

Volcanism and Geochemistry in Central America: Progress and Problems

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Most Central American volcanoes occur in an impressive volcanic front that trends parallel to the strike of the subducting Cocos Plate. The volcanic front is a chain, made of right-stepping, linear segments, 100 to 300 Km in length. Volcanoes cluster into centers, whose spacing is random but averages about 27 Km. These closely spaced, easily accessible volcanic centers allow mapping of geochemical variations along the volcanic front. Abundant back-arc volcanoes in southeast Guatemala and central Honduras allow two cross-arc transects. Several element and isotope ratios (e.g. Ba/La, U/Th, B/La, ¹⁰Be/⁹Be, ⁸⁷Sr/⁸⁶Sr) that are thought to signal subducted marine sediments or altered MORB consistently define a chevron pattern along the arc, with its maximum in Nicaragua. Ba/La, a particularly sensitive signal, is 130 at the maximum in Nicaragua but decreases out on the limbs to 40 in Guatemala and 20 in Costa Rica, which is just above the nominal mantle value of 15. This high amplitude regional variation, roughly symmetrical about Nicaragua, contrasts with the near constancy, or small gradient, in several plate tectonic parameters such as convergence rate, age of the subducting Cocos Plate, and thickness and type of subducted sediment. The large geochemical changes over relatively short distances make Central America an important margin for seeking the tectonic causes of geochemical variations; the regional variation has both a high amplitude and structure, including flat areas and gradients. The geochemical database continues to improve and is already adequate to compare to tectonic models with length scales of 100 Km or longer.

1. INTRODUCTION

The selection of Central America as a focus area by the National Science Foundation's Margins Program should increase the amount of research carried out in Central America and lead to improved understanding of all aspects of the subduction process. The primary goal of this paper is to facilitate future research in Central America; first, by updating regional data bases and second, by surveying current ideas with emphasis on assumptions, caveats, inconsistencies, flaws, unexplained observations and important problems. There are several reviews of Central American volcanology [e.g. *Stoiber and Carr*, 1973; *Carr et al.*, 1982; *Carr and Stoiber*, 1990] and progressively refined models attempting to explain the geochemistry of the arc [e.g. *Carr*, 1984; *Feigenson and Carr*, 1986; *Plank and Langmuir*, 1988; *Carr et al.*, 1990; *Plank and Langmuir*, 1993; *Leeman et al.*, 1994; *Reagan et al.*, 1994; *Walker et al.*, 1995; *Noll et al.*, 1996; *Chan et al.*, 1999; and *Patino et al.*, 2000].

This paper is structured as follows; first, an updated database of physical and geochemical parameters of Central American volcanoes; second, review of the Cocos Plate section that is critical for understanding the volcanic geochemistry; third, a volcanological framework for the

diverse magma types in the region; fourth, a summary of the regional, cross-arc, and local geochemical zoning; and finally, a summary of segmentation, including a proposed first-order geochemical segmentation of the arc.

2. DATA

Data are in three files located at M. J. Carr's web site: <http://www-rci.rutgers.edu/~carr/index.html>.

CAVolcFront.zip is Table 1. It lists physical parameters of 39 Quaternary volcanic centers that comprise the volcanic front of Central America. Figure 1 shows the tectonic setting of the volcanic front and Figure 2 names the volcanic centers. With only a few exceptions, the volcanic front centers are groups of vents, including explosive vents, ranging in size from maars to calderas, and including constructive morphologies, such as composite cones, domes, shields and cinder cones.

Deciding which volcanoes to group into a center is not always clear-cut. In Guatemala, the Atitlán center is based on the huge Atitlán caldera (25 Km in diameter). The caldera now includes two pairs of composite cones, Atitlán-Tolimán and San Pedro-Santo Tomás that, absent the caldera, would be grouped into two separate centers. The ring of composite cones near Apaneca, El Salvador,

merges with the huge Santa Ana volcanic complex; separating them or not is arbitrary. The same is true for the Tecapa and San Miguel centers in El Salvador. Geochemistry has not proven helpful in defining dividing lines between nearby centers because the geochemical variation within a center is commonly as great as that between adjacent centers. For example, in northern Central America there is strong cross-arc chemical zonation among vents in the same center [Halsor and Rose, 1988]. The volcanoes nearest to the trench have more mafic character and generally lower LIL element contents and higher Ba/La.

Another flaw in the assumption that it is wise to group volcanoes into centers is the presence of two small

volcanoes along the volcanic front at some distance from adjacent centers. Momotombito is a small composite cone in Nicaragua that is arbitrarily grouped with Momotombo even though it is 9 Km distant. Aramuaca is a maar located 13 Km southeast of San Miguel in El Salvador. It's chemistry is not known because no fresh samples were found. Most of Central America is volcanic and it is problematic to decide how eroded and old a volcanic structure should be to be excluded from the list. Until there is more extensive dating, it seems best to be conservative in deciding which volcanoes to include among the Quaternary centers.

Table 1. Physical parameters of Central American volcanoes

Center No.	Name	Distance Km	Back Km	Latitude	Longitude	Volcano Volume Km ³	Center Volume Km ³
1	Tacaná	22.3	154.1	15.13	-92.11	20	20
2	Tajumulco	46.7	155.9	15.04	-91.90	45	45
3	Santa María	93.9	147.0	14.76	-91.55	18	77
	Santiaguito	93.9	145.0	14.75	-91.57	2	
	Cerro Quemado	94.8	152.5	14.80	-91.52	5	
	Siete Orejas	84.7	148.7	14.81	-91.62	40	
	Chicabál	82.7	144.1	14.79	-91.66	12	
4	Atitlán	137.1	148.9	14.58	-91.18	33	330
	Tolimán	135.3	152.1	14.62	-91.18	18	
	San Pedro	125.5	151.5	14.66	-91.27	27	
	Los Chocoyos	137.6	148.7	14.58	-91.18	250	
5	Fuego	170.1	154.8	14.48	-90.88	73	135
	Acatenango	169.2	156.4	14.50	-90.88	62	
6	Agua	183.2	160.1	14.47	-90.75	68	68
7	Pacaya	201.6	159.8	14.38	-90.60	17	17
8	Tecuamburro	231.0	147.0	14.15	-90.42	39	39
9	Moyuta	266.5	152.3	14.03	-90.10	15	15
10	Santa Ana	319.4	159.2	13.85	-89.63	220	351
	Apaneca	304.5	149.6	13.84	-89.80	125	
	Izalco	321.2	156.1	13.82	-89.63	2	
	Cerro Verde	321.1	157.5	13.83	-89.63	2	
	Conejo	320.0	157.5	13.82	-89.60	1	
	San Marcelino	318.0	158.0	13.81	-89.58	1	
11	Boquerón	358.0	166.4	13.73	-89.28	63	63
12	Ilopango	383.0	172.4	13.67	-89.05	29	30
	Islas Quemadas	383.0	172.4	13.67	-89.05	1	
13	San Vicente	404.1	178.1	13.62	-88.85	59	60
	Apastapeque	405.9	192.1	13.72	-88.77	1	
14	Tecapa	442.7	185.5	13.50	-88.50	65	168

	Usulután	449.8	179.4	13.42	-88.47	15	
	Berlín	440.5	183.6	13.49	-88.53	60	
	Tigre	441.2	180.8	13.47	-88.53	20	
	Taburete	442.7	178.1	13.44	-88.53	8	
15	San Miguel	467.8	191.4	13.43	-88.27	58	68
	Chinameca	460.4	193.1	13.48	-88.32	10	
	*Aramuaca	480.7	198.6	13.43	-88.13	<1	
16	Conchagua	514.4	199.3	13.28	-87.85	27	27
17	Conchaguita	524.9	198.7	13.23	-87.77	1	1
18	Meanguera	531.8	198.9	13.20	-87.71	3	3
19	Cosigüina	556.9	185.9	12.98	-87.57	33	33
20	San Cristóbal	624.7	189.4	12.70	-87.00	65	110
	Casita	627.7	191.2	12.70	-86.97	45	
21	Telica	644.0	188.0	12.60	-86.85	28	30
	Santa Clara	648.8	186.6	12.57	-86.82	2	
22	Rota	655.0	187.0	12.55	-86.75	12	12
23	Las Pilas	664.9	187.5	12.50	-86.68	14	28
	Cerro Negro	663.3	186.6	12.50	-86.70	<1	
	El Hoyo	667.0	187.1	12.49	-86.67	14	
24	Momotombo	683.3	187.7	12.42	-86.53	18	18
	*Momotombito	692.1	184.6	12.35	-86.48	<1	
25	Apoyeque	711.2	182.8	12.25	-86.33	6	9
	Nejapa	720.0	170.0	12.11	-86.32	3	
26	Masaya	742.7	167.3	11.98	-86.15	168	178
	Apoyo	754.8	167.7	11.93	-86.05	10	
27	Mombacho	766.4	162.2	11.83	-85.98	19	20
	Granada	762.2	165.7	11.88	-86.00	1	
28	Zapatera	784.8	161.2	11.74	-85.84	5	5
29	Concepción	816.9	153.7	11.53	-85.62	19	19
30	Maderas	834.0	149.4	11.42	-85.50	22	22
31	Orosí	861.5	109.9	10.98	-85.48	50	100
	Cacao	863.0	110.0	10.96	-85.45	50	
32	Rincón de la Vieja	882.3	103.1	10.83	-85.33	201	201
33	Miravalles	903.9	105.3	10.75	-85.15	132	132
34	Tenorio	920.4	104.9	10.67	-85.02	95	95
35	Arenal	958.3	101.5	10.47	-84.73	13	15
	Chato	960.0	100.0	10.45	-84.69	2	
36	Platanar	1001.7	105.9	10.30	-84.37	32	48
	Porvenir	1003.8	103.3	10.27	-84.36	16	
37	Poás	1021.0	104.9	10.20	-84.22	168	168
38	Barba	1037.2	106.0	10.13	-84.08	326	326
39	Irazú	1067.3	104.8	9.98	-83.85	227	378
	Turrialba	1072.1	114.1	10.03	-83.77	151	

* volcano too small to be considered a separate center and not on the flank of the nearest center

CALine2.zip is Table 2. It lists the locations and relative ages of eleven volcanoes that comprise a secondary volcanic belt, landward of the volcanic front. These volcanoes are analogous to the double chains seen in parts of the Japanese arcs and other areas. Central America has few of these volcanoes and none have historic activity. This list should be modified and improved, as the ages of these volcanoes are determined.

Table 2. Volcanoes of the secondary front.

Name	Country	Latitude	Longitude	Age
Jumatepeque	Guatemala	14.33	-90.27	H
Jumay	Guatemala	14.70	-90.00	Q
Suchitán	Guatemala	14.40	-89.78	P
Ipala	Guatemala	14.55	-89.63	H
Retana caldera	Guatemala	14.42	-89.83	P
Masahuat	El Salvador	14.20	-89.40	P
Guazapa	El Salvador	13.90	-89.11	P
Cacaguatique	El Salvador	13.75	-88.20	P
El Tigre	Honduras	13.27	-87.63	H
Zacate Grande	Honduras	13.33	-87.63	P
Ciguatepe	Nicaragua	12.55	-86.15	Q

Age estimates; H is Holocene, Q is Quaternary. P is Plio-Quaternary

CAGeochem.zip provides geochemical data for samples from Central American volcanoes. Most of the data, including nearly all the Guatemalan data, were previously published as CENTAM [Carr and Rose, 1987]. The new file contains many new columns of data for the Salvadoran, Honduran, Nicaraguan and Costa Rican samples. To first order, all the samples from volcanoes northwest of Tecuamburro volcano in southeast Guatemala are from the work of W. I. Rose Jr. at Michigan Technological University and his colleagues. M. J. Carr and colleagues at Rutgers University collected most of the rest of the samples. Many others contributed samples (e.g. G. E. Alvarado and several students from Dartmouth College) and powders (e.g. A. R. McBirney, W. G. Melson, T. N. Donnelly, M. K. Reagan). The column headed, 'collector-location', notes the collector and the type of sample available at Rutgers University (ru) or Michigan Technological University (mtu). If a reference is given, the data are from the literature. If the entry is ru or mtu then the entire sample resides at that location. If the entry says 'ru powder' then only rock powder is available. The column titled 'Quality' is included to allow a quick sort of the samples with isotopic data and high quality REE and

other trace element data. Quality is zero if the only data available are major elements and a few trace elements or if the trace element data are less reliable or less consistent with the rest of the database.

The locations of the samples in CAGeochem are most accurately given by the easting and northing columns that refer to the map grid in Km units found on 1:50,000 scale topographic maps in Central America. Guatemala, Honduras and Nicaragua conveniently use the UTM grid system, but El Salvador and Costa Rica have local grids based on a Lambert projection. Other columns provide the latitude and longitude of the vent, not the sample locations. Two odd parameters are called 'Distance' and 'Back'. These units are in Km and refer to a Lambert conical conformal projection of the volcano locations and a subsequent 30° counterclockwise rotation. The origin of this reference frame is a spot near the Middle America Trench south of the northwesternmost volcano, Tacaná in Guatemala. Distance, measured parallel to the volcanic front, is a good estimate of distance along the arc. Back is the cross-arc direction, but it is not a good estimate of distance from the trench because the trench is not a great circle. 'Center volumes' were estimated from 1:50,000 scale maps and 100-meter contour intervals, whose areas were determined with a digitizer. The volumes of volcanic centers in Table 1 and CAGeochem are more precise than previous ones, which were made using simple geometric models. However, the accuracy is not much improved because most of the error is caused by pre-volcanic topography hidden by the volcanoes. The column entry, 'volcano volume', is incomplete because the partition of the volume of volcanic centers into the constituent volcanoes that comprise them has not been done systematically.

Silicic rocks are inadequately represented in CAGeochem for El Salvador, Nicaragua and Costa Rica because the Rutgers group has been biased toward the collection of mafic rocks. This data file should not be used to estimate unbiased average compositions. Current work in El Salvador initiated by W. I. Rose Jr. and others at Michigan Technological University, but now including several other universities, is refining the tephra stratigraphy and doing justice to the silicic rocks. Similarly, active research by T. A. Vogel and L. C. Patino of Michigan State University is rapidly establishing the tephra stratigraphy and geochemistry of silicic rocks in Costa Rica. In Nicaragua, the geology of all the volcanoes has been mapped and tephra stratigraphy established through a program of the Geological Survey of the Czech Republic. Maps are available in Managua, Nicaragua at the Instituto Nicaragüense de Estudios Territoriales (INETER). Geologic reports should be available soon [P. Hradecky pers. comm.]. Geochemical work remains to be done on

many large silicic deposits in Nicaragua, including Cosigüina, the Monte Galan caldera at Momotombo, Apoyeque and the Las Sierras section of Masaya. Williams [1983b] and Sussman [1985] describe the Mafic and silicic tephra from the youngest parts of the Masaya complex.

Panama has several Quaternary volcanic centers related to active subduction of the Nazca Plate [*de Boer et al.*, 1991; *Defant et al.*, 1992]. Adakites occur in young Panamanian volcanoes [e.g. *Defant et al.*, 1991]. Small bodies of adakite lavas and dikes occur in the Talamanca range (see Figure 1) in southern Costa Rica [*Drummond et al.*, 1995]. These dikes and domes are dated between 1.9 and 3.5 Ma [*Abratis and Wörner*, 2001] and occur above the subducting Cocos Ridge. In contrast, adakites appear to be absent along the Central American volcanic front. Panamanian volcanism is separated from the Central American volcanic front by plate boundaries cutting both the upper plate and the subducting plate. There is also a volcanic gap of about 175 Km, located above the subducting Cocos Ridge. Young and hot lithosphere of the Nazca Plate is subducting beneath Panama. The profound tectonic and magmatic differences between Panama and Central America make it appropriate to separate these volcanic belts if one seeks to explain variations within a single convergent plate margin. However, *Harry and Green* [1999] group the volcanic belts of Central America and Panama and relate the large geochemical contrasts between Central America and Panama to age variations among the subducting lithosphere segments.

3. COCOS PLATE SLAB SIGNALS

One of the fascinating characteristics of Central America is the pronounced regional variation in the geochemical ratios that define slab signals. A slab signal is a trace element or isotopic ratios that is enriched (e.g. Ba/La) or depleted (e.g. Nb/La) in arc magma, relative to the mantle, because of additions of hydrous fluids or silicic melts derived from a subducted slab. The wide range in ages and geologic histories of subducted slabs prevent a uniform global slab signal. Similarities in the subduction process and the relatively uniform composition of the basalt section of oceanic lithosphere allow many common features among arcs but the sediment input to subduction is variable and the resulting slab signal varies along with the sediment input (*Plank and Langmuir*, 1993). In Central America the slab provides several signals or ratios that trace different parts of the Cocos Plate stratigraphy.

Patino et al., [2000] showed that Central American magmas have special geochemical characteristics derived mainly from the two distinctly different sediments that form a 400 M thick veneer at the top of the Cocos Plate. The discussion here stresses how different element and isotope ratios can provide a variety of slab signals that have

different resolution and focus on different parts of the Cocos stratigraphy.

The oceanic crust and sediments input into the subduction system appear to have low variation along strike of the trench. From Guatemala to northwestern Costa Rica the age, source and stratigraphy of the Cocos Plate crustal section are similar, suggesting a near uniform input [*Aubouin et al.*, 1982; *Kimura et al.*, 1997]. The tectonic processes along the Cocos-Caribbean convergent margin result in the subduction of most of the Cocos sediment section, which is clearly imaged tens of kilometers landward of the trench [*von Huene et al.*, 2000]. Deeper processes that cannot be resolved with seismic images may remove some sediment but, to first order, the sediment section from DSDP 495, analyzed by *Patino et al.*, [2000], characterizes what is subducted into the arc to melt generation depths.

The crustal section of the Cocos Plate consists of three stratigraphic units, a basal MORB/altered MORB, a middle carbonate unit and an upper hemipelagic unit. The MORB section has not been directly characterized and so, in Figure 3 the NMORB and EMORB of *Sun and McDonough* [1989] (diamonds) represent the MORB section. The carbonate sediments are filled triangles and the hemipelagic sediments are open triangles. Figure 3 shows several trace element ratios that track different parts of the stratigraphy. These ratios are plotted on a log scale because of their wide variation in the Cocos Plate section.

Ba/La has little variation in the sediment section but the sediments have much higher Ba/La compared to MORB. This distribution makes Ba/La the best tracer of slab signal for the sediment section as a whole.

U/Th variation is large, especially in the carbonate sediments, which have low contents of both U and Th. The base of the hemipelagic section has values slightly higher than MORB and there is a progressive increase up section to a value of nearly 2.0. The mean values of U/Th for the two sediments are statistically indistinguishable and so, U/Th is a tracer for the entire sediment section. However, the much higher dispersion of this ratio indicates that U/Th might provide a less clearly resolved view of regional variation along the arc than Ba/La.

Ba/Th is exceptionally enriched in the carbonate section and provides a first order tracer of the carbonate section.

U/La is similar in MORB and carbonates but much higher in the hemipelagic section. The U content is especially high in the upper part of the Cocos section, apparently trapped by organic matter that also increases up section [*Patino et al.*, 2000]. The unusual distribution of U in the Cocos section make the U/La ratio a useful slab signal in Central America but this ratio may not be useful in other areas.

Because ^{10}Be decays with a half-life of about 1.5 Ma, it is concentrated in the upper part of the hemipelagic sediments and is essentially zero below 150 M in the Cocos Plate section [Reagan *et al.*, 1994]. The $^{10}\text{Be}/^9\text{Be}$ ratio therefore provides a unique fingerprint of the top of the section.

The slab signals found in Central American magmas provide different information. The $^{10}\text{Be}/^9\text{Be}$ data provide the most precise depth control because ^{10}Be is present only at the top of the sediment section. Ba/La and U/Th represent the entire sediment section but Ba/La has the least dispersion, suggesting it is the better of the two whole sediment signals. Ba/Th and U/La trace the carbonate and hemipelagic sediments, respectively.

4. FRAMEWORK

Central American volcanoes can be subdivided on the basis of location or tectonics, geochemistry and activity. The active system, the volcanic front, is further subdivided into segments defined both by location and by size of volcanic centers. The segmentation of the volcanic front is discussed below in section 6. This section focuses on three volcanic systems that can be geographically or tectonically separated: the volcanic front, the second line and behind the front volcanism (BVF) (see Figure 1). Each volcanic system has a typical geochemistry or magma type but there is some intermingling of magma types as magmas take opportunistic paths to the surface. Adding to the geochemical complexity is the existence of regional variation in both the volcanic front and BVF systems. This zoning is discussed in section 5.

4.1 Volcanic front

The volcanic front is the source of all the historic volcanic activity in Central America and most of the Quaternary volcanic rocks. Several narrow lines of active volcanic centers (Figures 1 and 2) define the volcanic front. These volcanic lines or segments are 165 to 190 Km landward of the axis of the Middle America Trench but the depth to the seismic zone beneath them is much more variable. The dip of the seismic zone appears to steepen toward the center of the volcanic front and so depths to the seismic zone range from less than 100 Km in Guatemala and central Costa Rica to about 200 Km in eastern Nicaragua (Carr *et al.*, 1990).

With few exceptions (e.g. Agua in Guatemala) each volcanic center is a group of several distinct vents of various types. The structure of the centers varies along the arc [Stoiber and Carr, 1973]. In Guatemala, there are prominent transverse lineaments, five to ten Km in length, with two or more overlapping composite volcanoes or domes. In El Salvador, the two largest volcanic centers are made from several composite volcanoes in arcuate or circular arrays (the Santa Ana center and the Tecapa center, respectively). In western Nicaragua, most centers are

clusters of small composite cones, shields, domes and cinder cones aligned in a grid-like pattern [van Wyk de Vries, 1993].

Throughout Central America, with the possible exception of central Costa Rica, the volcanic front coincides with a shallow seismic zone created by right-lateral, strike-slip faulting parallel to the volcanic lines and associated N-S normal faults and grabens [Carr and Stoiber, 1977; White and Harlow, 1993]. In this transtensional setting many volcanoes are associated with the N-S extensional structures.

The volcanic front has many calderas that erupt silicic tephra. The geology and geochemistry of the calderas in Guatemala and El Salvador are well investigated [e.g. Rose *et al.*, 1999]. Most of these calderas occur on the landward side of the volcanic centers. Rose *et al.* [1999] established a regional tephra stratigraphic framework for northern Central America based on the voluminous eruptions from the calderas. In Nicaragua, small silicic calderas occur in the following centers: Momotombo (Monte Galan caldera), Apoyeque and Masaya (Apoyo caldera). Masaya also includes the Las Sierras caldera complex that produced large volumes of predominantly andesitic tephra. In Costa Rica, large silicic tephra deposits occur in association with Rincón del la Vieja, Miravalles and Barva and a small silicic tephra deposit is associated with Platanar.

The individual vents within volcanic centers commonly have more than one lava field or magma batch. The lavas range from basalt to rhyolite, but few lavas have MgO contents greater than 6.0 weight percent. Where the crust is thinner, as in Nicaragua, mafic basalts are abundant. In central and western Guatemala, where thick, old continental crust occurs, basaltic lavas are usually present but their abundance and their MgO contents are low. Throughout Central America, large and extensively zoned plagioclase and pyroxene phenocrysts are typical. Magnetite is ubiquitous and olivine is common in basalts. An important weakness in the Central American database is the lack of regional scale mineralogical studies. The only systematic regional mineralogical variation, known to the authors, is the occurrence of hornblende in basalts and basaltic andesites that have Na_2O contents greater than about 3.5 weight percent. These high Na_2O contents are restricted to central and western Guatemala and central Costa Rica (Carr *et al.*, 1982).

The geochemistry of most volcanic front magmas is marked by a strong enrichment in trace element and isotopic ratios, associated with hydrous fluids or silicic melts derived from the subducted Cocos Plate (e.g. Ba/La >50 ; $^{10}\text{Be}/^9\text{Be} > 2$). Most magmas have strong depletions in high field strength (HFS) elements and low TiO_2 contents. High water contents were measured in melt inclusions in tephra from Fuego volcano in Guatemala [Sisson and Layne, 1993] and from Cerro Negro in Nicaragua

[Roggensack *et al.*, 1997] but not from Masaya in Nicaragua [Bosenberg and Lindsay, *pers. comm.*].

4.2 Second line

A weakly developed second line of composite volcanoes sporadically occurs parallel to and 20 to 75 Km behind the volcanic front (filled circles in Figure 1). The literature of Central American volcanism largely ignores this group because it lacks historic activity and most of the volcanoes are moderately to deeply eroded. However, El Tigre volcano in Honduras is a small composite cone that is minimally eroded and has fresh lavas and tephra. This cone is no older than many cones at the volcanic front.

In contrast to the complicated volcanic centers common at the volcanic front, most of the volcanoes in the second line grew as single composite cones. Younger cinder cones of the BVF system erupted through the flanks of several of these older composite volcanoes (e.g. Ipala and Suchitán in Guatemala and Zacate Grande in Honduras). However, these late cinder cones have a distinctively different geochemistry [Walker, 1981]. Systematic study of the secondary front is just beginning [Patino *et al.*, 1997]. The limited data available indicate that the lavas are calc-alkaline and are plagioclase and pyroxene phyric. Lavas have Ba/La ratios intermediate between the volcanic front and the BVF.

4.3 Behind the front volcanism (BVF)

Widespread back-arc volcanism occurs in Central America (open symbols in Figure 1). This volcanic system overlaps the second line and extends to the volcanic front, but has distinctive structural, morphological, and geochemical characteristics. Walker [1981] called this behind the front volcanism because it extends from the volcanic front to more than 200 Km behind it. Volcanism occurs with back-arc spreading in many circum-Pacific arcs and the BVF volcanism in Central America is analogous to it, but there is an important structural difference: back-arc rifts are commonly sub parallel to the volcanic arc whereas the N-S striking extensional structures in Central America trend at a high angle to the volcanic front, which strikes about N60W. The transverse nature of the rifting allows the back-arc magmas in Central America in some cases to extend all the way into the flanks of the volcanic front centers. In northern Central America, BVF volcanism extends to the left-lateral, strike-slip faults that mark the Caribbean-North America plate boundary (Figures 1 and 2). The extensional tectonics that gives rise to the BVF in southeastern Guatemala is likely dominated by the transform faulting of the nearby plate boundary [Burkart and Self, 1985].

Behind the volcanic front volcanism occurs in clusters of cinder cones, small shields and lava fields in strongly extensional settings, the largest of which is the Ipala graben in southeastern Guatemala. There are also a small number of rhyolite obsidian domes and small calderas that produce silicic tephra. Only a few of these numerous vents are shown in Figure 1. The approximate extents of the major subalkaline BVF fields are shown in Figure 2. There has been no historic activity in the back-arc but Holocene activity is certain given the youthful morphology of many southeast Guatemalan and Salvadoran cones and lavas. In several cases, morphologically young cinder cones occur on the flanks of the second line of composite volcanoes. In El Salvador, cinder cones with typical BVF geochemistry occur on the flanks of the historically active volcanic front centers Santa Ana [Pullinger, 1998] and Boquerón [Fairbrothers *et al.*, 1978]. Contrarily, a recent maar, erupted 12 Km behind Boquerón, has geochemistry more like Boquerón than the BVF cones. Clearly the plumbing is opportunistic. There is a clear geographic overlap between the volcanic front and the BVF in western El Salvador. In contrast, there is a clear separation in southeastern Guatemala [Walker *et al.*, 2000].

Geochemically, most BVF samples have Ba/La ratios in the range 15 (typical mantle) to 45 (moderate slab signal). Many samples are depleted in Nb but Zr and Ti depletions are rare. Compared with volcanic front basalts, the BVF basalts have high TiO₂ contents and are good examples of high-Ti magma (see discussion in section 4.5). These geochemical characteristics indicate a low to moderate input of fluids from the subducting plate. Typical lavas are nearly aphyric with rare olivine phenocrysts, although more evolved, phyric lavas are present, especially at the larger shield volcanoes. In a few exceptional cases (Volcán Culma northeast of Jutiapa, Guatemala and some young lavas north of Estelí, Nicaragua) there are BVF lavas with very large (>1 cm) phenocrysts. BVF lavas from southeast Guatemala to Tegucigalpa, Honduras to central Nicaragua (Estelí) are geochemically similar, at least as far as has been sampled. Very different alkaline lavas occur in central and northern Honduras (Yojoa and Utila in Figure 1). Lavas from these volcanoes have no apparent contribution from the subducted slab, no HFS depletion and minimal crustal contamination. They appear to be the clearest window into the geochemistry of the local asthenosphere [Patino *et al.*, 1997; Walker *et al.*, 2000]. They are similar to the EMORB source of Sun and McDonough [1989]. In Costa Rica, the BVF lavas are substantially different from the BVF lavas in the rest of Central America. Instead, they are similar to ocean island basalts (OIB). Pliocene lavas at Guayacán are alkaline and are derived by low and variable degrees of melting from an OIB-like source [Feigenson *et al.*, 1993]. At Aguas Zarcas (AZ in Figure 1), BVF cones and lavas extend from the back-arc to the flanks of the Platanar center on the front.

The lavas are very rich in incompatible elements, plot near the alkaline/subalkaline discrimination lines and have shoshonitic affinities [Malavassi, 1991; Alvarado and Carr, 1993].

4.4 Magma genesis

Two different melt generation processes occur in Central America, flux melting and decompression melting. Most magmas from the volcanic front and the second line are depleted in HFS elements and enriched in the slab signals described above. Recent studies of Central America [e.g. Patino *et al.*, 2000] infer that these magmas form because a hydrous or silicic flux, derived from the subducted slab, enters the mantle wedge, lowers the melting point of mantle peridotite and causes melting. In the back-arc, magmas have negligible to moderate input of elements from the subducting slab but they occur in an extensional setting. Mantle upwelling, similar to what occurs at mid-ocean ridges but on a much smaller scale, appears sufficient to cause decompression melting that generates BVF magma [Walker *et al.*, 1995].

Cameron *et al.* [in press] identify magmas from the volcanic front that have geochemical characteristics compatible with decompression melting. It is probable that the dichotomy of flux melting at the volcanic front and decompression melting in the back-arc is oversimplified.

4.5 Low-Ti and high-Ti lavas on the volcanic front

Along most of the volcanic front, there is a bimodal distribution of TiO₂ in basalts and basaltic andesites. Exceptions include eastern Nicaragua, where the TiO₂ distribution is unimodal, and northwestern Costa Rica, where all samples have low TiO₂ contents. There is no regionally consistent TiO₂ value that separates high-Ti and low-Ti lavas because the modal values of the high-Ti lavas range from 1.15 weight percent TiO₂ in El Salvador to 1.5 weight percent in western Nicaragua. The low-Ti lavas are more consistent with modes between 0.7 to 0.9 weight percent. The high-Ti and low-Ti groups usually define overlapping distributions on histograms, so precise separation is impossible. Part of the overlap is the result of magma mixing because many vents erupt both high-Ti and low-Ti magmas. The low-Ti and high-Ti basalts are separate magma types in the sense that they are sufficiently geochemically distinct that it is not possible to derive one from the other by low-pressure assimilation-fractional crystallization processes (AFC).

High-Ti is a misleading term because the TiO₂ contents of the lavas appear high only relative to the abundant lavas with strong HFS depletions and low TiO₂. Thus, basaltic lavas called high-Ti in Central America have normal TiO₂ contents compared to the global basalt population. The

high-Ti lavas differ substantially along the length of the arc and therefore, they are discussed in separate, local contexts below.

In northern Central America, Halsor and Rose [1988] pointed out several examples of paired volcanoes or short, cross-arc volcanic lineaments (e.g. Santa María-Cerro Quemado, Atitlán-Tolimán, Fuego-Acatenango, and Izalco-Santa Ana). In each case, the seaward volcano is more active, more explosive and more mafic and has steeper slopes and generally lower incompatible element contents. At the Fuego and Santa Ana centers, the more seaward volcano also has lower TiO₂ and HFS element contents. The cross-arc volcanological and geochemical gradients in the paired volcanoes can qualitatively be explained by mixing a magma derived from flux melting (high water content and strong HFS depletion) with a BVF magma derived from decompression melting (low water content and weak HFS depletion). Quantitative tests of this mixing hypothesis have been inconclusive so far. Establishing the cause of the gradients seen in the paired volcanoes remains an important problem.

Pacaya volcano is at the southeast end of the central Guatemala segment, adjacent to Agua and Fuego volcanoes (Figure 2). The next volcanic segment to the SE, which consists of Tecuamburro and Moyuta volcanoes, is 13 Km closer to the trench. Behind Tecuamburro is a Holocene BVF cinder cone field called Cuilapa. The westernmost cones of this field sit on the flanks of Pacaya. The basaltic lava, currently erupting at Pacaya, has a TiO₂ content of about 1.15 weight percent, a level similar to that of BVF lavas in the Cuilapa field and substantially higher than is found at the adjacent volcanic front centers. Pacaya is on the volcanic front, but its current eruption has characteristics between the low-Ti volcanic front and the high-Ti back-arc. No cross-arc geochemical gradient has been described at Pacaya. However, the volcano does appear to be receiving a back-arc input from its SE flank.

The most unusual examples of high-Ti lavas occur in the generally N-S oriented lines of rifts, explosion pits and cinder cones that cross the volcanic front in several places in Nicaragua but most notably at Nejapa and Granada. Granada is on the northwest flank of the Mombacho center (Figure 2). Ui [1972] first described the mafic and LIL-poor lavas from these alignments. Walker [1984] and Walker *et al.* [1990] discovered a mixture of high-Ti, low-Ti and hybrid magmas at both the Nejapa and Granada volcanic alignments and called these NG basalts. Walker suggested that these two small rift zones fortuitously expose the real complexity of magma genesis in Central America. In contrast, large volcanic centers may partially or completely obscure the complexity through mixing processes in large magma chambers, as appears to be the case at Masaya volcano [Walker *et al.*, 1993]. Carr *et al.* [1990] discovered up-bowed REE patterns in NG basalts, consistent with sequential batch melting, which depletes

the more incompatible light rare earth elements and allows an up-bowed REE pattern in the later melts. These same lavas had lower Nd isotope ratios than the adjacent low-Ti lavas, suggesting they came from a more enriched source. Carr *et al.* [1990] explained the low light REE and LIL element contents, coupled with the relatively enriched Nd isotopes, by proposing an initially enriched source that had recently been depleted of its incompatible elements by an episode of low degree melting. Reagan *et al.* [1994] prefer to derive the high-Ti lavas from the same source as the low-Ti lavas. Walker *et al.* [2001] explain the high variability in the NG basalts through variable contributions from the subducting slab.

In central Costa Rica, high-Ti and low-Ti lavas are present in each volcanic center. The high-Ti lavas here differ only slightly from the low-Ti lavas; they have higher REE and HFS contents and lower Ba, Sr and Pb, indicating an origin involving lower degrees of melting and a weaker slab input [Reagan and Gill, 1989].

4.6 Non-uniform distribution of high-Ti magmas

The presence of two or more magma types at the same volcanic center should be considered normal in Central America. Many volcanic front centers erupt all the magma types found in the region, while others do not. Field observation suggest some controls on where the magmas come from and their ascent paths. For example, the volcanoes Moyuta and Tecuamburro (Figure 2) have only low-Ti lavas and are separated from the Cuilapa high-Ti cinder cone field by a gap of about 15 Km. The immediately adjacent volcanoes, Santa Ana in El Salvador and Pacaya in Guatemala, are overlapped by BVF cinder cone fields. Both of these centers have some lavas with high-Ti, BVF characteristics. In this region high-Ti lavas appear to migrate to the front from the back-arc in some cases but not in others. These field observations suggest separate locations for the generation of high-Ti and low-Ti magmas, followed by migrations to the same vent. The low-Ti magmas are likely generated in the mantle wedge by a slab-derived flux. The back-arc magmas occur in extensional structures forming behind the volcanic front. Extensional structures in the crust can facilitate the along strike movement of magma. Where these structures extend into the volcanic front, as they do at Pacaya and Santa Ana, back-arc magmas have easy access to the volcanic front centers.

Nicaraguan volcanoes have the clearest examples of distinct high-Ti and low-Ti magmas. The relatively thin crust in Nicaragua and the N-S striking extensional structures that cross the volcanic front promote rapid transit of magmas through the crust, allowing less fractionated basalts to erupt and minimizing hybridization of the different magma types. The high-Ti magmas erupt in apparently random locations. It seems each vent has the

potential to erupt either type of magma, regardless of distance from the trench. At the extreme, these field observations suggest the high-Ti and low-Ti magmas follow the same flow paths and share a common locale for the melting processes. The presence of both high-Ti and low-Ti lavas with minimal soil development at the Las Pilas and Telica centers argue that there is minimal time lag and random sequencing in the eruptions of these magma types. The apparently low level of hybridization in these young lavas is surprising if they indeed share an extensive subcrustal plumbing system.

The intimate association of high-Ti and low-Ti magmas at Nicaraguan centers could be due to tectonic factors. First, there are no large extensional structures extending north of the volcanic front, limiting decompression melting due to extension in the back-arc. Second, the Nicaraguan seismic zone progressively steepens and becomes nearly vertical below about 150 Km (Protti *et al.*, 1995). Steep descent of the slab may lead to steep counterflow in the mantle that rises into the arc to replace mantle drawn down by the slab. In this model, decompression melting occurs without extension in the back-arc and the sites of magma generation for the low-Ti and high-Ti magmas would be closer than they are in northern Central America but still separate.

The only relationship between the physical characteristics of the volcanoes and the variety of erupted magmas is that many large volcanic centers have a more restricted range of chemistry. The clearest example of this is Masaya, a shield volcano, with a volume of about 180 Km³, which makes it the largest center in the eastern Nicaragua segment. Walker *et al.* [1993] explained the compositional homogeneity of Masaya's lavas by magma mixing and AFC processes in a large shallow magma chamber. San Cristobal, the largest volcanic center in western Nicaragua, is not as homogeneous as Masaya, but does have the smallest range in Ba/La and U/Th ratios among the centers in this segment. The tendency for large centers to be more extensively mixed argues that the best places to find the widest range of magma types are small to medium sized volcanic centers with multiple distinct vents. In Nicaragua, the widest range of magmas occurs at Telica, a moderate sized center made from as many as six small, overlapping volcanoes [Patino *et al.*, 2000].

5. GEOCHEMICAL ZONING

Geochemical zoning occurs both along and across Central America and within volcanic centers. These chemical variations arise from changes in the mantle and crust, changes in the strength of the slab signal and changes in the type of slab signal, primarily the extent of the hemipelagic sediment component. Zoning will be briefly reviewed here because it is well defined in a series of recent papers. Regional zoning is extensively described

[e.g. Carr, 1984; Plank and Langmuir, 1988; Carr *et al.*, 1990; Leeman *et al.*, 1994; and Patino *et al.*, 2000]. Similarly, cross arc zoning is thoroughly described by Patino *et al.*, [1997] and Walker *et al.*, [2000].

5.1 Mantle zoning

The first order mantle zoning is the presence of unusual isotopic ratios and trace element contents in basalts from central Costa Rica and northern Panama. Geochemically, these basalts are similar to the basalts produced by the Galapagos hot spot. Although the unusual nature of central Costa Rican volcanics was apparent in their steep REE patterns and high LIL element contents, Carr *et al.* [1990] tried to integrate this group into the rest of the arc. Tournon [1984], Malavassi [1991], Kussmaul *et al.*, [1994] and Leeman *et al.*, [1994] showed that the magmas of central Costa Rica were distinct from those of the rest of Central America and had an ocean-island basalt (OIB) character. More recently, Reagan *et al.* [1994] showed that the distinction between the central Costa Rican lavas and the lavas in western Costa Rica and Nicaragua was clear in U-series isotopes and that the boundary was gradational across western Costa Rica and possibly into eastern Nicaragua. In Pb isotope space the Quaternary and Tertiary lavas of central Costa Rica plot in the OIB field and, like the Galapagos hot spot, extend from the MORB field toward the high mantle uranium (HIMU) variety of OIB [Feigenson *et al.*, 1996].

Figure 4a shows $^{206}\text{Pb}/^{204}\text{Pb}$ values along the volcanic front. $^{206}\text{Pb}/^{204}\text{Pb}$ values are sharply higher in central Costa Rica, with values of 18.8 to 19.3. Northwest of central Costa Rica, the $^{206}\text{Pb}/^{204}\text{Pb}$ values are less than 18.7, indicating a source similar to EMORB-source mantle. Refining the location and nature of the boundary between the two mantle domains in Costa Rica is an important problem.

There is little agreement on the origin of the unusual magmas in central Costa Rica. Most studies agree that the mantle source has Galapagos hot spot characteristics, but there are many ideas on how that source gets into the present volcanic system. Abratis and Wörner [2001] cite a window in the subducting Cocos Plate, inferred from plate reconstructions [Johnston and Thorkelson, 1997], that allows Galapagos mantle to rise into central Costa Rica. Herrstrom *et al.* [1995] cite S-wave splitting evidence for mantle flow parallel to the Andes that brings unusual mantle from the southeast. Feigenson *et al.* [1996] show that the Galapagos signature is present in Eocene to Quaternary lavas in easternmost Nicaragua and on islands in the Caribbean, including La Providencia (Figure 1), well behind the arc. Wherever the Galapagos signature occurs in active volcanoes, it coincides with the track of the hotspot during the last 90 my. They conclude that the hotspot added its geochemical signature to the mantle that

passed over it and Galapagos-like magma erupts where this mantle is currently melting.

A second aspect of mantle zoning consists of possible variations in the EMORB-like mantle that seems to be the primary source for Central American magmas [Patino *et al.*, 2000]. Very little is known about possible variations because inputs from the slab prevent clear views of this source. One exception is the alkali basalt field near Lake Yojoa, Honduras. These back-arc basalts are close to and likely related to the transform fault system that separates the Caribbean and North American plates [Walker *et al.*, 2000]. The isotopic and trace element characteristics of Yojoa lavas are consistent with derivation by low degree melting of a source like the EMORB-source of Sun and McDonough [1989]. Chan *et al.* [1999] found $d^6\text{Li}$ values in two high-Ti Nicaraguan lavas and one back-arc lava at Aguas Zarcas in Costa Rica that are higher than MORB, suggesting the mantle beneath much of Central America may have isotopically light composition, consistent with a source, less depleted than MORB.

5.2 Crustal zoning

The crust along the volcanic front of Central America is thicker at both ends of the arc. In central and western Guatemala the volcanoes sit on the edge of a plateau comprising Paleozoic schists through Tertiary volcanics, whereas in Costa Rica, the basement appears to be Cretaceous and younger oceanic crust, sediments and volcanics [Weyl, 1980]. The Costa Rican crust contrasts with neighboring Nicaragua. In Costa Rica, most Tertiary and Quaternary volcanics appear to be superposed, suggesting voluminous intrusive and extrusive arc magmas created the thick crust in central Costa Rica. In Nicaragua, the Tertiary and Cretaceous volcanic deposits are, for the most part, progressively further inland [McBirney, 1985; Ehrenborg, 1996], resulting in a relatively thin crust beneath the Nicaraguan volcanic lines. These crustal variations have isotopic and major element consequences.

From El Salvador to western Costa Rica, the Sr and Nd isotopes of lavas define an array with an unusual positive correlation [Feigenson and Carr, 1986]. The high Nd and high Sr end of the array has isotopic values consistent with derivation from EMORB-like mantle after addition of Sr from the slab. Sr derived from the subducted Cocos crust has a higher isotopic ratio because of interaction with sea water. A crustal overprint disrupts the unusual positive correlation of Sr and Nd isotopes in central and western Guatemala. In this region, Paleozoic rocks crop out along strike with the volcanic lines and Nd ratios become progressively lower as Sr ratios become progressively higher (Figure 4b). These relationships are common in arcs with continental crustal contamination. Although the thick crust in Guatemala most likely increases the amount of assimilation, the main reason crustal contamination is

obvious here is the highly radiogenic nature of the older crust found only in this area. Crustal contamination occurs all along the arc, but outside of central and western Guatemala, the assimilant is young enough and similar enough to present magmas that contamination is a minor consideration.

The most interesting zoning, related to the crust, occurs in major elements and physical parameters. Carr [1984] and Plank and Langmuir [1988] related volcano heights, maximum magma density, minimum SiO₂ contents and Na₂O and FeO contents to estimated crustal thickness (Figure 5). Carr [1984] explained the correlations between crustal thickness, volcano heights, maximum magma density and minimum SiO₂ content through a model that used ponding at the base of the crust and magma compressibility to set maximum magma densities along the arc. Magma density then controlled the other parameters, except for Na₂O. Although thicker crust should increase fractionation and moderate pressures, coupled with high water contents, should suppress plagioclase crystallization, these two effects increase Na₂O only a modest amount. The positive correlation between Na₂O and crustal thickness was not explained.

Plank and Langmuir [1988] argued that Na₂O and FeO contents in arc lavas, both in Central America and globally, are controlled by the extent of melting and the mantle potential temperature, a model well established for mid-ocean ridges. The thickness of the crust was assumed to control the extent of melting because the sharp density contrast at the base of the crust will stop rising diapirs that are undergoing decompression melting. This model easily explains the regional variations in major elements and is consistent with the magma ponding model of Carr [1984]. However, this major element derived model is very different from the magma genesis model derived from trace elements and described below in section 5.4. Reconciling these different models is an important issue.

5.3 Zoning of slab signals

Across the arc, the intensity of slab signal, as estimated from Ba/La, U/Th, ⁸⁷Sr/⁸⁶Sr, B/La or ¹⁰Be/⁹Be, decreases behind the front but not in a consistent manner [Walker *et al.*, 2000]. Cross-arc transects more than 100 Km in length occur across southeast Guatemala and central Honduras, both the result of extensional tectonics related to the strike-slip Caribbean-North America plate boundary. In southeast Guatemala, Ba/La abruptly drops to mantle level just 10 to 30 Km behind the volcanic front [Walker *et al.*, 1995]. In Honduras, Ba/La, U/Th and ¹⁰Be/⁹Be decrease with distance across the arc in a more or less progressive manner [Patino *et al.*, 1997].

Along the volcanic front, the primary zoning arises from changes in the strength or intensity of the slab signal,

which varies in a symmetric pattern centered on western to central Nicaragua. Ba/La and U/Th, which vary only slightly down the Cocos Plate sediment stratigraphy, most clearly show this regional variation but other ratios are also useful (see Figures 4b, 5c, 5d and 7c). Maxima occur in Nicaragua between Telica volcano, which has the maximum Ba/La, and Masaya volcano, which has the maximum ¹⁰Be/⁹Be and maximum ⁸⁷Sr/⁸⁶Sr outside of Guatemala. The intensity of the slab signal varies by at least a factor of four in Ba/La, so the signal is robust. Ba/La and U/Th correlate well enough ($r > 0.80$) with ¹⁰Be/⁹Be to be proxies for it and therefore are unambiguous, easily measured indicators of subducted sediment. Ba/La is a superior slab signal because of its lower variation in the Cocos Plate stratigraphy (see section 3).

Since 1990, the working model to explain the regional variation in intensity of slab signal has been based on the positive correlation between slab signal and apparent degree of melting, estimated from the overall slope of REE patterns. For magmas derived from the same source, higher La/Yb equals steeper REE slope and implies lower degree of melting. The mirror image in the along strike variations of La/Yb and U/Th (Figure 5c and 5d) shows the regionally consistent, positive correlation between slab signal and degree of melting. The La/Yb plot has a log scale to allow for the anomalously high La/Yb values in central Costa Rica derived from the Galapagos-like mantle in this area. Even excluding the central Costa Rican data (crosses at distances of 1000 Km and greater in Figure 5), there is a convincing mirror image between La/Yb and U/Th. A further constraint on models attempting to explain the regional variation in slab signal arises from a crude negative correlation between degree of melting and volumes of erupted volcanics. Nicaragua, which has the lowest La/Yb (or highest degree of melting), also has smaller volcanoes, just the opposite of what would be expected. Although there are huge variations in volcano size over short distances, Figure 7a shows that there has been less magma production in Nicaragua than in other segments of the arc.

[Carr *et al.*, 1990] reconciled the positive correlation between slab signal and apparent degree of melting and the negative correlation between degree of melting and volumes of erupted volcanics by proposing a constant slab flux that is more and less focused depending on external tectonic factors, such as the dip of the slab. Regions with concentrated flux produce small volumes of high degree melt magmas with high slab signal. Regions with diffuse flux produce large volumes of low degree melt magmas with low slab signal. A key assumption is that higher flux concentration leads to higher degrees of melting but not necessarily in a linear manner. Equal increments of flux concentration result in progressively smaller increments of melting, allowing elements, carried in the flux, to be

enriched in the lavas. Measurements of H₂O and incompatible elements in Mariana Trough lavas indicate this assumption is valid [Stolper and Newman, 1994].

The regional variations in slab signal reflect an unresolved combination of changes in slab flux and changes in magma production rate. A high slab signal is not the same as a high slab flux. The ratios used as slab signals are dimensionless, whereas a flux should be in units of mass per unit time per arc length. A very high slab signal, such as a Ba/La ratio of 100, could be either a high flux of Ba into an average sized magma batch or an average flux of Ba into a small magma batch. The relative amounts of slab flux and magma are the same, but the fluxes and batch sizes are different. It is well established that there are strong regional variations in slab signal along the volcanic front. These may reflect changes in flux or a linkage between flux focusing and degree of melting, as suggested by Carr *et al.*, [1990]. This problem will not be unraveled until there are well-determined estimates of magmatic flux along the arc, or reliable geochemical methods of relating a signal to a flux.

A local (intravolcano) variation adds more complexity to the slab signal [Patino *et al.*, 2000]. Separate magma batches at a volcanic center differ in the major and trace element ratios that most emphasize the contrast between the carbonate and hemipelagic sections of the subducted Cocos Plate, which are Ba/Th and U/La (Figure 3). Lavas with apparently low hemipelagic content (high Ba/Th and low U/La) also have slightly lower K₂O contents, as would be expected if the K₂O-rich hemipelagic muds do not contribute to the flux. At well-sampled volcanoes, there are binary mixing arrays in Ba/Th versus U/La, two of which, Telica and Arenal, are shown in Figure 6, along with all the data for the eastern Nicaragua segment. The upper left end of the Telica array (the high Ba/Th end) can be modeled as a mixture of mantle + altered oceanic crust + carbonate. The other end of the array (the high U/La end) is reached just by adding hemipelagic component to the previous mix. The Arenal array differs from the Telica array primarily by having smaller sediment amounts. In general, the distance of a mixing array from the mantle point, EM, corresponds with the strength of the slab signal, with western Nicaragua (Telica) being the maximum. These apparent binary mixing hyperbolae occur in all segments of the arc, except for eastern Nicaragua. In eastern Nicaragua available data (Figure 6) indicate that all the magmas are near the right hand side of the data array, suggesting that the hemipelagic component is strongly represented in all the lavas.

The regularity in the local mixing arrays is perplexing because it implies repeated similar magma generation and mixing events. The order of mixing, derived from the array geometry, is first; create two separate melts; one from asthenosphere and the entire slab section (high U/La); the other from asthenosphere and the entire slab section, except

for the hemipelagic sediments (high Ba/Th). These two melts are then mixed, creating the array. For most of the arc, this presumably complicated process generates parallel arrays, implying some unknown process that generates constant proportionality. Similarly, Reagan *et al.* [1994] discovered that slab tracers, presumed the result of fluid transport, correlated well with Th addition, even though Th should be immobile in a hydrous fluid. Delivering the correct amount of Th in a separate melt is possible only if the fluid-melt proportions are just right. These aspects of Central American geochemistry have a suspicious just right quality, which strongly suggests an important process that is not understood.

The hemipelagic sediments carry the bulk of the incompatible elements in the sediment section. Removing some or all of the hemipelagic section can generate the arrays in Figure 6. If this is the sole cause of the local variation, then the hemipelagic section is sequestered, removed or redistributed on short time and length scales. Because the oceanic crust offshore Nicaragua has a graben and horst structure, the hemipelagic section could be removed from the horsts and doubled into the grabens [von Huene *et al.*, 2000; Patino *et al.*, 2000]. Alternatively, there may be a melt of hemipelagic sediments that mixes with a hydrous flux that mobilizes elements from the rest of the Cocos Plate section. The cause of the local variation is not well understood.

5.4 Are regional variations in degree of melting controlled by slab flux, extent of melting column or both?

Two models call upon differences in degree of melting to explain regional variations across Central America. The earlier model, Plank and Langmuir [1988], relies on changes in crustal thickness to change the melting heights of diapirs feeding the volcanoes. This model has global application to arcs and is widely accepted in the mid-ocean ridge setting. The later model [Carr *et al.*, 1990] attempts to explain the correlation of slab signal (e.g. U/Th in Figure 5d) with degree of melting (inverse to La/Yb in Figure 5c). In this model, an external physical control, slab dip, controls the focusing of slab flux, which, in turn, controls degree of melting. The crustal thickness model has a realistic physical basis (variation in crustal thickness) but does not explain the regional variation in slab signals like Ba/La or ¹⁰Be/⁹Be. The slab flux model explains the slab signals but lacks a reliable physical control. It is based on an assumption that fluid movements in the mantle wedge vary with dip of the slab. The two models could complement each other if slab dip and crustal thickness are linked by a physical process that causes a negative correlation between them. The seismic data used to determine slab dip are only fair in coverage and quality but most reviewers of the data [see Protti *et al.*, 1995] find the steepest dips in Nicaragua, as is required to generate the

negative correlation. Therefore, the two models seem to be complementary, but whether by cause or by accident is not known.

6. SEGMENTATION OF THE VOLCANIC FRONT: GEOGRAPHY, VOLUME AND GEOCHEMISTRY

The volcanic front can be segmented in two ways. The locations of the active volcanic centers define eight lineaments or volcanic segments that are separated by changes in strike and or dextral steps of as much as 40 Km. The boundaries between the segments are the stippled bars in Figure 7b. The distribution of volumes of erupted volcanics in Figure 7a defines a less obvious segmentation. The volumes of volcanic centers are lognormally distributed, but this distribution does not appear to be spatially random because there are several progressions starting from a large volcanic center and proceeding to successively smaller ones. There are seven very large volcanic centers (named in Figure 7a) that define volume-segments. The boundaries between the volume segments are roughly located at the small volcanoes out on the tails of the volume progressions. These two methods of segmenting the arc do not give exactly the same results but there is considerable overlap. One difference is that the volume distribution is continuous across the two northwesternmost volcanic segments in Guatemala, apparently unaffected by the step in the volcanic front. The other two differences are minima in volumes in central El Salvador and eastern Nicaragua where there is no volcanic segmentation.

Most of the eight geographic lineaments were recognized by *Dollfus and Montserrat* [1868] but, despite their long residence in the literature, their origin is not explained. *Stoiber and Carr* [1973] and *Carr and Stoiber* [1977] pointed out numerous geological features that were discontinuous at the same places as the volcanic lineaments and suggested that segmentation of the upper plate was initiated by breaks in the lower plate. However, this was not proved and the question of whether lower plate irregularities broke the upper plate or upper plate structures imposed a structural pattern on the descending plate was not resolved. Extensive marine geologic investigations offshore Costa Rica discovered structures in the subducting Cocos Plate, such as the Quepos and Fisher Ridges (Figure 7b), whose influence is clearly traceable to the coastline and even as far as the volcanic front [*von Huene et al.*, 2000]. Seismological mapping of the Wadati-Benioff zone [*Protti et al.*, 1995] revealed an apparent tear in the subducting slab, the Quesada Sharp Contortion (QSC in Figure 7b) that coincides with the Fisher Ridge. The offshore structures strike parallel to the direction of plate convergence, so their impact on the structure of the upper plate is the result of a sustained period of subduction. The Quepos Ridge coincides with the abrupt end on intermediate depth seismicity in Central Costa Rica. The

boundary between oceanic crust generated by the East Pacific Rise (EPR) and oceanic crust generated by the Cocos-Nazca spreading center (CNS) (dotted line in Figure 7b) does not generate an obvious volcanic segment. *Protti et al.*, [1995] also tentatively identified a small bend in the intermediate depth seismicity that coincides with the largest right step in the volcanic front. Overall, the geophysical data are beginning to identify the causes of the volcanic segmentation. In central Costa Rica, the subducting Cocos Plate initiates segmentation.

The average spacing between volcanic centers is 27 Km and the distribution of spacings is Poisson with $\lambda = 24$ Km. *D'Bremond d'Ars et al.*, [1995] derived Poisson or random distributions of volcano spacings at arcs by superposing several generations of diapirs originating via Raleigh-Taylor instability. The distribution and spacing of volcanic centers in Figures 1, 2 and 7b agrees with their model but the distribution of erupted volumes (Figure 7a) suggests that earlier generations of diapirs influence later ones. Along Central America, seven peaks in the volume distribution occur at intervals of 120 to 180 Km. The seven distinctly larger centers in Figure 7a may have originated from an initial generation of diapirs. Atitlán, Tecapa, and Rincon de la Vieja are flanked on both sides by progressively smaller centers, suggesting an underlying physical control to the volume distribution. The minima in the volume distributions commonly coincide with one end or the other of the geographically defined segments.

It is surprising that there is any order (Figure 7a) in the distribution of volumes of volcanic centers. Radiometric dating is needed to determine to what extent the volume differences are caused by different ages or by different rates of eruption. Volume is the cumulative result of eruptions that are large enough and durable enough to resist vigorous tropical erosion processes. Tephra eruptions of 10 Km³ size can be largely removed in a few centuries [*Williams*, 1983a]. Furthermore, substantial volume can be instantaneously removed by caldera-forming events. Persisting volume is added primarily by lava fields and domes, created in decades-long eruptions, such as the ongoing eruptions of Pacaya, Arenal, and Santiaguito (part of the Santa María center. In Guatemala, there are morphologically young cones and barely recognizable roots but few volcanic edifices at intermediate stages of erosion. There is either a continuing recent pulse of activity or very rapid reduction of volcanoes when eruptions cease. The age of the current volcanic front in Guatemala is estimated as <84,000 years, based on the age of the last caldera-forming eruption of Atitlán caldera. The large Atitlán-Tolimán center postdates and partly fills the caldera. Most other Guatemalan centers are smaller so it is reasonable to estimate their ages as <84,000 years as well. In Nicaragua, parts of the Las Sierras formation that underlies Masaya volcano correlates with the 135,000 year old J1 marine ash layer [*Walker et al.*, 1993]. These admittedly weak

stratigraphic relationships suggest that the volumes of volcanic centers are the sum of roughly the last 100,000 years of activity minus substantial volumes of distal and eroded pyroclastic deposits and moderate volumes of lava that were eroded.

The physical segmentation shown by volcano locations has been recognized for a long time but attempts to relate this structure to geochemical features have failed. Accumulating geochemical data (Figure 7c) now allow a provisional geochemical segmentation of the arc based on three changes in gradients of Ba/La versus distance along the arc and three offsets that coincide with the geographically defined segment boundaries. The recent discovery of the local variation, caused by variation in the hemipelagic component of slab flux, adds an additional tool for measuring abrupt changes in regional variation.

Close examination of the Cocos Plate sediment section (section 3) shows that Ba/La is has the most uniform distribution in the section. Plotting Ba/La versus distance along the arc (Figure 7c) provides evidence for geochemical segmentation. The Ba/La distribution along the arc shows two types of discontinuities; changes in the gradient of Ba/La versus distance; and abrupt offsets. An additional factor is the local variation described above, which is best seen in U/La versus Ba/Th space. The signal of the uppermost unit of the Cocos Plate stratigraphy (U/La) is reduced or missing in many lavas, presumably by loss or redistribution of hemipelagic muds as they are subducted. Examination of U/La versus Ba/Th allows qualitative description of the amount of hemipelagic component present in each segment. In the summary below, which runs from SE to NW along the arc, slab signal is synonymous with Ba/La (Figure 7c).

Central Costa Rica (crosses in Figure 7c) has a constant, low slab signal with hemipelagic component present and variable.

Western Costa Rica (Xs) has a constant, moderate slab signal with hemipelagic component present and variable.

Eastern Nicaragua (pointed crosses) has a very strong gradient in slab signal from low in the SE to high in the NW. Masaya volcano near the NW end of this segment is the global maximum in Be isotope ratio. The hemipelagic component is not only present but, in contrast to other areas, apparently always present (Figure 6). Further sampling is in progress to test this observation.

Western Nicaragua (diamonds) has the highest Ba/La in Central America. This ratio has very high dispersion, especially at the smaller volcanic centers, but it does not vary significantly along the length of the segment. The hemipelagic component is present and variable.

El Salvador (squares) has a sharp decrease in Ba/La at the border with Nicaragua. There is a strong gradient in

slab signal from high (SE) to low (NW). The hemipelagic component is present and variable.

Guatemala (circles) has an increase in Ba/La at the border with El Salvador. This offset coincides with the onset of extensive back arc volcanism in southeast Guatemala. There is a strong gradient in slab signal from high (SE) to low (NW) across Guatemala. The hemipelagic component is present and variable. Central and western Guatemala have Sr and Nd isotope systematics that are perturbed by assimilation of Paleozoic crust [Carr *et al.*, 1990].

One possible explanation for the offsets in Ba/La could be that the steps in the volcanic front change the depth to a smoothly varying Wadati-Benioff zone and that depth to the seismic zone controls Ba/La. The cross-arc zoning in Honduras [Patino *et al.*, 1997] does show decreasing Ba/La with increasing depth to the seismic zone. If depth to the seismic zone controls Ba/La, then large geographic steps by the volcanic front should produce large jumps in Ba/La and the segment to the NW (always further from the trench because the steps are all dextral) should have lower Ba/La. At the boundary between central and western Costa Rica there is no step in the volcanic front but there is a tear in the Cocos Plate allowing the western Costa Rica segment to have a greater depth to the seismic zone. However, that segment has higher Ba/La, not lower. The largest step along the volcanic front occurs at the boundary between western Costa Rica and eastern Nicaragua, but instead of a sharp drop in Ba/La into Nicaragua, there is no obvious change. The step between eastern and western Nicaragua is at least 10 Km, but Ba/La does not drop, instead it increases. The step between western Nicaragua and El Salvador is on the order of 10 Km and here the Ba/La ratio sharply decreases. The boundary between El Salvador and Guatemala is a change in strike rather than a rightward step and a large increase occurs not a decrease. The two assumptions, that the Wadati-Benioff zone has a simple geometry and that depth to the seismic zone controls Ba/La, fail to explain the Ba/La offsets and lack of offsets seen in Central America.

7. CONCLUSIONS

Central American volcanoes provide a rich physical and geochemical data set. Several layers of geochemical insight result from selecting isotopic and trace element ratios that maximize the differences between different sources. Although a rich framework of data and interpretation made Central America a selection for focused study in the NSF Margins Subduction Factory Initiative, much remains to be done and many important problems are essentially untouched. A partial list of problems, unexplained observations and remaining work follows.

1. The first-order geochemistry of the mafic volcanic front is known, but few volcanic centers have been comprehensively studied.
2. Silicic volcanic centers have been or are being studied in Guatemala, El Salvador and Costa Rica, but, in Nicaragua, there are several small silicic calderas that have not been investigated.
3. The secondary front of isolated composite volcanoes, located 20 to 75 Km behind the main front, should be integrated into regional volcanological and geochemical investigations.
4. Important aspects of the magma genesis of the high-Ti lavas in Nejapa and Granada, Nicaragua remain unresolved.
5. Are the short, cross arc gradients in the paired volcanoes of northern Central America the result of mixing between low-Ti basalts and back-arc, high-Ti basalts?
6. The existence of cross-arc geochemical variation within most volcanic front centers in Guatemala contrasts with the lack of such variation in Nicaragua. This discrepancy emphasizes how little is known about magma flow paths and the loci of melting.
7. The transition between EMORB mantle beneath Nicaragua and OIB mantle beneath central Costa Rica occurs in easternmost Nicaragua and western Costa Rica. Is the transition, sharp, gradual or intermingled?
8. Do the regional variations in slab signal mean there are regional variations in slab flux or constant flux with regional variations in degree of melting caused by variable focusing of the flux? If the volcanic output rate were constant along the arc, the former would be the case, but currently available volume data and age estimates favor the latter because there is low magma output in Nicaragua, where the slab signal is at the maximum.
9. Some of the detailed systematics in isotopic and trace element ratios are difficult to explain unless the sources involved are repeatedly tapped in just the right proportions. This just-right phenomenon is not understood.
10. Are regional variations in degree of melting controlled by flux focusing, extent of melting column or both? In other words is the *Plank and Langmuir* [1988] model correct, the *Carr et al.* [1990] model, or both?
11. The variation in the sizes of volcanic centers along the arc is an observation that needs to be integrated into models of magma genesis.

12. The breaks between the volcanic lines that comprise the Central American volcanic front corresponds with discontinuities in the regional slab signal, including three changes in the gradient and three abrupt offsets in the slab signal.

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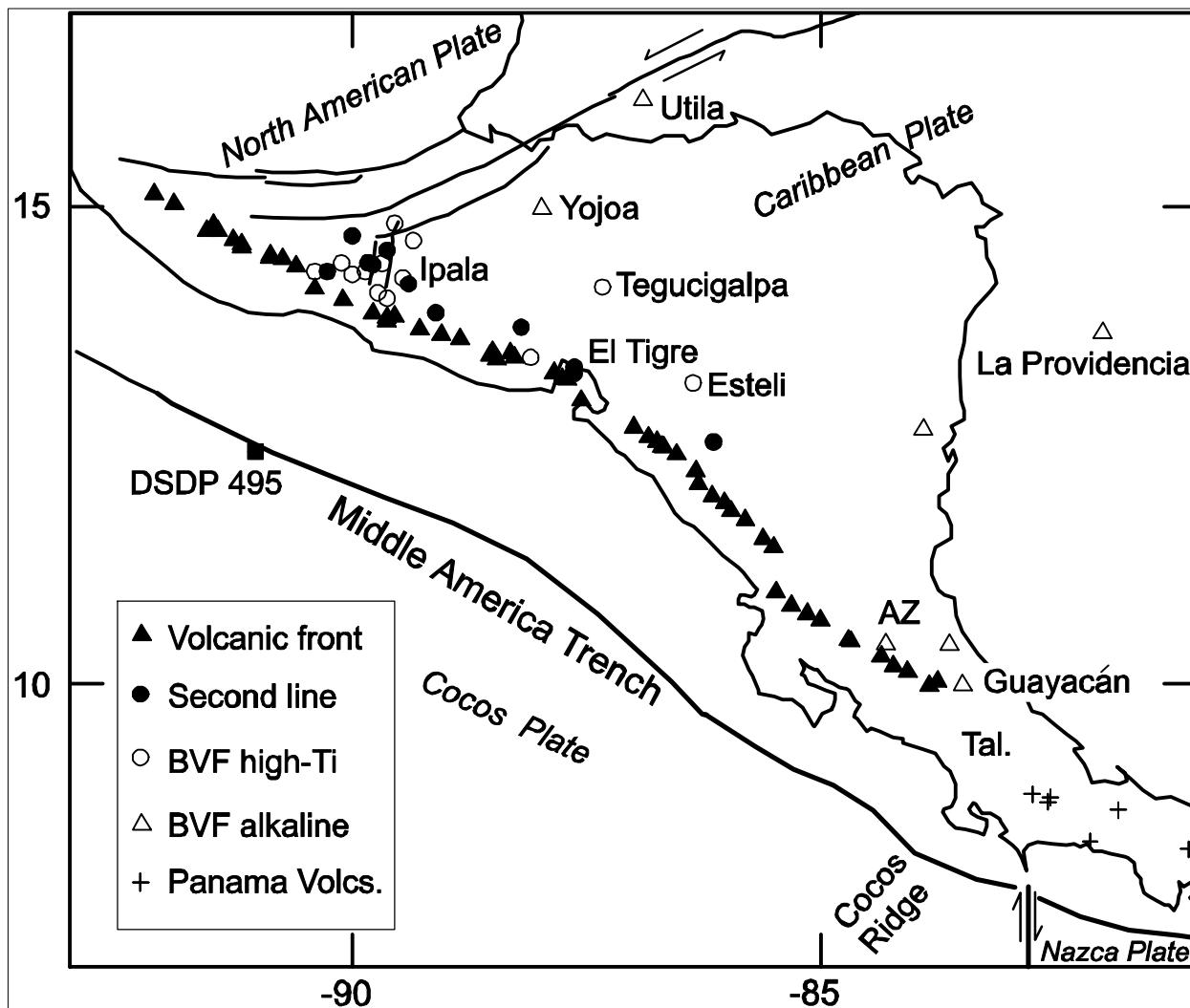


Figure 1. Volcanological and tectonic framework of Central America. AZ is Aguas Zarcas. Tal. is the Talamanca range in southern Costa Rica.

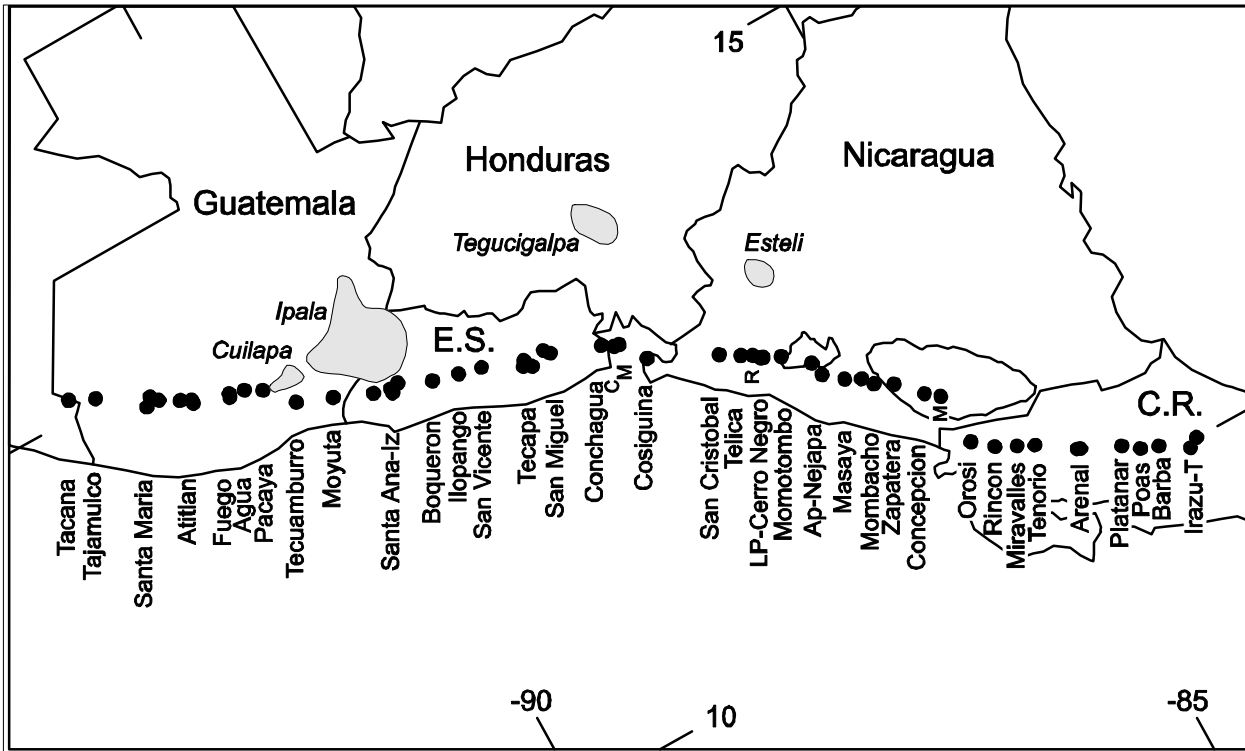


Figure 2. Locations of volcanic centers and BVF fields. E.S. is El Salvador, C.R. is Costa Rica. The abbreviations are: in El Salvador, Iz for Izalco, C for Conchagua, M for Meanguera; in Nicaragua, R for Rota, M for Maderas; in Costa Rica, T for Turrialba. The stippled areas show approximate extents of the BVF volcanic fields with high-Ti character.

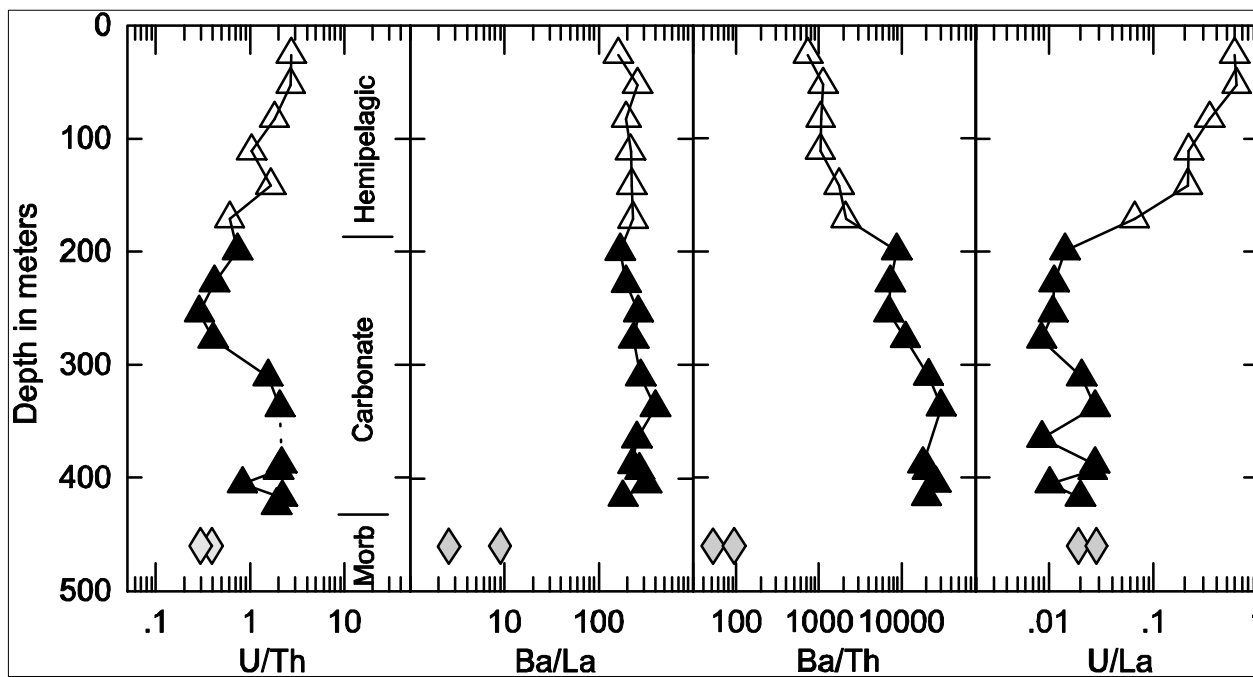


Figure 3. Geochemistry of DSDP 495 section. Stippled diamonds are EMORB and NMORB from *Sun and McDonough* [1989]. Filled triangles are carbonate sediments. Open triangles are hemipelagic sediments.

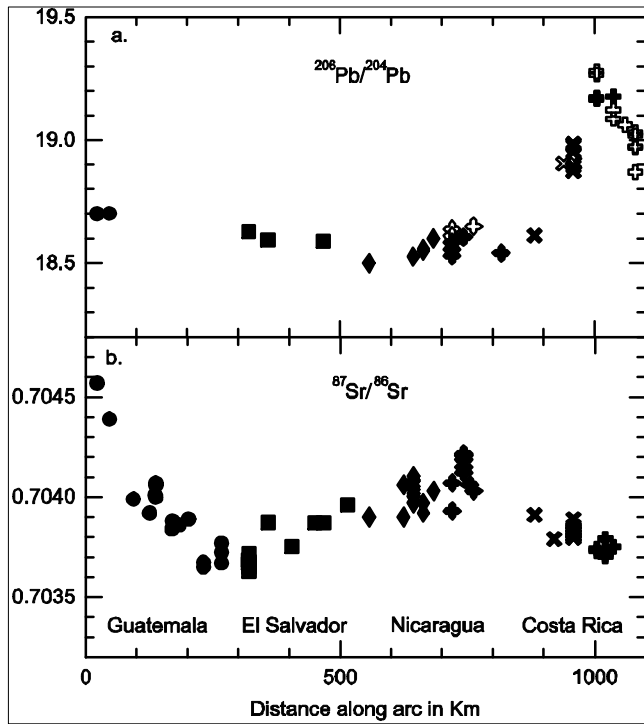


Figure 4. Crustal and mantle variations along the strike of the Central American volcanic front.

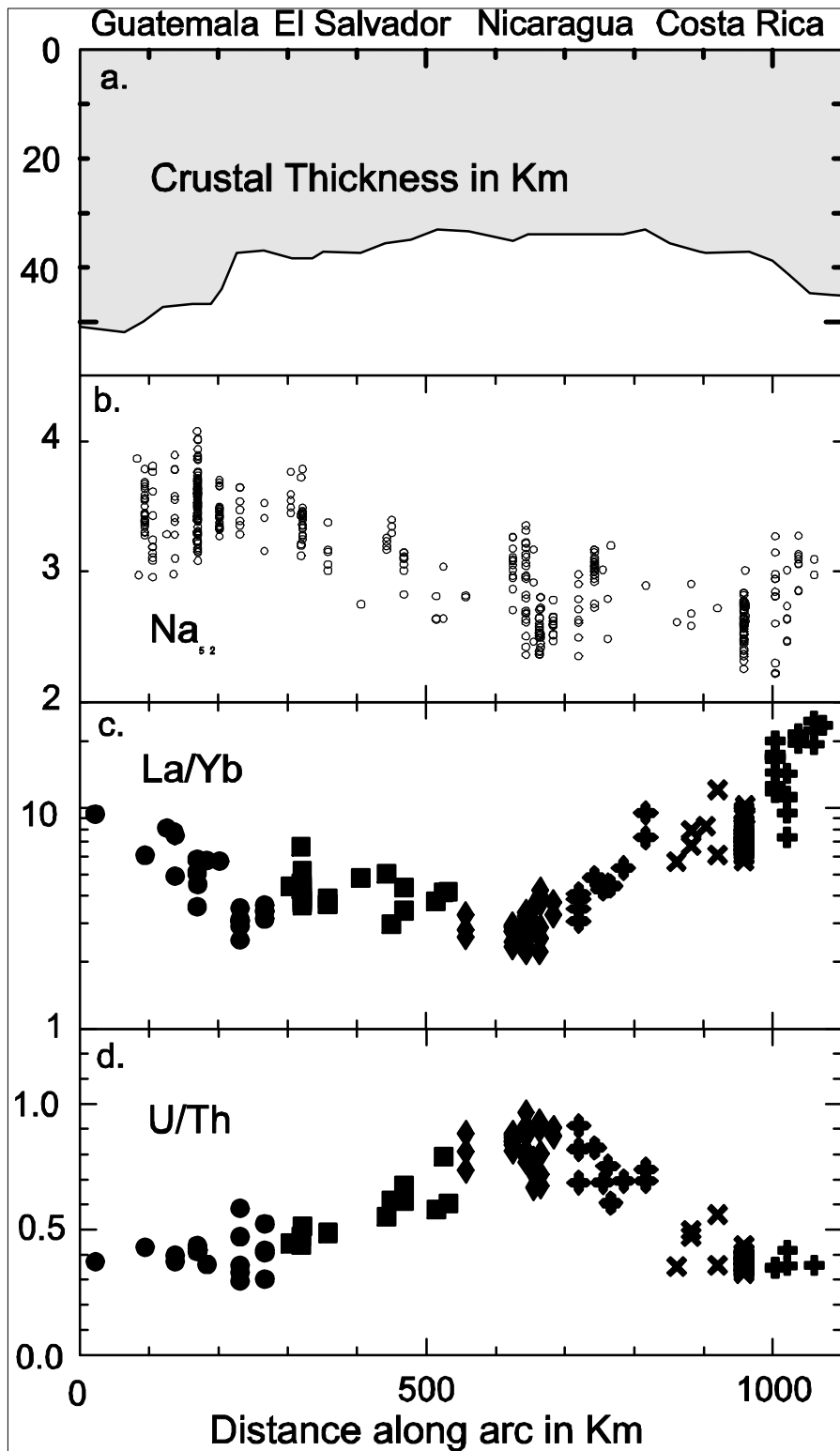


Figure 5. Regional variation in crustal thickness, Na_{52} , U/Th and La/Yb. Na_{52} is Na_2O content of lavas with SiO_2 contents between 48 and 55, corrected to 52% SiO_2 via $Na_{52} = Na_2O - (SiO_2 - 52) \cdot 0.14$.

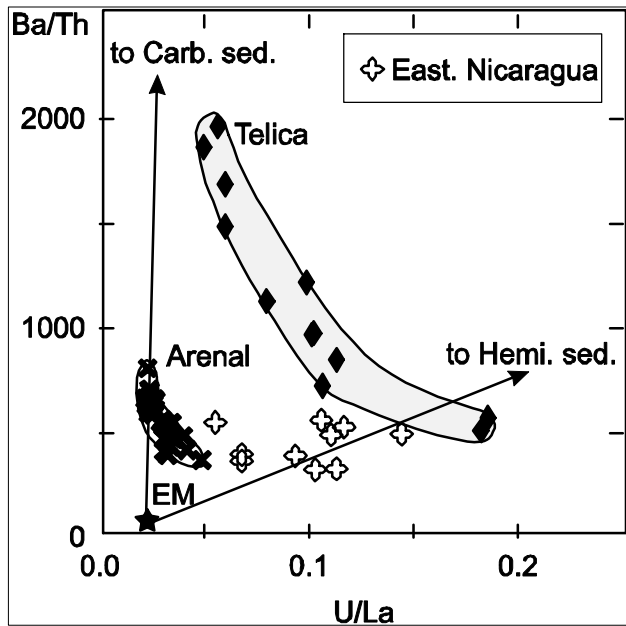


Figure 6. Intravolcano variation at Arenal and Telica volcanoes. Balloons enclose low-Ti lavas at Arenal and Telica volcanoes, which define arrays, called the local variation by *Patino et al.* (2000). The open symbols are low-Ti lavas from eastern Nicaragua, where no local variation is present. The eastern Nicaragua array extends from near the mantle (EM) to progressively closer to the sediment array that is parallel to the Telica array but well outside the diagram. The arrows point toward the locations of the ends of the sediment array.

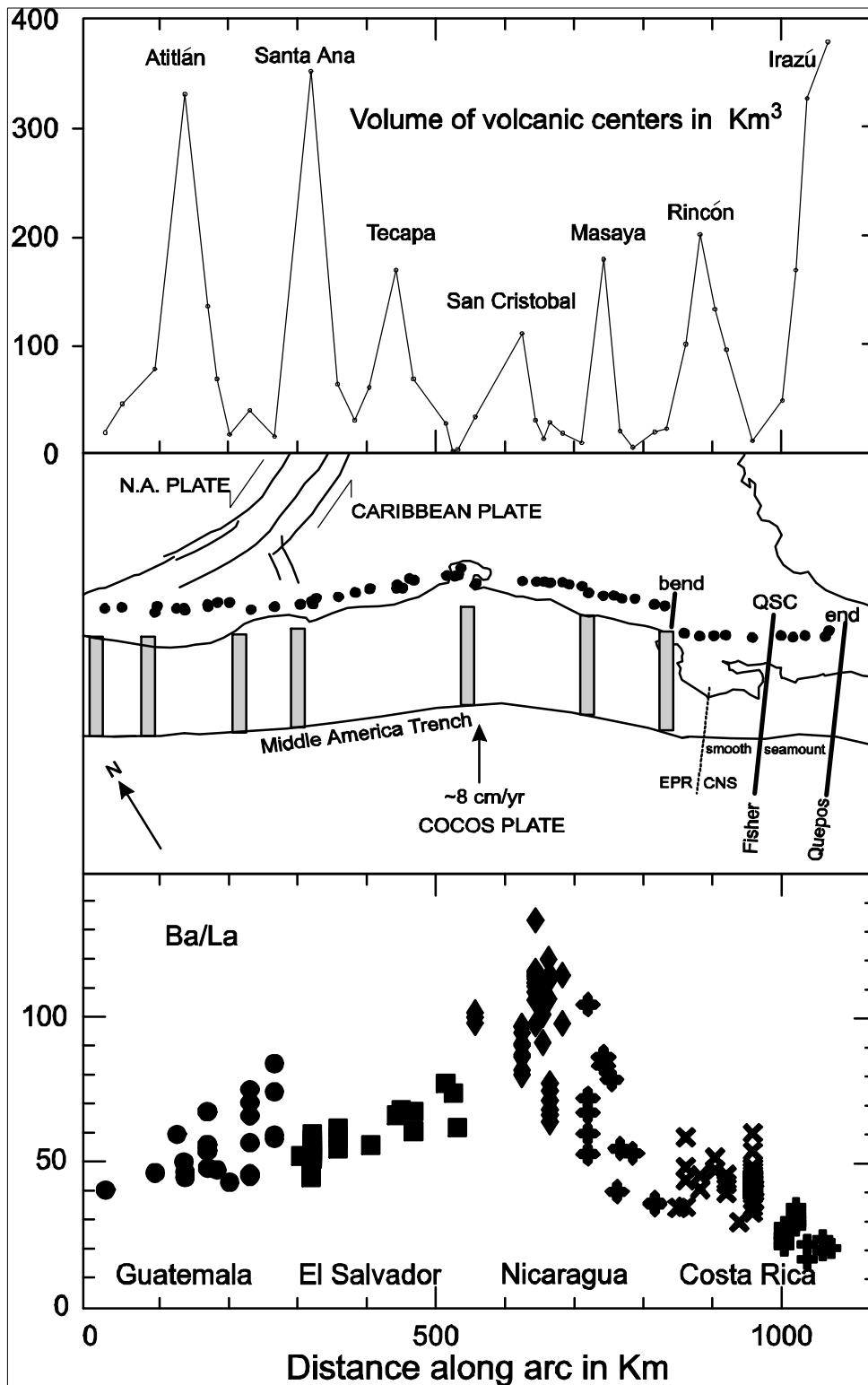


Figure 7. Segmentation of the volcanic front. Panel 7a shows the volumes of the 39 Central America volcanic centers. Panel 7b shows the plate boundaries, the volcanic front (circles), boundaries of volcanic segments (stippled bars) and structural boundaries in the Cocos Plate [von Huene *et al.*, 2000] and inclined seismic zone; bend, QSC, and end [Pratti *et al.*, 1995].