wedge magma mixing". MM melt reaches the surface of western Nicaragua with only a trace of alkaline, EM-derived fluid. In central Costa Rica alkaline cones with nearly pure EM isotopic signature and low Ba/La extend from behind the VF to the flanks of the major central volcanoes. At Poas (Prosser and Carr 1987) and Turrialba (Reagan and Gill 1989) lavas with EM trace element signature have erupted from the central vents of the VF. Various mixtures of EM and MM melts are also present. We can see the actual intermingling of these different magmas in Costa Rica, and to a lesser extent in El Salvador and eastern Nicaragua, and thus we propose that the primary origin of the EM to MM trend is magma mixing. Two representative mixing hyperbolas are shown in Fig. 9. At one end is a field of low- but variable-degree melts derived mostly from the EM component of the asthenosphere. At the other end is a field of magmas with MM isotopic signature and high Ba/La ratios that are produced by IRS fluxing of dominantly DM asthenosphere. Mixing between island-arc magma and EM-derived magma has also been proposed for nascent back-arc basin lavas in the Izu arc (Ikeda and Yuasa 1989).

The high-Ti lavas on the VF of Nicaragua are a special problem. Their isotopic ratios define a trend between MM and EM, but reach much closer to EM than do the adjacent low-Ti VF lavas of Nicaragua. Although the high-Ti lavas approach EM isotopically, they have very low contents of highly incompatible elements and La/Yb ratios that approach those of DM. The high-Ti lavas may result from remelting EM residue, yielding REE patterns characteristic of sequential batch melting (Fig. 10), but with isotopes between EM and DM. High-Ti lavas are relatively scarce and small alkaline volcanoes with EM isotopic character are widespread behind the VF. These observations are further indications that high-Ti lavas are melts produced by IRS fluxing of EM mantle that has reached the fluxing zone after a previous episode of alkaline melt extraction. The high-Ti lavas are thus a predictable consequence of this melting model and should always be present in small quantities. Such lavas are rarely delivered to the surface sufficiently unmixed with MM melt to be recognized.

The mixing between EM and MM melts appears to correlate with dip of the seismic zone. Where the dip is shallow, as in central Costa Rica, EM melt reaches the VF. This can occur with a mantle structure like that

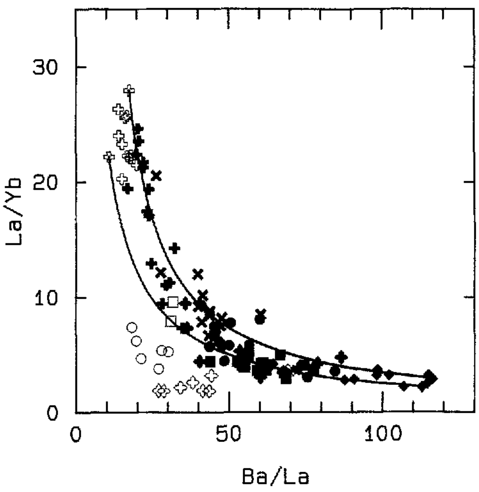


Fig. 9. Mixing models for incompatible element ratios. Two mixing hyperbolas between MM melt and EM melt, CN1-D7 (*lower*) and TE1-PP8, generate the range of Ba/La and La/Yb ratios found at the Central American volcanic front. Samples with $SiO_2 > 60$ wt% not plotted

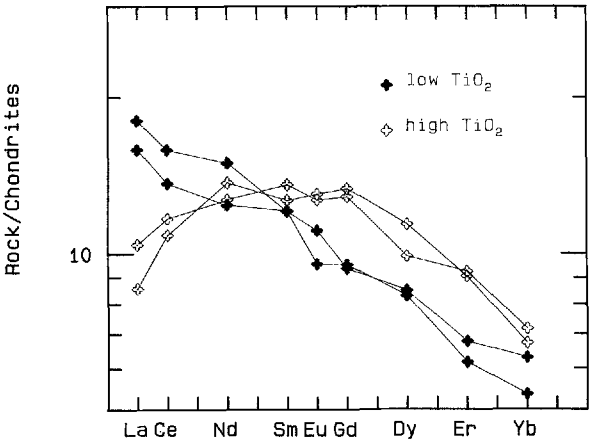


Fig. 10. REE patterns of high-Ti, low-Ti Nicaraguan lavas. The high-Ti lavas, GR3 and GR5 (*open symbols*), have a distinctive REE pattern characteristic of sequential batch melting. The low-Ti lavas, GR101 and AP5 (*filled symbols*), have REE patterns consistent with moderate-degree melting of metasomatized mantle source

in Fig. 8a because the MM melt, derived from IRS fluxing, extends behind the VF into the back arc, where EM melts occur. Melt-extraction lines sweep subhorizontally and collect both melts at the volcanic front (Spiegelman and McKenzie 1987). Where the dip is steep, as in western Nicaragua, little or no EM reaches the VF and it either erupts behind the VF or solidifies in the mantle or lower crust. We suggest that this occurs because the MM melt-zone is shifted trenchward of the VF (Fig. 8b). Melt-extraction paths have not been calculated for these conditions but it is likely that they would be more vertical than in the shallowly dipping case, making it more difficult for EM melts to reach the VF.

The differences in volcanic flux between segments will result from decreasing efficiency of MM melt extraction with increasing dip (Spiegelman and McKenzie 1987) and from decreasing the amount of EM melt brought to the VF, as described above. The variations in volcano size within a segment are related to spacing between volcanoes (Carr 1984). This implies that the melt-extraction process will be better modeled as a three-dimensional problem. It appears that large volcanoes receive EM melt from a wedge-shaped area behind the VF and, in effect, steal EM melt from adjacent, smaller, less incompatible-element-rich volcanoes.

Central Costa Rica has an anomalously high volcanic flux and a unique tectonic setting. The huge volcanoes here are immediately adjacent to a volcanic gap that extends across southern Costa Rica to the Panama Border. This gap covers the subduction of the aseismic Cocos Ridge. The volcanic line extending south of the gap through Panama is a mirror image of the line of volcanoes in central Costa Rica (de Boer et al. 1988). Very large volcanoes rich in incompatible elements are adjacent to the gap and progressively smaller and less incompatible-element-rich volcanoes follow. This pattern suggests that EM melt, generated in the gap region, is not efficiently brought forward to the wedge corner, but is diverted laterally to the central-Costa-Rica and western-Panama segments of the arc.

We favor the magma-mixing model because of its geochemical simplicity and its ability to explain readily associated magmas such as the high-Ti basalts of Nicaragua and the BVF lavas of Costa Rica and Guatemala. Our model (Fig. 8) differs from that of Reagan and Gill (1989) in the location and geometry of the melting regions. We also suggest that magma mixing is likely at the base of the crust as well as at the top of the asthenosphere. Reagan and Gill have a large-degree melt, identical to our MM melt, but require two small-degree melts, one with and one without a residual titanate, to explain variable Nb depletion. We have deferred discussion of Nb because in the arc as a whole it shows variable and localized behavior separate from the regional variations defined in Fig. 4.

Conclusions

Central American arc magmas appear to be derived from a mantle very similar to that which produces oceanic basalts. DM is the main constituent and small amounts of EM are present. The VF magmas differ because of subducted components that metasomatize or flux the mantle, creating a modified mantle source (MM). Lavas from western Nicaragua appear to be the most pronounced examples of melts produced by this process. Their isotopic and trace element characteristics can be modeled as a mix that is dominantly DM and has less than 0.5% marine sediments or IRS fluid.

Nearly all calc-alkaline VF samples lie in an array connecting MM and EM. The simplest explanation for this array is mixing between two magmas. The MM melt is generated beneath the VF by release of fluid into the asthenosphere. The EM melt is generated by decompression of asthenosphere as it is drawn in and up toward the wedge corner. This melt is generated in the back-arc region and may or may not be swept into the VF, depending on the dynamics of plate subduction and especially on the dip of the subducted lithosphere.

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