Contrib Mineral Petrol (2000) 138: 265–283

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Local and regional variations in Central American arc lavas controlled by variations in subducted sediment input

Received: 7 September 1998 / Accepted: 30 September 1999

Abstract The sedimentary section (at DSDP Site 495) on the subducting Cocos Plate has large stratigraphic changes in incompatible elements and element ratios, the result of early carbonate deposition followed by late hemipelagic deposition. Lavas from Central America define both local and regional geochemical trends that reflect the strong influence of the two Cocos Plate sediment units. Element ratios with large stratigraphic variations on the Cocos Plate (e.g. Ba/Th, U/La) define local variations within individual volcanic centers in Central America, indicating that marine stratigraphy controls some geochemical characteristics of the lavas. These local trends can be explained by changing the proportions of hemipelagic sediment input into the magma generation process. These local trends are observed in all the segments of the arc, regardless of the intensity of the slab signature. Regional variations are most clearly seen in element ratios that are nearly constant through the Cocos Plate sediment stratigraphy (e.g. Ba/La, U/Th), suggesting that regional variations reflect differences in the intensity of the flux from the subducting slab. The slab signal is strongest in Nicaragua and along the volcanic front. The signal decreases to the northwest and southeast of Nicaragua and toward the back arc. The large slab signature in the lavas from western Nicaragua occurs in the area with the thinnest continental crust and steepest dip of the slab. The mass flux of incompatible elements into the system is easily estimated, except for elements, like Pb, that have high and variable abundances in the basaltic oceanic crust section. The mass flux of elements out of the system depends on eruption rates, which are variable along the arc and only approximately known. Comparison of input and output fluxes for five different segments of the arc reveals that some elements (K, B, Cs, and Rb) are very efficiently delivered to the volcanoes from the subducted slab. Other elements (Sr, Ba, and U) are returned to the surface with moderate efficiency, whereas some elements (REEs) may come mostly from the mantle wedge with minor slab contribution. The relative order of recycling efficiencies of incompatible elements implies that a hydrous fluid dominates the transfer of material from the slab to mantle.

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Editorial responsibility: A. Hofmann

Supplementary material Table 1e has been deposited in electronic form and can be obtained from http://link.springer.de/link/service/journals/00410

Introduction

Subducted lithosphere contributes material to the mantle, modifies the thermal structure of the mantle wedge, and induces melting (Peacock 1991). Igneous rocks associated with subduction zones are commonly enriched in large ion lithophile elements (LILE) relative to light rare earth elements (LREE) and high field strength elements (HFSE) (e.g., Arculus 1994). Arc lavas have different systematics for several isotopic systems, e.g., ^{10}Be, ^{87}Sr/^{86}Sr, δ^{11}B, Pb isotopes, and the U–Th disequilibrium series (e.g., Morris 1991; Condomines and Sigmarsson 1993; Ishikawa and Nakamura 1994; Hawkesworth et al. 1997). However, only a very small percentage of the mass of the subducted oceanic crust contributes to the generation of arc magmas; most returns to the mantle.

It is generally accepted that subducting slabs contribute to arc magmatism (e.g., Morris 1991; Plank and Langmuir 1993). The problem now is to determine the contributions from different components of the subducting slab (Gill et al. 1993; Ishikawa and Tera 1997) and to understand the processes that transfer material (Maury et al. 1992; Schiano et al. 1995). In this paper we examine the components of the Central American subduction system to understand the interactions between the slab and the mantle wedge that generate arc lavas. First, we define the geochemical stratigraphy of sediments on the subducting Cocos Plate. Second, we define the local and regional variations in the composition of arc lavas. Finally, we examine slab–mantle interaction by calculating the mass fluxes into and out of the arc system.

There are several factors that make the Central American volcanic arc a good candidate to gain insight into slab–mantle interactions. First, the sediments on the Cocos Plate subducting underneath the Caribbean Plate are dominated by biological material, with sparse layers of detrital material derived from the volcanoes themselves. Second, the arc is divided into eight structural segments with variable geological and geophysical characteristics. Furthermore, the northern half of the arc, El Salvador and Guatemala, has abundant back-arc volcanism; thus, transects across the arc allow the tracing of geochemical parameters that vary with increasing distance behind the volcanic front. These important features of the Central American volcanic arc can help constrain the element flux through an arc system.

Tectonic setting of Central America

The Central American volcanic arc results from the subduction of the Cocos Plate beneath the Caribbean Plate (Fig. 1), and, as in many arcs, there are two regions of magmatism, the volcanic front and back-arc volcanism. The present volcanic front consists of eight distinct segments of stratovolcanoes (Carr and Stoiber 1990). Back-arc volcanic fields coincide with breaks between some of the linear volcanic front segments (Carr and Stoiber 1977). The characteristics of volcanic front lavas were summarized by Carr et al. (1990); back-arc lavas by Walker et al. (1995) and Patino et al. (1997).

The continental crust of southern Central America is relatively young and thin, compared to the crust of other continental margins, making it less radiogenic (Carr 1984; Donnelly et al. 1990). Thus, crustal assimilation does not cause drastic changes in the isotopic and geochemical characteristics of the lavas. In northwest Guatemala, where the crust is thick and where Paleozoic rocks outcrop, the Sr, Nd, and Pb isotopes are modified by crustal assimilation (Carr et al. 1990; Walker et al. 1995). Lavas from the volcanic front in southeast Guatemala, El Salvador, Nicaragua, and northern Costa Rica do not show obvious isotopic evidence of crustal assimilation. The crust in these regions is both thinner and younger than in northwest Guatemala (Carr 1984).

The dip of the subducting slab underneath the volcanoes changes along the arc, with the steepest dip beneath Nicaragua and the shallowest dip beneath central Costa Rica (Protti et al. 1995). The NUVEL-1 convergence rate varies only from 70 mm/year in Guatemala to 90 mm/yr in Costa Rica (DeMets et al. 1990). Davies and Stevenson (1992) show that geophysical parameters such as crustal thickness, angle of subduction, and convergence rate contribute to the thermal structure of the subduction zone, which is a major control on the generation of the magmas. Therefore, magma generation along Central America occurs under a range of different thermal structures because of variation in crustal structure and slab dip.

Analytical methods

The major and minor elements of the volcanics from Central America are taken from Carr et al. (1990). Major, minor, and some trace elements for some of the sediments from Deep Sea Drilling Project (DSDP) Site 495 were analyzed by DCP–AES following Feigenson and Carr (1985). The major elements for other sediments are from T.W. Donnelly (personal communication with M.J. Carr 1990). Trace elements (Rb, Nb, Y, Cs, Pb, Th, and U) and rare earth elements (REE) for the lavas and sediments were analyzed by inductively coupled plasma mass spectrometry (ICP–MS), using a VG Plasma Quad II Plus ICP–MS following Patino et al. (1997). The high Ba content (up to 7000 ppm) of the sediments facilitated the formation of large amounts of BaO (mass/charge ratio 151 and 153) in the ICP–MS, inhibiting the accurate determination of Eu. Strontium and neodymium isotopes were analyzed in a VG Sector thermal ionization mass spectrometer. Sr and Nd isotope ratios are reported as measured, and normalized to $^{86}Sr/^{88}Sr$ of 0.1194 for Sr and $^{146}Nd/^{144}Nd$ of 0.7219 for Nd. NBS 987 Sr standard is

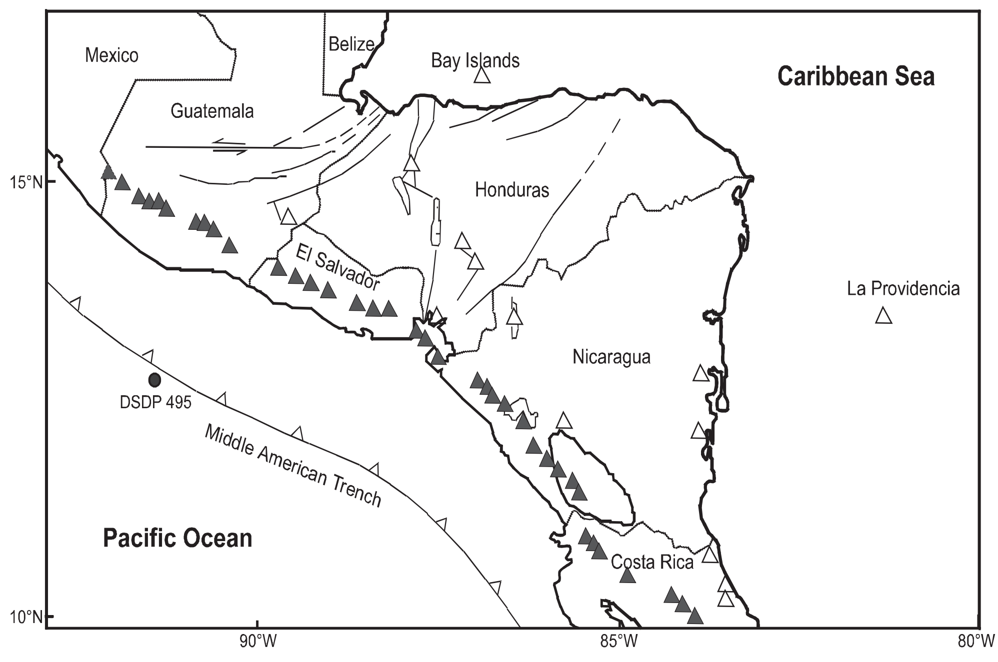


Fig. 1 Map of Central America. *Filled triangles* represent the volcanic front. Back-arc volcanic fields are represented by *open triangles*. The location of DSDP Site 495, off the coast of Guatemala, is also indicated

measured at 0.710255, and La Jolla Nd standard is measured at 0.511851 (both long-term averages). External reproducibility, based on repeated analyses of standards, is estimated at better than ± 0.000024 (2σ error) for both Sr and Nd isotopes.

Due to space considerations Tables 1 and 2 lists the chemical composition of selected lavas from Central America as well as the mean geochemical composition of the hemipelagic and carbonate sediments from DSDP Site 495. The complete chemical data set has been archived at the Internet site for *Contributions to Mineralogy and Petrology* as electronic supplementary material (http://link.springer.de).

Input: signatures of the slab and mantle wedge

DSDP leg 69, off the coast of Guatemala, and leg 170, off the coast of Costa Rica, sampled sediments on the subducting Cocos Plate adjacent to the Middle American Trench (Coulbourn et al. 1982; J. Morris, personal communication 1997). Both areas have very similar sedimentary sequences and lack extensive accretionary prisms. Thus, the subducting sedimentary contribution to the magma generation process should be very uniform from Guatemala through northern Costa Rica.

Sediments from DSDP Site 495

DSDP Site 495 (Fig. 1) is located on a horst 22 km seaward from the Middle American Trench. The sediment column overlying the basaltic oceanic crust is 428 m thick (Coulbourn et al. 1982). The upper part of the column (177 m) consists of Quaternary to upper Miocene hemipelagic diatomaceous mud and middle Miocene brown abyssal clay (Fig. 2); the lower part consists of middle–lower Miocene chalky carbonate ooze and manganiferous chalk and chert (Fig. 2; von Huene et al. 1982).

The geochemical characteristics of the two major sedimentary units from DSDP Site 495 (hemipelagic and carbonate oozes) reflect their markedly different lithologies (Fig. 2). The geochemistry is mainly controlled by the following components: carbonate-rich biogenic sediments, detrital material, and organic matter. The mean composition from each sedimentary unit is reported in Table 2. These results agree well with those reported by Plank and Langmuir (1998), with the only difference being that Plank and Langmuir adjusted the composition of the sediments from the lower section for the carbonate contribution. The biogenic sediments include carbonate and siliceous material with high concentrations of Ba and Sr, and low contents of Th, REE, Rb, and Cs (Fig. 2). Detrital material increases with decreasing age due to the motion of the Cocos Plate toward the Middle American Trench. Adding detrital material (aluminosilicates and volcanic ashes) increases the concentration of trace elements like Sc, Cs, Rb, and Th in the hemipelagic muds relative to the carbonate oozes (Fig. 2). The upper 100 m of DSDP Site 495 are enriched in organic carbon (up to 2.4%) and organic carbon decreases with increasing depth (Harrison et al. 1982). Uranium concentration follows the same pattern. The unusual enrichment of uranium over thorium in the younger hemipelagic sediments from DSDP Site 495 is most likely due to the reducing effect of the organic carbon in the rapidly buried sediments.

Altered oceanic crust (Site 504)

The basaltic oceanic crust plays an important role in the generation of arc-related lavas (e.g., Plank and Langmuir 1993; Ishikawa and Nakamura 1994; Turner et al. 1997). Much information exists on the nature of sedimentary sequences subducting along trenches (e.g., Plank and Langmuir 1998), but relatively little is known about the composition of the subducting basaltic oceanic crust. There are only major element data for the basaltic oceanic crust retrieved from DSDP Site 495, so we used the extensive data from Site 504, also in the eastern Pacific. The stratigraphy at Site 504 consists of three units: a volcanic section, a transition zone, and lower dikes (e.g., Alt et al. 1996). The upper volcanic section interacted with large volumes of seawater that circulated freely causing oxidation and alkali enrichment of the rocks. These basalts have higher K, Rb, B, CO_2, H_2O, $\delta^{18}O$, δD, $\delta^{11}B$, and $^{87}Sr/^{86}Sr$, and lower S and $\delta^{34}S$ relative to fresh MORBs (Ishikawa and Nakamura 1992; Alt et al. 1996). In addition, Staudigel et al. (1995) indicate that the uranium concentrations of the upper altered oceanic crust are higher than those observed in MORBs. The middle section or transition zone consists of highly fractured, hydrothermally altered and brecciated pillow basalts and an upper dike sequence. This zone is heavily mineralized and enriched in chalcophile elements (e.g., Pb, Cu, Zn; Alt et al. 1996). The rocks from the lower dikes display hydrothermal alteration (Alt et al. 1996) in which hydrothermal fluids leached elements from the lower dikes and selectively transported them to the transition zone.

Constraints on the mantle in Central America

Feigenson and Carr (1993) used inverse modeling of rare earth elements (REE) from mafic lavas from Central America to infer the ratio of garnet to clinopyroxene in the mantle source. In this arc, it seems appropriate to use the REE to infer the mantle source because there is evidence of only a minor contribution from the slab. The biogenic nature of the sediments makes them poor in REE relative to terrigenous sediments (Taylor and McLennan 1985), there is a weak correlation between $^{10}Be/^{9}Be$ and La/Be ($r' = 0.54$), and the regional REE patterns are not what is expected if these elements were readily mobilized from the slab. Lavas from Guatemala, El Salvador, northern Costa Rica, and back-arc regions are more enriched in LREE than the lavas from Nicaragua, where the largest slab signature is consistently observed (detailed discussion in a later section of the

Table 1 Geochemical data set. Selected lavas from Central America. Distance indicates the distance (in km) along the arc from the Guatemala–Mexico border. Boron concentrations for Te114, Za2, Za7, and C118 (*italics*) are preliminary data

Sample	Gu TA-4 C	Gu AT-50	Gu E1	Gu T102	Gu M4	Sal SA22	Sal IZ108	Sal B-21	Sal SM-7	Hon ZA2	Hon ZA4B	Hon ZA7	Nic COS9 A	Nic TE1
SiO_2	58.31	51.69	51.40	54.10	56.90	54.40	52.60	59.00	51.10	53.23	52.10	51.83	58.90	52.60
TiO_2	0.76	1.03	1.15	0.83	0.72	0.87	0.81	1.14	0.97	0.87	0.95	0.88	0.71	0.80
Al_2O_3	18.90	19.37	19.85	19.00	18.80	18.30	19.60	14.80	19.70	18.23	19.12	19.53	18.50	17.70
FeO	6.94	9.55	8.90	5.51	3.20	7.26	7.16	7.09	6.57	8.51	9.02	9.17	7.13	9.80
MnO	0.15	0.13	0.16	0.18	0.12	0.16	0.15	0.22	0.18	0.17	0.17	0.18	0.16	0.18
MgO	2.08	4.56	3.50	4.82	2.58	3.75	4.31	2.05	3.38	5.44	4.97	3.63	2.20	4.47
CaO	7.34	9.28	9.89	9.42	7.70	8.50	9.49	5.54	10.31	8.88	9.22	9.71	7.60	9.90
Na_2O	3.12	3.24	3.57	3.47	3.90	3.51	3.54	4.42	2.93	3.34	3.16	3.18	3.88	2.77
K_2O	1.91	0.89	0.84	0.61	0.93	1.53	0.94	2.23	0.87	1.18	0.84	0.62	1.27	1.34
P_2O_5	0.23	0.22	0.27	0.15	0.14	0.27	0.14	0.40	0.23	0.32	0.29	0.19	0.22	0.18
Sc	12.86	23.25	24.55	29.15	20.22	23.14	25.16	28.60	33.20	25.78	24.81	30.58	23.11	29.44
V	125.10	226.80	266.50	234.60	191.40	225.40	276.30	106.10	302.80	214.40	257.50	290.90	160.90	301.70
Cr	2.33	101.10	22.69	35.19	4.52	7.62	11.74	0.81	14.37	104.80	39.77	16.81	10.72	14.99
Ni	2.77	40.97	16.09	21.08	9.17	12.65	15.74	4.25	12.52	78.94	54.64	58.98	11.87	15.89
Cu	12.18	66.88	83.38	58.15	55.86	129.80	114.40	64.24	212.60	101.20	340.50	131.70	89.28	178.70
Rb	43.00	19.20	13.53	7.40	16.40	41.00	21.80	52.95	15.50	18.70	9.16	9.08	23.30	28.80
Sr	568.90	589.50	622.90	435.90	443.40	502.20	491.40	347.50	523.50	514.50	547.20	534.30	446.30	469.30
Ba	678.40	474.40	442.30	335.50	525.30	575.60	409.60	931.00	526.30	624.90	682.00	484.20	879.30	817.70
Y	23.12	16.73	22.94	18.72	22.01	26.94	19.46	59.11	23.96	24.50	26.80	26.50	30.43	24.07
Zr	127.60	117.50	96.80	82.94	97.34	144.50	71.12	212.30	81.69	107.20	81.44	49.38	108.70	93.07
Nb	3.00	1.80	5.16	2.60	2.00	3.20	2.90	8.94	2.60	14.30	5.19	2.92	9.50	2.40
B	nd	15.20	8.00	nd	nd	nd	18.80	37.00	20.00	*11.34*	nd	*12.56*	46.00	36.00
Be	1.27	0.91	0.50	0.65	0.79	1.15	0.46	1.27	0.49	nd	nd	nd	0.46	0.39
La	16.56	10.48	10.15	4.44	6.21	12.74	6.78	16.87	8.61	14.34	11.50	7.76	8.61	7.02
Ce	36.07	24.72	24.75	12.89	16.58	30.45	16.65	42.24	20.93	28.78	24.75	14.80	21.86	17.72
Nd	18.94	15.54	15.47	10.52	10.33	19.19	10.31	27.98	14.60	17.19	16.81	12.38	15.01	11.97
Sm	4.39	3.12	3.60	2.41	2.44	4.61	3.32	7.13	3.98	3.82	3.90	3.19	4.50	2.64
Eu	1.17	0.99	1.23	0.85	0.85	1.19	0.95	1.84	1.15	1.32	1.38	1.25	1.20	0.92
Gd	4.00	3.45	4.16	3.00	3.39	4.75	3.19	8.33	4.55	4.09	4.24	3.72	5.25	3.83
Dy	3.99	3.12	3.91	3.46	3.85	4.56	3.38	8.37	4.66	3.61	3.66	3.47	5.56	3.73
Er	2.18	1.49	2.17	1.80	1.91	2.50	1.94	5.22	2.52	2.23	2.26	2.20	2.94	2.41
Yb	1.77	1.40	1.77	1.44	1.71	1.91	1.60	4.32	1.98	2.19	2.17	2.02	2.63	2.41
Cs	1.83	0.75	0.58	0.27	0.83	2.20	1.05	2.21	0.63	0.39	0.20	0.27	1.54	1.33
Pb	12.28	7.77	5.51	2.90	4.12	6.70	5.75	8.75	3.34	4.44	2.98	3.07	5.32	4.46
Th	3.24	1.09	1.47	0.36	0.87	3.45	1.57	3.27	0.71	1.52	0.71	0.49	1.34	1.43
U	1.21	0.41	0.58	0.21	0.46	1.63	0.81	1.58	0.44	0.53	0.34	0.36	1.18	1.30
$^{87}Sr/^{86}Sr$	0.70457	0.704	0.70389	0.70365	0.70367	nd	0.70365	0.70385	0.70387	0.7037	0.70386	0.70382	0.7039	0.70402
$^{143}Nd/^{144}Nd$	0.51268	0.51283	0.51293	0.51298	0.51304	nd	0.51301	nd	nd	0.51296	0.51297	0.51299	0.51311	0.51309
Latitude (N)	15.13	14.58	14.38	14.15	14.03	13.85	13.82	13.73	13.43	13.352	13.313	13.316	12.98	12.60
Longitude (W)	92.11	91.18	90.60	90.42	90.10	89.63	89.63	89.28	88.27	87.606	87.586	87.617	87.57	86.85
Distance	22.30	137.10	201.60	231.00	266.50	319.40	321.20	358.00	467.80	545.00	545.00	545.00	556.90	644.00

paper). Ryan et al. (1995) indicate that elements that increase with increasing depth to the Benioff zone would have a uniform or small contribution from the slab accompanied by lower degrees of melting. In transects along and across the Central American arc, we observe increases in the light to heavy REE ratios with increasing distance to the northwest and southeast of Nicaragua and away from the volcanic front. Such geographical distributions can be interpreted as decreases in degree of melting. Furthermore, any REE contribution from the slab to the magma would be very small because of the low distribution coefficient of the REE in fluids (Brenan et al. 1995a, b).

Feigenson and Carr (1993) propose two types of mantle underneath Central America. One mantle reservoir has a composition similar to the source of depleted mid-ocean ridge basalts. The other mantle type is less abundant and has a more enriched composition. The mantle beneath Central America was envisioned as a veined mixture of these two sources. The main difference between the different regions of the arc is the degree of melting of the mantle source. As Carr et al. (1990) proposed, the degree of melting is higher in Nicaragua and it decreases to the northwest and southeast, correlating with changes in the dip of the subducting slab.

The mantle beneath central Costa Rica was most distinct, with the highest garnet to clinopyroxene ratio (Feigenson and Carr 1993). Recently, Feigenson et al. (1996) and Abratis and Wörner (1997) have shown that the $^{206}Pb/^{204}Pb$ ratios of lavas from central Costa Rica are higher (>18.8) than the rest of the arc, pointing toward a HIMU component. Feigenson et al. (1996) and

Nic TE114	Nic CN1	Nic MT101	Nic MS4	Nic GR101	Nic C922	CR RV1	CR TE9	CR AR82	Sal C502	Gu C1004b	Gu C1001	Hon C112	Hon C114	Hon C118
51.34	50.80	54.40	50.90	46.90	58.75	56.59	53.56	54.64	51.70	52.65	53.30	51.07	54.46	53.54
0.87	0.77	0.73	1.14	0.55	0.71	0.69	0.77	0.61	1.29	1.33	1.10	0.99	1.21	0.87
20.45	19.50	16.90	14.80	15.90	16.58	16.90	18.97	19.04	17.40	18.50	20.20	17.98	16.77	17.38
9.31	9.70	9.10	11.90	10.03	8.00	7.13	8.78	7.19	7.40	nd	nd	9.18	9.18	8.68
0.20	0.18	0.18	0.23	0.18	0.17	0.16	0.17	0.15	0.16	0.17	0.15	0.19	0.17	0.20
3.78	4.73	4.47	5.26	8.72	3.72	4.46	4.75	4.76	5.73	4.91	3.73	5.17	3.27	5.98
10.37	11.50	9.20	9.90	14.40	7.11	8.29	9.02	9.04	9.40	8.59	8.94	8.76	7.40	9.38
3.09	2.20	2.89	2.82	1.46	3.17	3.01	2.94	3.08	3.61	3.66	3.47	3.11	3.31	2.72
0.66	0.46	0.91	1.16	0.30	1.70	1.37	0.76	0.64	1.15	1.00	1.14	1.26	1.65	2.05
0.16	0.12	0.15	0.27	0.11	0.23	0.18	0.16	0.17	0.36	0.26	0.22	0.33	0.33	0.34
22.47	31.69	29.69	38.42	49.67	23.51	25.83	32.06	22.75	0.00	24.85	24.72	29.36	27.98	29.10
249.70	332.30	304.80	439.90	335.90	237.00	216.00	275.30	190.50	191.00	235.15	232.30	250.00	254.90	252.20
4.26	21.18	14.69	46.94	173.30	20.40	65.78	20.28	47.97	182.00	22.58	11.53	91.58	13.92	124.90
3.15	17.81	13.58	31.18	52.82	18.60	23.50	15.57	41.69	60.00	5.70	1.76	45.10	17.17	57.87
175.70	162.90	127.80	258.60	145.90	84.40	115.40	93.13	106.30	0.00	34.43	23.09	82.79	10.15	74.44
7.73	7.90	15.90	22.10	6.10	51.34	24.80	9.60	10.10	15.00	14.58	31.66	21.90	42.20	54.10
736.00	480.80	480.10	433.20	472.10	589.10	554.60	530.30	748.40	580.00	619.90	592.73	587.90	550.20	659.70
546.70	406.60	693.30	893.20	211.60	990.30	752.90	515.10	577.70	426.00	508.36	496.27	912.40	877.50	942.30
23.18	16.63	22.64	25.86	14.95	44.16	27.66	27.81	15.52	32.03	27.35	29.88	54.20	71.90	53.90
41.39	47.85	77.58	105.10	44.80	119.80	109.60	67.75	61.75	nd	138.35	114.33	123.80	134.60	119.40
2.44	2.40	3.30	2.90	2.70	30.06	1.60	3.40	4.60	nd	5.92	5.71	6.66	9.70	3.89
17.72	13.30	25.00	24.50	4.80	14.40	12.00	5.30	11.50	nd	nd	nd	nd	nd	*9.20*
nd	0.33	0.39	0.74	0.50	1.59	0.99	0.80	0.63	nd	nd	nd	nd	nd	nd
5.14	3.60	6.03	10.32	5.24	nd	18.28	11.19	13.16	17.47	14.21	11.48	34.47	41.22	24.50
11.70	9.15	14.77	23.67	11.82	nd	37.31	22.30	26.63	40.90	31.06	26.11	75.77	76.51	40.31
10.91	7.10	10.08	16.87	7.83	nd	21.60	17.13	13.13	24.18	20.14	16.70	43.98	48.74	27.92
3.06	1.95	3.13	4.24	2.46	nd	4.99	4.08	2.88	5.42	4.62	4.01	9.67	10.57	6.24
1.21	0.77	0.94	1.29	0.74	nd	1.34	1.34	0.99	1.67	1.52	1.35	2.88	3.12	2.01
3.16	2.53	3.61	4.71	2.64	nd	5.00	4.66	2.97	5.60	4.98	4.23	10.04	11.24	7.33
3.38	2.95	3.86	4.93	2.85	nd	4.77	4.59	2.82	5.34	4.33	3.92	8.51	9.55	5.79
1.97	1.73	2.22	2.57	1.39	nd	2.34	2.14	1.55	3.00	2.60	2.29	4.84	5.49	3.57
1.98	1.62	1.84	2.14	1.18	nd	2.32	1.83	1.49	2.67	2.32	2.16	4.49	4.79	2.89
0.34	0.49	0.69	0.87	0.13	0.95	0.73	0.35	0.17	nd	0.47	nd	0.69	1.17	0.77
7.36	2.90	4.50	4.82	1.37	5.84	5.67	2.39	4.31	nd	7.43	7.67	6.14	9.03	6.66
0.29	0.41	0.81	1.81	0.39	3.68	2.51	1.02	0.94	nd	1.35	2.27	1.46	3.50	2.07
0.26	0.38	0.73	1.49	0.29	2.35	1.25	0.57	0.35	nd	0.53	0.85	0.57	1.06	0.94
0.70391	0.70397	0.70405	0.70419	0.70403	0	0.70391	0.70379	0.70389	nd	nd	nd	0.70396	0.70451	0.70408
nd	0.51311	nd	nd	0.51307	nd	0.51304	0.51302	0.51302	nd	nd	nd	0.51292	0.5128	0.51289
12.60	12.50	12.42	11.98	11.88	11.53	10.83	10.67	10.47	nd	nd	nd	14.076	14.163	14.077
86.85	86.70	86.53	86.15	86.00	85.62	85.33	85.02	84.73	nd	nd	nd	87.24	87.325	87.311
644.00	663.30	683.30	742.70	762.20	816.90	882.30	920.40	958.30	nd	nd	nd	500.00	500.00	500.00

Abratis and Wörner (1997) suggest that this HIMU component represents remnants of the Galapagos hot spot. Due to the clear involvement of a distinct mantle component in central Costa Rica, the samples from this section of the arc will be excluded from the following discussion.

Output: incompatible element variations in Central America lavas

Identifying sediment signatures

Given the drastically different lithologies of the two sedimentary units on the Cocos Plate, it is possible to select some trace element ratios that reflect the contribution of each unit and other ratios that reflect the total sediment input to the magma generation process. Ratios of incompatible elements should change very little over the range of mantle melting (5–25%) proposed for Central America (Carr et al. 1990; Leeman et al. 1994). Subsequent modification of the magmas by assimilation–fractional crystallization processes will have little effect on any ratios except those involving Sr. However, incompatible element ratios are greatly affected by processes acting directly on the subducting slab, e.g., selective element transport by a fluid or sediment accretion prior to deep subduction.

The first criterion used to define useful trace element ratios was to identify the incompatible elements with the largest difference between the two sedimentary units. In the carbonate section most incompatible elements are either in low concentration or do not vary with depth (Fig. 2). Within the hemipelagic section, there are some

Table 2 Geochemical data set. Mean composition of hemipelagic sediments (*HS*) and carbonate sediments (*CS*) from DSDP Site 495, altered oceanic crust, and EMORB. The composition for the altered oceanic crust (*AOC*), upper and lower sections (*UAOC* and *LAOC*, respectively) is taken from Alt et al. (1996) and references therein. The EMORB composition is taken from Sun and McDonough (1989). Non-determined values (*nd*)

Sample	Mean HS	Mean CS	UAOC	LAOC	EMORB
SiO_2	55.78	7.39			
TiO_2	0.58	0.02	1.00	1.00	1.00
Al_2O_3	11.82	0.37			
FeO	6.25	1.97			
MnO	0.14	0.29			
MgO	2.20	0.73			
CaO	2.70	49.90			
Na_2O	2.08	0.24			
K_2O	1.84	0.18	0.20	0.02	0.25
P_2O_5	0.12	0.13			
Sc	17.07	2.63			
V	147.02	49.47			
Cr	44.85	15.52			
Ni	204.52	27.27			
Cu	262.89	76.11	150.00	50.00	50.00
Rb	40.78	4.28	3.85	0.20	5.04
Sr	336.16	1504.12	68.00	55.00	155.00
Ba	3941.49	2145.48	33.00	12.00	57.00
Y	31.06	17.69	22.00	22.00	22.00
Nb	5.03	0.44	0.55	0.90	8.30
B	nd	nd	5.00	0.60	0.60
Be	nd	nd	0.45	0.45	0.45
La	17.96	8.78	4.50	1.20	6.30
Ce	28.05	2.40	11.00	3.50	15.00
Nd	17.77	6.79	8.00	7.00	9.00
Sm	4.05	1.45	2.60	2.60	2.60
Eu	nd	nd	0.91	0.91	0.91
Gd	4.13	1.65	2.97	2.97	2.97
Dy	4.72	1.99	3.55	3.55	3.55
Er	3.19	1.40	2.31	2.31	2.31
Yb	2.78	1.18	2.50	2.10	2.37
Cs	2.17	0.15	0.06	0.01	0.06
Pb	9.59	3.70	2.50	5.00	0.60
Th	3.00	0.16	0.50	0.80	0.60
U	4.89	0.15	0.10	0.05	0.18
$^{87}Sr/^{86}Sr$	0.70763	0.70858			
$^{143}Nd/^{144}Nd$	0.51274	0.512415			
Thickness (m)	200	200	500	1500	
Density (g/cm^3)	1.3	1.75	2.75	2.75	

strong gradients. Ba, La, Y, and Pb increase with depth, and U decreases. Th, K, Rb, Cs, and Sr do not vary with depth in the hemipelagic section (Fig. 2). In terms of mean values, Ba, La, Y, and Pb are only slightly higher in the hemipelagic section than in the carbonate section (a factor of 2 or less). In contrast, the mean values of U, Cs, Th, K, and Rb are much higher in the hemipelagic section, by a factor of 10 or more. Only Sr is higher in the carbonate section than the hemipelagic section. Arranging the elements in order of their overall hemipelagic/carbonate ratio (U, Cs, Th, K, Pb, La, Y, Ba, Sr), we see maximum differences by comparing element ratios from opposite sides of this spectrum (e.g., Ba/Th and U/La; Fig. 2).

One distinctive indicator of sediment input into magma genesis is $^{10}Be/^{9}Be$ (Tera et al. 1986). We compared several element ratios with $^{10}Be/^{9}Be$ in the lavas from Central America to see which ratios could be used as proxies. U/Th, Ba/La, and U/La all have significant positive correlations with the Be isotopic ratio ($r' > 0.8$). No ratio including Sr correlates with $^{10}Be/^{9}Be$ isotopic ratio, most probably because Sr is highly concentrated in the carbonates, where there is no ^{10}Be. K/Th, Pb/Th, and Ba/Th have weak or no correlation with Be isotopic ratio ($r' < 0.5$), and in each case the value of the ratios is similar in the hemipelagic sediments and in MORB or depleted mantle. Thus, the hemipelagic component is effectively hidden.

The final criterion for selecting ratios and especially pairs of ratios is separation; the potential magma components (mantle wedge, subducted MORB, carbonate sediments and hemipelagic sediments) should occupy separate fields in ratio/ratio plots. The mantle wedge and MORB components are likely to overlap for the highly incompatible elements. Therefore, we preferentially selected pairs of ratios where MORB + mantle, carbonate sediment and hemipelagic sediment define a triangle. Where two components are close to each other, as the two sediments are in Ba/La versus U/Th (Fig. 3a), the field of volcanic data collapses into an apparent binary mixing array between mantle and bulk sediment. The same four elements, expressed as U/La versus Ba/Th (Fig. 3c), clearly separate the two sediment components.

From the considerations above we selected several useful ratios. The ratios Ba/La, U/Th, Ba/Th, and U/La have in common that they are all soluble/insoluble element pairs, although Th is not nearly as insoluble as La (Brenan et al. 1995a). They differ in that Ba/La and U/Th are nearly constant down the DSDP Site 495 core whereas U/La and Ba/Th have strong and opposite gradients (Fig. 2). U/La ratio is higher in the hemipelagic sediments and Ba/Th is higher in the carbonate sediments. This difference results in very different ratio versus ratio plots (cf. Fig. 3a, c).

Local variations in lava compositions

Figure 3c shows local variations among the lavas from Central America. For each segment of the arc there are lavas with higher Ba/Th and lower U/La, and vice versa. Similar local variations are observed in all segments of the arc, in some back-arc regions in southeast Guatemala and Honduras, and even within one well-sampled volcano in western Nicaragua, Telica (Fig. 3d). The different segments of the arc define roughly parallel arrays at different distances from the MORB–mantle end. The lavas from western Nicaragua are furthest from MORB–mantle and those from the back arc in Guatemala and Honduras are closest to MORB–mantle (Fig. 3c). This regional variation in the intensity of the slab signal will be discussed below.

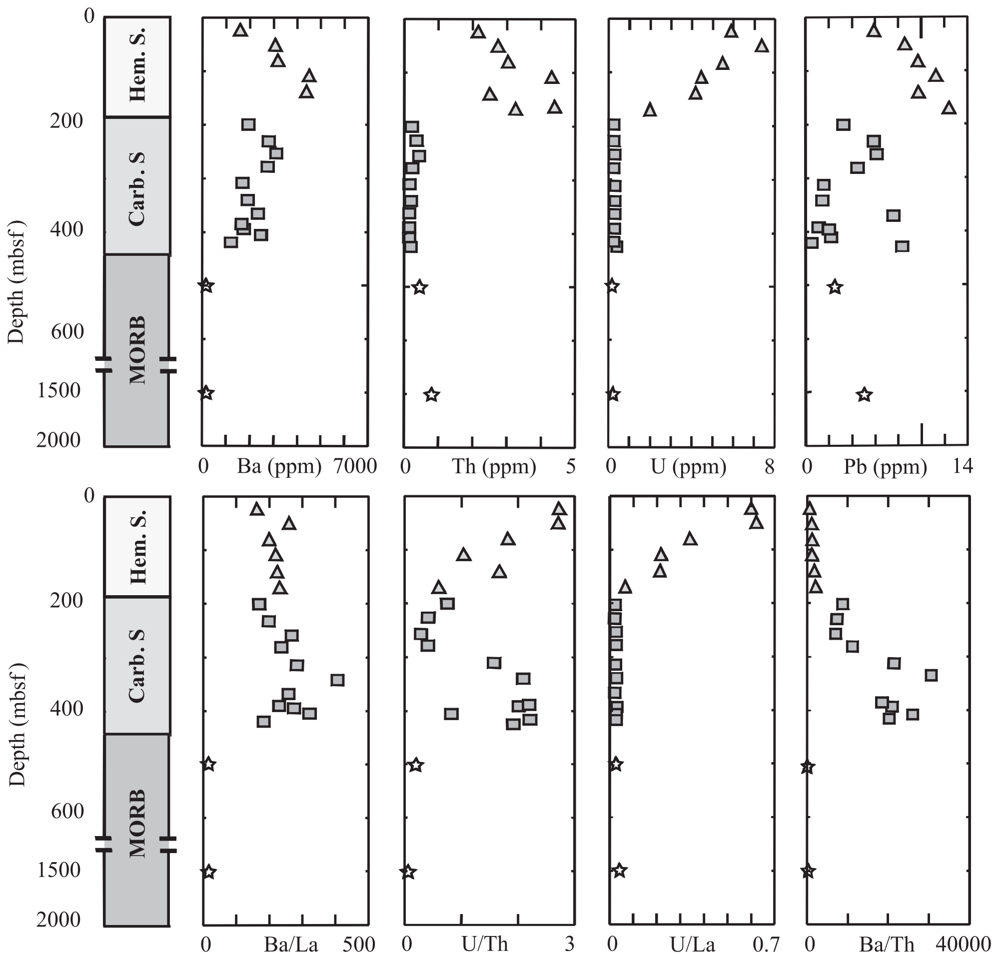


Fig. 2 Trace element variations at DSDP Site 495. Hemipelagic sediments (*triangles*) are enriched in U and Th relative to the carbonate sediments (*squares*) and the altered oceanic crust (*stars*). The mean value for Ba and Pb does not change significantly down the core. The lower section of the altered oceanic crust is enriched in Pb relative to the upper section of the basaltic oceanic crust. Ba/La and U/Th ratios are similar in both sedimentary units, whereas the carbonate sediments have higher Ba/Th and the hemipelagic sediments have higher U/La. These incompatible trace element ratios can be used to identify the sediment input to the arc magmas. These ratios are not affected by the input of basaltic oceanic crust or mantle. The altered oceanic crust has significantly lower ratios

In Telica, the most extensively sampled volcano in western Nicaragua, the local variations occurred progressively with time (Fig. 3d). The older lavas have higher Ba/Th and lower U/La ratios (sample Te114), and the younger lavas have higher U/La ratio and lower Ba/Th (sample Te1). Balzer et al. (1996) found differences between Quaternary lavas and Pliocene to older lavas in Nicaragua. The older rocks have lower U/Th for a given Ba/La ratio compared to the younger samples. Stratigraphic variations, at least within the Holocene, are not a common feature in other young Nicaraguan volcanoes or in other segments of the arc, such as southeast Guatemala (Carr, unpublished data).

Local variations shown in Fig. 3c define arrays that could be explained by changing the degree of melting or by binary mixing. This binary mixing is best defined by the clearly hyperbolic data array for Telica volcano (Fig. 4). We tested several melting models and found that melting of amphibole might explain the arrays in Fig. 3c. Increasing melting of an amphibole-rich component should decrease the Ba/Th ratio ($D_{Ba} = 0.12$, $D_{Th} = 0.017$; Brenan et al. 1995b). However the La/Yb ratio, a better indicator of degree of melting, shows no correlation with Ba/Th (Fig. 5a). Furthermore, in K/Ba versus Ba/Sr space ($D_K = 0.25$, $D_{Sr} = 0.28$; Brenan et al. 1995b), the melting trend for amphibole is at a high angle to the trend displayed by the lavas from Telica (Fig. 5b). Thus, there is not yet a plausible melting model to explain the local variation.

The ratios that best display the local variation (e.g., Ba/Th and U/La) have markedly different values for the carbonate and the hemipelagic sediments from DSDP Site 495 (Fig. 2). Therefore, the local geochemical variations in Central America appear to be first order manifestations of differing mixes of carbonate and hemipelagic sediment. The sediments cannot be added in bulk because many lavas are clearly outside the triangular area defined by bulk mixing lines between EM-ORB mantle-like and the two sediments (Fig. 3c). The lava arrays point to an end member with lower Ba/Th and higher U/La than bulk mixing allows. This end member can be approached by extracting a fluid from the hemipelagic sediments or by adding in a realistic component, a fluid extract from AOC.

Across-arc variations

Patino et al. (1997) showed that the slab contributes to magma generation for volcanoes in Honduras about

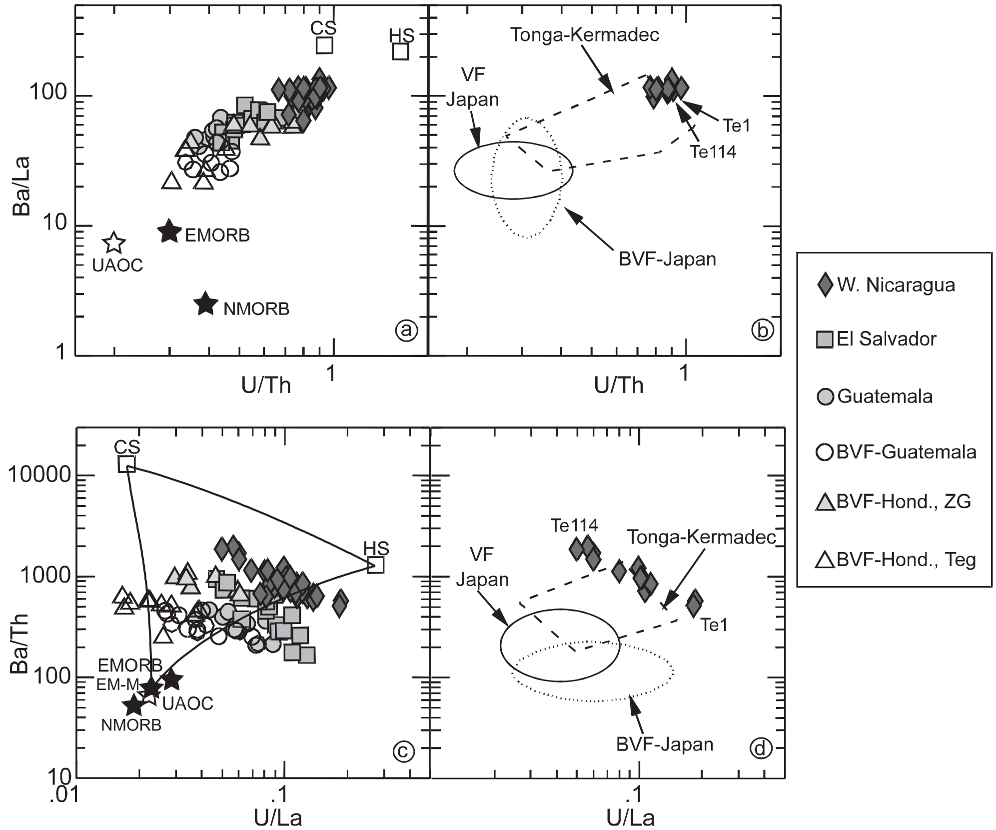


Fig. 3a–d Trace element ratios used to identify sediment input. **a** In the U/Th versus Ba/La space the carbonate sediments (*CS*) and the hemipelagic sediments (*HS*) plot close to each other and the arc lavas are distributed in a linear array, implying a binary mixture between the mantle and the sediments. The larger sediment contribution is observed in the samples from western Nicaragua and the smallest contribution in the back-arc lavas. **b** The lavas from Central America have a similar distribution to the lavas from the Tonga–Kermadec volcanic arc in the U/Th versus Ba/La space. **c** In the U/La versus Ba/Th space the two sedimentary units plot apart from each other and the lavas from the arc take on a different distribution. Local variations are produced by changing the ratio of carbonate to hemipelagic sediment in the slab component during magma genesis. With increasing hemipelagic sediment involvement, Ba/Th decreases and U/La increases. **d** The lavas from western Nicaragua display the highest Ba/Th ratio, and the samples from the back-arc regions of Central America are also enriched in Ba/Th compared with the other arcs. The back-arc samples from Honduras [**c** Zacate Grande (*ZG*) and Tegucigalpa (*Teg*)], have higher Ba/Th than the back-arc lavas from Japan (**d**)

100 km from the volcanic front. Zacate Grande, a volcanic complex just 17 km behind the volcanic front in Honduras, has some lavas with a strong slab signature, like that of the volcanic front (Fig. 6), and other lavas with limited slab signature and back-arc characteristics (Patino et al. 1997). A slab signature in back-arc volcanoes has been observed in other arcs, such as Taupo, the Kuriles, and Japan (Price et al. 1992; Ryan et al. 1995; Shibata and Nakamura 1997, respectively). These results are in contrast to those from Walker et al. (1995), who found the slab signature to be absent in monogenetic volcanoes just 20 km from the front in southeast Guatemala.

Ba/La and U/Th have been used as indicators of slab input, and, more specifically, sediment input to the generation of magmas from Central America (e.g., Carr et al. 1990; Balzer et al. 1996). The lavas from behind the volcanic front in Central America show lower Ba/La ratios than those from the volcanic front (Fig. 3a; Walker et al. 1995; Patino et al. 1997). However, the ratios in some samples from the back arc are similar (Fig. 3), if not higher, to ratios from volcanic front lavas in other arcs,

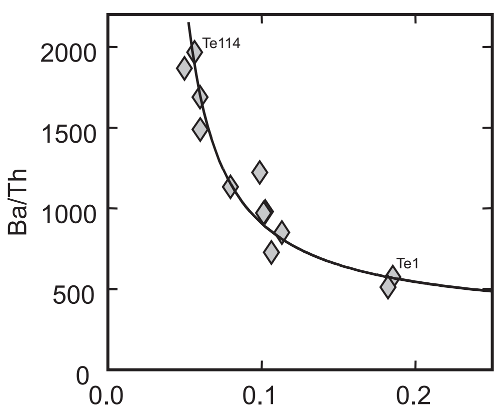


Fig. 4 Compositional variation in lavas from Telica volcano, Nicaragua. In the U/La and Ba/Th space, these lavas display a hyperbolic trend representing binary mixing between melts that have variable contributions from the hemipelagic sediments. Larger contribution from the hemipelagic sediments produces higher U/La and lower Ba/Th

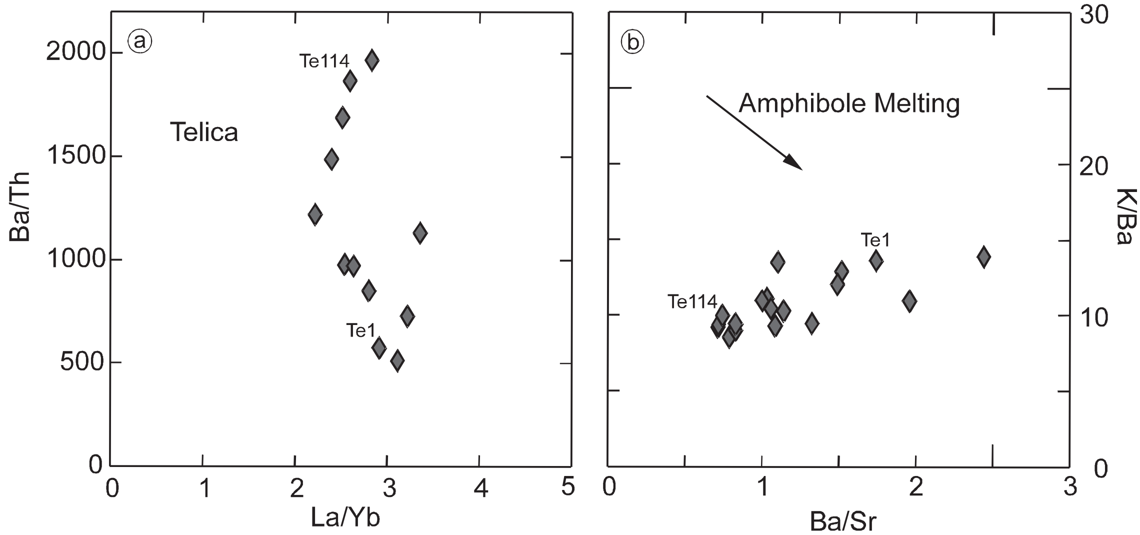


Fig. 5a, b Test of amphibole melting. **a** The lack of correlation between La/Yb and Ba/Th implies that the variation in the Ba/Th is not due to different extents of melting. **b** The melting of an amphibole-rich source generates a trend almost perpendicular to that observed in the lavas from Telica

e.g., northeast Japan (Shibata and Nakamura 1997). Even though the back-arc lavas from Central America have significantly less input from slab material, the extremely high Ba/La of the subducting sediments on the Cocos Plate makes it possible to observe the otherwise weak slab signature in these back-arc lavas.

Back-arc lavas from Central America have U/Th ratios that are similar to mantle values (Fig. 3a), but they have some of the highest Ba/Th ratios in the arc (Fig. 3c). The lower uranium contents in the back-arc lavas and higher Ba/Th, as in the older Nicaraguan lavas (Balzer et al. 1996), imply that the input from the hemipelagic-rich component to the magmas is relatively small (Figs. 3c, 6). The decreased hemipelagic contribution to the back-arc magmas is likely due to metasomatic events that generated the volcanic front magmas, where significant amounts of the hemipelagic sediments were involved.

Regional variations in lava compositions

Large along-arc geochemical variations occur in Central American lavas (Carr et al. 1990; Morris et al. 1990; Leeman et al. 1994). Ba/La, B/La, and $^{10}Be/^{9}Be$ ratios are highest in Nicaragua and decrease to the northwest and southeast. New data presented here show similar distributions along the arc in U/Th and Ba/Th (Fig. 7). These trace element ratios are closely associated with contributions from the subducting Cocos Plate (Fig. 2). In nearly all the regional variations one extreme is consistently found in western Nicaragua. The only exception is described by Morris et al. (1990), who show that the highest $^{10}Be/^{9}Be$ ratio of any arc lava is found in Masaya volcano in eastern Nicaragua (Fig. 7).

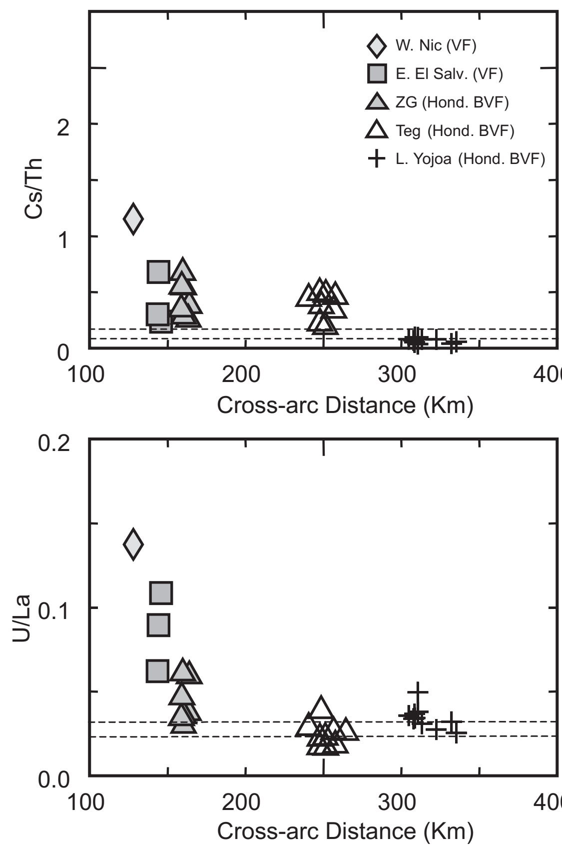


Fig. 6 Variations in trace element ratios with increasing distance from the volcanic front in Honduras. Distances from the volcanic front are as follows: Zacate Grande 17 km, Tegucigalpa 100 km, and Lake Yojoa 170 km. The Cs/Th ratios of the lavas from Tegucigalpa are similar to the ratios from the volcanic front. However, the U/La ratios of the lavas from Tegucigalpa are closer to mantle values. Magmas from back-arc regions have some contribution from the slab (high Cs/Th), but the composition of the material derived from the slab is different to that modifying the volcanic front magmas (lower U/La). *Dashed lines* represent the MORB range

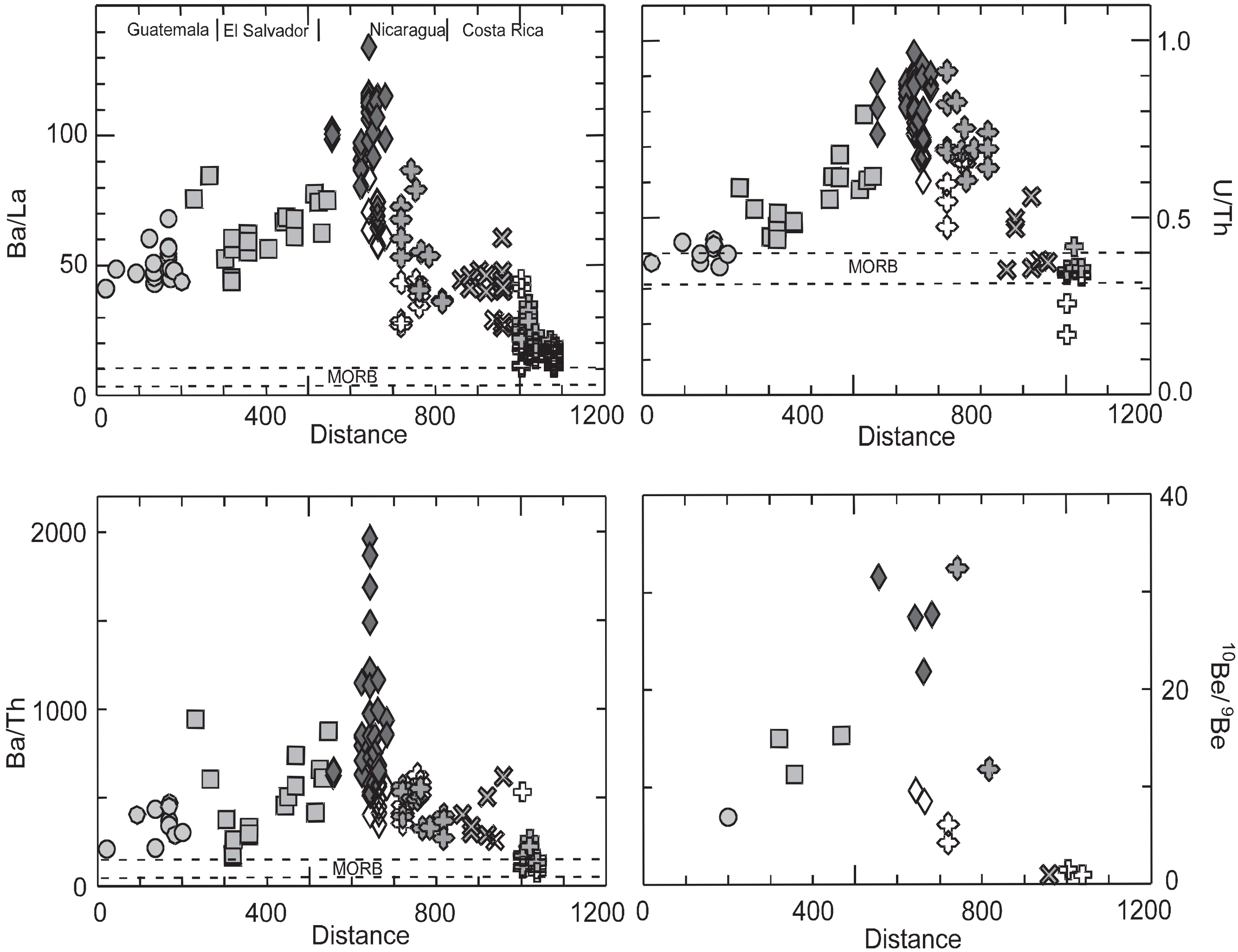


Fig. 7 Regional variations in trace element ratios. Maximum values occur in western Nicaragua, except for $^{10}Be/^{9}Be$. Ba/La and U/Th show the least scatter for any one segment of the arc; Ba/Th and $^{10}Be/^{9}Be$ display wider ranges within a giving arc segment. Be data from Morris et al. (1990)

Changes in the dip of the subducting slab along Central America were documented in Costa Rica and Nicaragua by Protti et al. (1995). The dip of the slab is steepest in Nicaragua (65–75°) and it becomes shallower toward the northeast and southwest (Carr 1984; Protti et al. 1995). The geochemical variations along the arc (Fig. 7) coincide with the dip variations. Carr et al. (1990) concluded that slab fluid is better utilized in Nicaragua where the steeper dip of subduction induces intensive metasomatism and melting of a smaller volume of mantle. A relatively small amount of high degree melt is produced and the melt generated in the mantle is heavily imprinted with the subducted slab signature. In the segments of the arc where the dip of the slab is shallower, a larger volume of the mantle is modified and then melted to a low or moderate degree, producing a larger volume of melt with diluted slab signature. The new regional variations shown in Fig. 7 are consistent with this model.

Along-arc variations occur in other arcs, e.g., Japan, Kamchatka, and Tonga–Kermadec (Kepezhinskas et al. 1997; Shibata and Nakamura 1997; Turner et al. 1997). In some instances, the variations along the arc are attributed to changes of geophysical parameters. The variations in Kamchatka are attributed to differences in the age of the subducting oceanic plate, older in the southern part of the arc (Kepezhinskas et al. 1997). Regional variations in Japan are related to differences in the amount of sediment involved in the magma generation process, higher in the northeast, due to changes in the dip and rate of subduction.

Turner et al. (1997) observed variations in the strength of the slab signature along the Tonga–Kermadec arc. The lavas with the strongest slab signature were those located in front of areas of extensive back-arc magmatism. They concluded that the slab signature was strongest in those lavas because the mantle from which they originated was most depleted (Turner et al. 1997). Similar conclusions were reached for lavas from southeast Guatemala, where there is extensive back-arc magmatism (Walker 1981; Walker et al. 1995). However, in western Nicaragua, where the strongest slab signature is observed, there is no clearly contemporaneous back-arc magmatism.

Differences between Central America and other arcs

The lavas from Central America display the common enrichment of LILE relative to REE and HFSE seen in other arcs (Fig. 8). However, the sediments from the Cocos Plate give Central American lavas special characteristics that set them apart from other arc-related lavas (Fig. 3). The composition of the sedimentary units makes some ratios, such as Ba/La, more robust, but may confuse other geochemical systems. For example, Hawkesworth et al. (1997) compared U and Th isotope systematics in several arcs, but did not include Central America because of the uranium-rich nature of the sediments.

In Ba/Th versus U/La space most of the samples from the Central American volcanic arc show a distribution similar to that observed in other arcs (Fig. 3c). However, there are some samples from Central America that stand out. The lavas from Telica, in western Nicaragua, have unusually high Ba/Th; only the lavas from Tonga–Kermadec and Kamchatka arcs have Ba/Th almost as high as those from Telica. In these two arcs from the western Pacific, the high Ba/Th ratios are clearly not related to the sediment composition, but instead it is inferred that their high Ba/Th ratios are related to the contribution from a fluid, likely derived from the altered oceanic crust (Tuner et al. 1997, 1998). The other samples from Central America that stand out in Fig. 3 are those from back-arc regions. The back-arc samples from Japan have higher U/La and lower Ba/Th compared to the volcanic front. An opposite trend is observed in Central American back-arc lavas (Fig. 3c). The overall higher Ba ratios in volcanic rocks from Central America are a direct manifestation of the biogenic nature of the subducting sediments.

It is apparent that the composition of the metasomatic agent in subduction zones is not homogenous (Ryan et al. 1995; Hochstaedter et al. 1996; Thirlwall et al. 1996; Elliott et al. 1997; Hoogewerff et al. 1997; Turner et al. 1997), and Central America is no exception. Some argue that the slab input consists of two components: a hydrous fluid (mostly from the altered oceanic crust; e.g., Hawkesworth et al. 1997) and a melt (mainly derived from the sediments, e.g., Plank and Johnson 1997). Presumably, the geochemical variations in arc-related lavas are produced by changing the ratio of fluid/melt that modifies the mantle to generate the magmas (Ryan et al. 1995; Hochstaedter et al. 1996; Thirlwall et al. 1996; Elliott et al. 1997; Hoogewerff et al. 1997; Turner et al. 1997). In Central America the processes that transfer material from the slab to the mantle wedge may change as a function of the carbonate/hemipelagic sediment ratio in the slab component; thus, the heterogeneity is vertical rather than lateral.

Discussion

The processes that transfer material in the subduction zone system are poorly understood. In many instances, heterogeneities in the chemical composition of arc lavas have been explained by variation in the ratio of fluids to melts (e.g., Ryan et al. 1995). Models of the processes that mobilize material from the slab to the mantle wedge are limited by lack of knowledge of the mineral changes in the slab upon subduction and by poorly constrained partition coefficient data (Langmuir 1994). The forward modeling of fluids and melts for Central America (Patino 1997) produces weak results due the poorly constrained parameters of the models, especially the lack of experimental data and partition coefficient data on carbonate phases. However, forward models do provide a general idea of what is happening geochemically along the arc; namely, that very little slab input ($< 2\%$) is

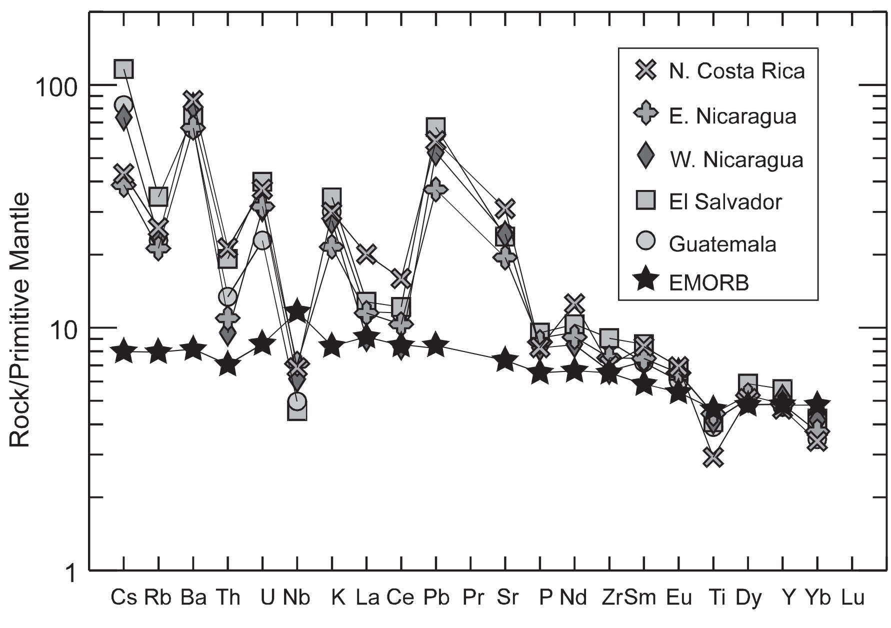


Fig. 8 Primitive mantle normalized diagram for mean lavas from different segments of the Central American arc. The mean lava compositions display the common enrichment of LILE relative to REE and HFSE in arc lavas. The REE of the lavas is parallel to that of EMORB. Normalization factors and EMORB composition are from Sun and McDonough (1989)

needed to reproduce the geochemical characteristics of the lavas from the arc.

Another positive result of forward modeling is establishing the necessity of significant contributions of Sr from the basaltic oceanic crust. Carr et al. (1990) proposed bulk mixing between a very small amount of average DSDP Site 495 sediment and MORB mantle to explain the Sr and Nd isotope systematics of western Nicaragua. This model fails because the Sr concentration of the modified mantle, and melts derived from it, are too low to match the actual lavas. To satisfy the concentration constraint, a second source of depleted $^{87}Sr/^{86}Sr$ is needed and the obvious choice is the basaltic oceanic crust, most likely altered oceanic crust (AOC). Contribution from AOC has also been invoked to explain the Sr and Pb isotope composition of lavas from other arcs, like the Tonga–Kermadec and Aleutians arcs (Miller et al. 1994; Turner et al. 1997). Adding altered oceanic crust in bulk would, however, raise the Nd contents unacceptably, so it is necessary to separate the large ion lithophile elements from the rare earth elements in the subducted MORB. The results of Brenan and coworkers (1995a, b) clearly show that hydrous fluid from the subducted AOC can carry sufficient Sr, leaving behind virtually all the REEs.

Order of mixing

The local variation in the lava composition defines a binary mixing process between end members that both have a strong sedimentary character in several LIL elements (Figs. 3, 4). One end member is plausibly derived from mantle + fluid from AOC + carbonate extract. The other end member differs by adding in a hemipelagic component, either a fluid or a melt. Forward modeling is currently inadequate for more than a qualitative estimate of the proportions and character of the various components. However, the main difference between the end members appears to be the presence or absence of the hemipelagic component. Both mechanical and physical–chemical processes might cause the random alternation of hemipelagic-rich and hemipelagic-poor magmas that occurs in Central America.

The clear binary mixing systematics at Telica volcano (Fig. 4) are most simply explained if the last stage in the magma generation process mixes two mafic basalts whose LILE contents are quite distinct, but whose major, compatible trace element and REE contents are not obviously different. The similar major element, REE, and isotope data for the end-member basalts suggests that they originate from a common MORB-source mantle by similar degrees of melting. An additional mechanism is needed to explain the sporadic contribution of the hemipelagic component.

One mechanical way to generate a range in sediment input is by having sediment traps present on the Cocos Plate, such as those inferred by Miller et al. (1992) seaward of the Aleutian Trench. Small-scale topographic variations on the surface of the subducting Cocos Plate were documented by Aubouin et al. (1982) off the coast of the Middle American Trench, and DSDP Site 495 was deliberately located on a horst. When a horst subducts, the upper part of the hemipelagic unit may be scraped off into the adjacent graben, or added to the upper plate by accretion. In any case, a horst-derived slab component will lack the hemipelagic component. When a graben subducts, the sedimentary sequence is preserved except that there may be extra hemipelagic sediments. This results in lavas with a high hemipelagic component. One difficulty with this model is that along the Middle American Trench accretion is minimal (Coulbourn et al. 1982). There may be underplating at depths greater than can be resolved by seismic profiles, but this is hypothetical. Redistribution of hemipelagic sediments from horsts to grabens would lead to the two distinct magmas required by geochemistry.

A physical–chemical way to generate two separate sedimentary inputs is to have two stages of flux extraction. The first flux would be a silicic melt from the hemipelagic sediment that is intruded in a localized manner into the mantle immediately adjacent to the slab. This creates patches of hemipelagic material in the mantle being drawn down by the slab. The second flux is a hydrous fluid from AOC that passes through the ubiquitous carbonate, which adds Ba and Sr. If this fluid passes through a patch of hemipelagic intrusive, it becomes a hemipelagic-rich flux; if the fluid misses the hemipelagic patches, it remains a hemipelagic-poor flux. This hydrous event causes melting in the mantle wedge. Different melting events are similar, just with or without a hemipelagic component. This model is more complicated than the mechanical scenario presented above but it may also be more generally applicable.

Mass flux modeling

One way to explore the subduction zone system that is free from the constraints of limited partition coefficient data, is to estimate the mass fluxes into and out of the system. The output/input flux ratio estimates the efficiency with which the magma production process recycles material from the subducting slab. This approach makes no a priori attempt to distinguish the processes that mobilize material from the slab to the mantle wedge. Instead, it just compares the subducted slab and the erupted lavas. This approach is similar to the one used by Plank and Langmuir (1993), who compared the composition of sediments from eight trenches and lavas from the respective arcs.

Input flux

In Central America there are relatively few uncertainties in the calculation of the input flux. The calculations are based on the comprehensive geochemical data set for the sediments described earlier. The lack of an accretionary prism (Coulbourn et al. 1982) led us to assume minimal loss of sediment in the forearc. The flux into the system was calculated taking into account convergence rate, density, thickness, and composition of the different slab units (Tables 1 and 2). The largest uncertainty in the calculation of the input flux is the composition of the altered oceanic crust. There are gaps in the geochemical data on the volcanic section of Site 504, and the concentrations of important elements like Ba, Cs, U, Th, and Pb are poorly constrained.

Table 3 shows the percentage of the input flux from the different units of the Cocos Plate. The hemipelagic sediments contribute all of the ^{10}Be, most of the B, Cs, Rb, U, K, and some of the Ba. The carbonate oozes contribute most of the Sr, and significant quantities of Ba. The upper section of the altered oceanic crust also contributes B, Rb, Cs, and K. The hydrothermally altered oceanic crust supplies most of the Pb.

Output flux

The flux out of the system has more uncertainties than the input flux, with the greatest uncertainties related to the production of magma in the arc. The output flux calculations were performed for five different segments of the arc: Guatemala, El Salvador, western Nicaragua, eastern Nicaragua, and northern Costa Rica. The output flux was not calculated for the back-arc regions because of large uncertainties in the rate and timing of magmatism. In calculating the output fluxes, the following parameters were used: the composition of the mean lavas corrected for the mantle input, the density of basalts (2.65 g/cm^3), the measured volume of the volcanoes, the length of the arc segments, and the duration of magmatism (Table 4).

Table 3 Percentages of the contributions to the input flux from different units of the subducted slab

	Altered oceanic crust		Carbonate sediments	Hemipelagic sediments
	Lower	Upper		
B	8.0	22.1	11.3	58.6
Cs	3.4	11.4	7.3	77.9
Rb	4.5	29.1	8.2	58.2
Ba	2.6	2.4	40.1	54.8
Th	68.4	14.3	1.2	16.2
U	12.4	8.2	3.1	76.2
Nb	62.6	12.8	2.6	22.1
K	9.2	30.6	7.0	53.2
La	26.2	32.8	16.3	24.7
Ce	38.3	40.1	2.2	19.3
Pb	74.1	12.3	4.6	9
Sr	24.3	10	56.4	9.4
P	68.2	22.7	5.4	3.7
Nd	61.6	23.5	5.1	9.9
Be	65.6	21.9	4.2	8.3
^{10}Be	0	0	0	100
Zr	70.3	23.4	0.8	5.5
Sm	67.6	22.5	3.2	6.6
Eu	65.2	21.7	5.0	8.1
Dy	68.3	22.8	3.2	5.7
Y	67.1	22.4	4.6	6.0
Yb	65.4	26	3.1	5.5

The volume of the volcanoes introduces a significant error because it represents only a portion of the total magma produced. It ignores distal tephras, intrusive rocks, and back-arc lavas, and does not take into account the volume of lava that has been removed by erosion since eruption. Because of these uncertainties, the calculated output flux represents a minimum value. Another weakly constrained factor is the duration of magma production. This parameter is well constrained for Guatemala and Nicaragua, based on tephrachronology of two extensive units from Central America (Ledbetter 1985). In Guatemala all the active volcanoes sit on Los Chochoyos tephras dated 84,000 year B.P. In Nicaragua the widespread Las Sierras tephras appear to be from a proto-Masaya. Their distinctive Fe-rich mafic composition allows them to be correlated with layer J1 of Ledbetter (1985) with an estimated age of 135,000 years. Most of the active Nicaraguan volcanoes appear to sit on this unit. Unfortunately, the lack of mapping and age dating for the younger volcanic rocks in Central America prevents us from selecting an age that will clearly allow a minimum flux estimate.

Another complicating factor is the contribution from the mantle to the magmas. It is difficult to infer the mantle composition in arc-related lavas because small contributions from the slab can modify the magmas significantly. However, as discussed in the earlier section on constraints on the mantle in Central America, we use the REE to infer the mantle composition in the arc. The REE pattern for the mean lava from western Nicaragua is similar (Fig. 8) to the EMORB of Sun and McDonough (1989). Therefore, we use the composition of EMORB source to correct for the mantle contribution in the calculation of the output fluxes. Assuming a uniform source composition for most of the arc, the enriched LREE patterns of the mean lavas (Fig. 8) from eastern Nicaragua, El Salvador, Guatemala, and northern Costa Rica imply lower degrees of melting than in western Nicaragua. For western Nicaragua, we

Table 4 Duration of magmatism, volume, and arc length used for the output calculations for the different segments of the Central American volcanic arc

	Duration of magmatism (kyr)	Volume (km$^{3)}$	Arc length (km)
Northern Costa Rica	100[a]	441	100
Eastern Nicaragua	135[b]	243	130
Western Nicaragua	135[b]	224	175
El Salvador	200[c]	736	252
Guatemala	84[b]	163	116

[a] Alvarado et al. (1992)
[b] Ledbetter (1985)
[c] Pullinger (1998)

assume the highest degree of melting, 15%; and for the other segments, lower degrees, 12.5% for eastern Nicaragua, 10% for El Salvador and Guatemala, and 7% for northern Costa Rica. To account for shallow crustal processes, only the most mafic lavas from each segment were selected for the output flux calculations.

Output/input ratios and efficiency of recycling

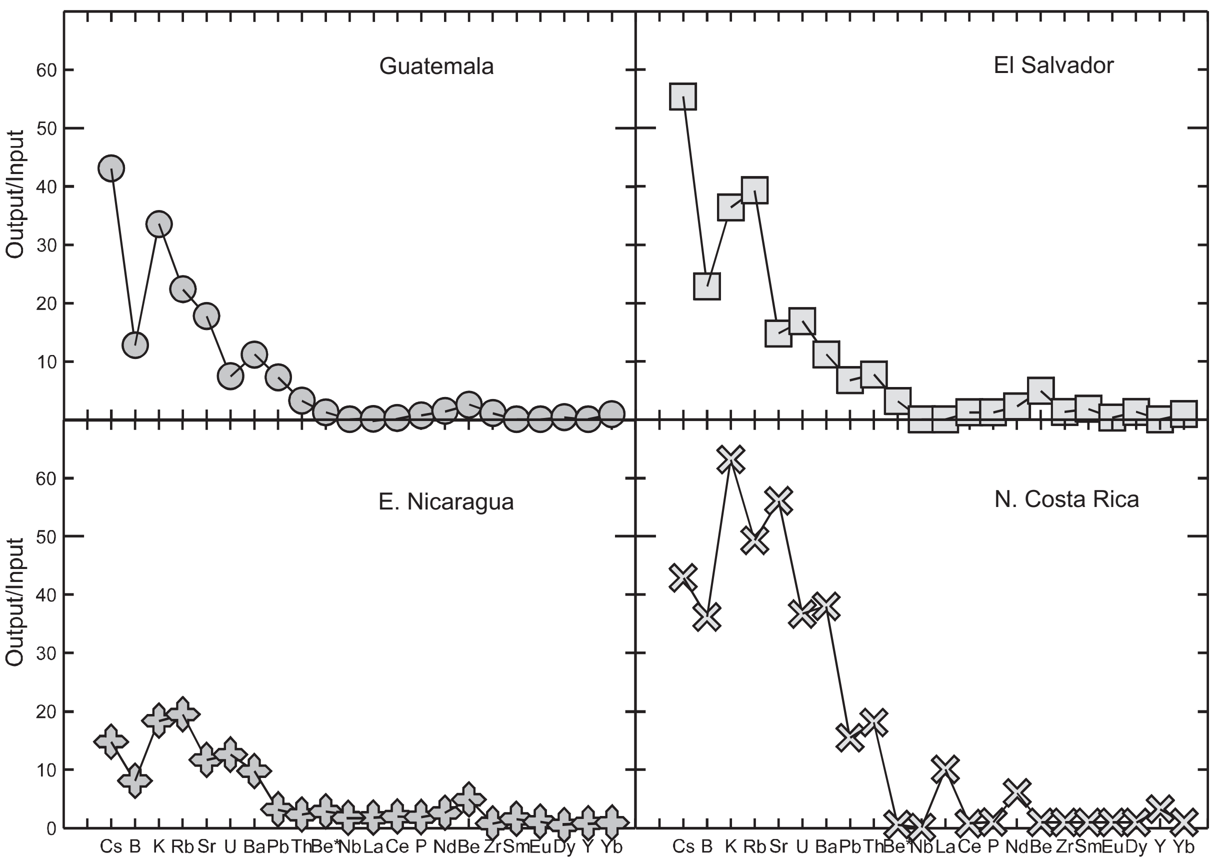
The output/input ratio estimates the efficiency of the system in recycling elements from the slab through the volcanoes. The relative efficiency of different elements can be used to infer the dominant process that transfers material from the slab to the mantle wedge. Furthermore, the output/input ratio can be used to infer the parts of the slab that contribute to the magma generation process, providing that the compositions of the slab units are well constrained and significantly different from each other.

The similarities in the compositions of the mean lavas (Fig. 8) suggest that the ratio of output to input flux will also be similar for the different segments of the arc. However, this is not the case, as observed in Figs. 9 and 10, which show the output/input ratios for the different segments of the arc expressed as a percentage.

The scale of the output/input flux ratio is not well defined, as the patterns for the El Salvador, Guatemala, and northern Costa Rica segments demonstrate (Fig. 9). The output/input flux ratios are greatly affected by the uncertainties discussed earlier (e.g., magma volume and duration of magmatism). The flux ratios are plausible minima for Nicaragua, where there is some age control (Fig. 10). The higher flux ratios in El Salvador, Guatemala, and Costa Rica suggest that the lava volume estimates are too high or the time estimates are too short. Even though the scale of the output/input flux model is not well constrained, the models give valuable information if we compare the relative order of enrichment of the elements within the segments.

Even though a sample from Masaya volcano in eastern Nicaragua has the highest ^{10}Be content of any arc lava (Morris et al. 1990), the output/input flux models indicate that relatively little of the subducted ^{10}Be is recycled through the volcanic arc (Figs. 9, 10). The minimum recycling efficiencies for ^{10}Be obtained in this study are consistent with the higher values estimated by Morris et al. (1990), only if we add in a large volume of other magmatic products (tephra, intrusives, etc.)

Fig. 9 Recycling efficiency for different segments of the arc. The LILE have large recycling efficiencies and the REE very low. The four panels show that B has similar recycling efficiencies to U and Ba. Input flux (g cm^{-1} year^{-1}) = convergence rate × ppm$_i$ × density$_i$ × thickness$_i$ [i = slab unit (hemipelagic sediments, carbonate sediments, altered oceanic crust); convergence rate = 8.1 cm year^{-1}; ppm$_i$ = concentration of a given element in the slab unit i]. Output flux (g cm^{-1} year^{-1}) = (rock × density × volume)/(arc length × time) [rock = mantle corrected average lava from an arc segment; lava density = 2.65 g cm^{-3}]



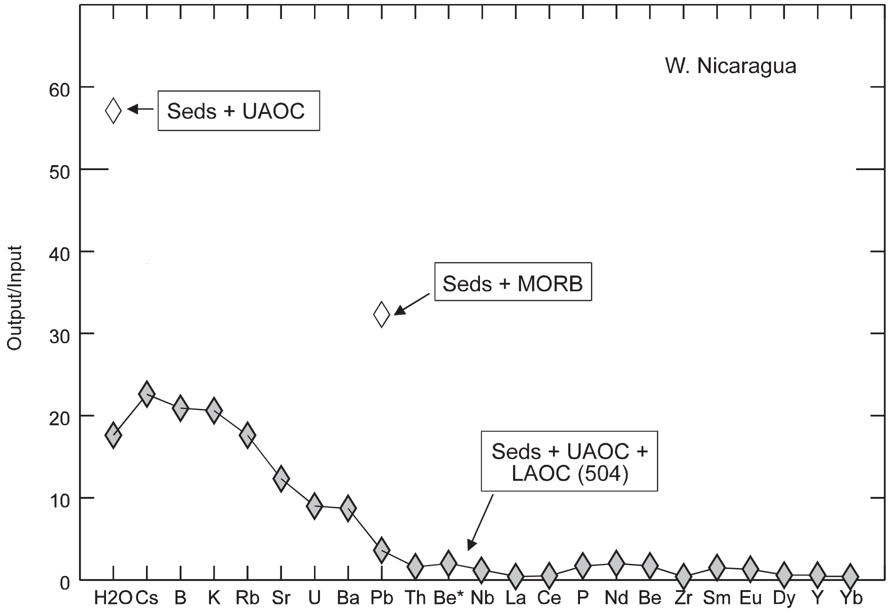


Fig. 10 Recycling efficiency for western Nicaragua. The *solid symbols* result from taking into account all four units of the subducting slab (hemipelagic sediments, carbonate sediments, upper and lower altered oceanic crust) and assuming that the altered oceanic crust has a composition similar to that of DSDP Site 504. The high recycling efficiency of water, as well as Cs, B, K, and Rb, lead us to conclude that a hydrous fluid is the agent that mobilizes material from the slab to the mantle wedge. The low recycling efficiency of Pb, when the concentration of the altered oceanic crust is assumed to be that of DSDP Site 504, does not agree with other published models (see text for details). Thus, the Pb concentration of the subducting altered oceanic crust is likely to be within the range defined by MORB and DSDP Site 504. The water concentration of the subducted material and of the magmas is also poorly constrained, leading to large errors in the output/input calculations. Be* represents Be^{10}

when calculating the volume in the output flux. Several researchers have suggested that Be, along with LREE, Th, and HFSE, is more easily mobilized by a melt than by a hydrous fluid (e.g., Reagan et al. 1994; Plank and Johnson 1997). The poor efficiency in the recycling of beryllium and thorium (Figs. 9, 10) from the subducted slab is an indication that, at most, only small amounts of melt derived from the hemipelagic sediments contributed to the magma generation process.

Taking the results from western Nicaragua as the reference model (Fig. 10), the elements can be classified into three groups depending on how efficiently they are recycled through the arc system. Water, Cs, B, K, and Rb are efficiently recycled; Sr, U, and Ba are intermediate; and Pb, Th, and ^{10}Be are weakly recycled through the system. The similarity in the recycling efficiency of H_2O with Cs, Rb, B, and K is not surprising considering that these elements are easily mobilized by hydrous fluids (Tatsumi et al. 1986; Moran et al. 1992; Stolper and Newman 1994). Furthermore, the significantly higher recycling efficiency of this group of elements combined with lower recycling efficiencies of Th, ^{10}Be, and LREE indicates that a hydrous fluid is the process that dominates the transfer of material from the slab to the mantle wedge.

The recycling efficiency of Pb is surprisingly low (Figs. 9, 10). Many researchers have suggested that Pb behaves similarly to Sr and Ba in arc magmatism (e.g., Shibata and Nakamura 1997). Kogiso et al. (1997) indicated that Pb is more mobile than other LILE by fluids that are produced during the dehydration of amphibolite. The initial output/input flux models disagree with this conclusion. Table 3 shows that the contribution of Ba and Sr is dominated by the sedimentary component of the subducting Cocos Plate. However, the concentration of Pb, as well as Th, in these biogenic sediments is considerably lower than in terrigenous sediments, like those subducting underneath the Aleutian arc (Taylor and McLennan 1985; Miller et al. 1994; Plank and Langmuir 1998).

There is controversy regarding the Pb composition of the altered oceanic crust, mainly because it has been difficult to determine its concentration in drilled samples due to contamination with drilling mud (Staudigel et al. 1995). However, Chauvel et al. (1995) and Alt et al. (1996) indicate that hydrothermal alteration modifies the Pb content of the oceanic crust by promoting the deposition of sulfide minerals in the transition zone. Based on the reported Pb concentrations for DSDP Site 504, most of the Pb resides in the hydrothermally altered oceanic crust. The unusually low recycling efficiency of Pb in Central America is the result of the high Pb concentration reported for this unit. The efficiency of Pb recycling can be greatly increased by changing the Pb concentration of AOC to a value intermediate between MORB (0.42 ppm) and DSDP Site 504 (5 ppm; Fig. 10).

The recycling efficiency of water through subduction zone systems is a difficult question that has important implications for a wide range of geochemical studies.

Determining the water content of arc magmas is difficult because most of the water is lost by degassing as the magma ascends. Recently, Roggensack et al. (1997) have measured H_2O in melt inclusions in olivines in volcanic products from Cerro Negro, western Nicaragua. Their data indicate that the inclusions with the most mafic compositions also have the highest content of volatiles. Based on their conclusions, we assume that the water content for the average western Nicaragua magma is 5 wt%. The other segments of the arc lack similar data sets, so the output/input mass flux ratios of water were not calculated.

The sediments from DSDP Site 495 have large quantities of water (44 and 63% for the hemipelagic and carbonate sediments, respectively). However, we expect that most of this water, which is not bound to mineral phases, would be expelled in the early stages of subduction. On the other hand, most of the water in the altered oceanic crust is hosted in mineral phases. This water will only leave the oceanic crust as minerals break down due to metamorphic reactions.

The recycling efficiency of H_2O depends greatly on whether the hydrothermally altered oceanic crust is taken into account when calculating the input flux (Fig. 10). If we assume that the lower section of the altered oceanic crust contributes to the slab component, the recycling efficiency of H_2O is similar to that of B, K, and Rb (Fig. 10, filled diamond). However, if we assume that the hydrothermally altered oceanic crust does not contribute to the mantle metasomatism, the output/input flux ratio is significantly higher (Fig. 10, empty diamond). This high recycling efficiency is unrealistic because we did not take into account the total volume of magma produced. This high efficiency is most likely due to the poorly constrained water content of the magma and of the slab components. Lowering the H_2O content of the mean lava or increasing the contribution from the slab units by a factor of 2 will lower the efficiency of H_2O to values similar to those of Cs, B, and K.

It has been suggested that in arc lavas, uranium is mostly transferred to the mantle wedge via a fluid from the AOC. This conclusion is supported by U-disequilibrium series and the similar behavior of U and other elements like LILE that are easily mobilized by fluids (e.g., Turner et al. 1997). However, the output/input models for lavas from the Central American volcanic arc does not agree completely with such a conclusion. The recycling efficiencies of U, Ba, and Sr are consistently lower than the recycling efficiencies of K, Cs, and Rb. It is important to keep in mind that the biogenic nature of the sediments subducting underneath the Central American volcanic arc makes them particularly enriched in U, Ba, and Sr. Thus, the enrichment of the LILE and U in the magmas from this arc results not only from the contribution of fluid from the AOC, but also from the sediments which contribute a significant proportion of U as well as Ba and Sr. Further evidence of the sedimentary origin for U in lavas from Central America is the positive correlation between U/La and U/Th with $^{10}Be/^{9}Be$ ($r' > 0.8$), and the drastic decrease of U ratios in back-arc lavas to mantle values (Fig. 6).

The classification of elements based on the efficiency of recycling (Fig. 10) is consistent in each segment of the arc, with the exception of boron. In western Nicaragua, boron is efficiently recycled through the system (Fig. 10), but in the other segments its recycling efficiency is only intermediate (Fig. 9). In western Nicaragua, the boron efficiency is similar to that of Cs, Rb, and K (Fig. 10), whereas in other segments of the arc, it is closer to that of U and Ba (Fig. 9). For Central American magmas, the possible sources of boron are the subducted hemipelagic sediments and the low temperature altered oceanic crust (Table 3). The difference in the recycling efficiency of boron can be explained by assuming different sources for boron for western Nicaragua and the other arc segments. Table 3 shows that the hemipelagic sediments are the major source for U, Ba, Rb, Cs, B, and K, and that the upper altered oceanic crust is the next most important source for B, Cs, Rb, and K. Relative to the sediments, the altered oceanic crust contributes little U and Ba to the Central American subduction system.

The close association of B with U and Ba in the models in Fig. 9 implies that the hemipelagic sediments are the dominant source for B along most of the arc as would be expected from the stratigraphic distribution of B (Table 3). However, in western Nicaragua (Fig. 10) boron efficiency appears to be much higher than U. We suggest that the additional B is from an unusually large contribution from the upper altered oceanic crust, which has high B and low U (Table 3). In other words, the hydrous fluid involved in the generation of western Nicaraguan magmas is relatively enriched in material from the upper 0.5 km of the altered oceanic crust, which is consistent with the very strong slab signature in western Nicaragua (Figs. 3, 6).

One way of confirming the proposed variations in the boron source for Central American lavas is to look at the behavior of boron with increasing distance from the volcanic front. Preliminary boron data on back-arc lavas from Honduras indicate that Cs and B behave similarly. The close association between Cs and B ($r' = 0.9$ for Cs/La versus B/La) was also reported by Ryan et al. (1995). Thus, we will use Cs as a proxy for boron because of the limited number of boron analyses on the samples from Honduras. From the available data, we infer that back-arc magmas are modified by slab material dominated by fluids from the AOC and carbonate sediments (high Cs/Th; Fig. 6), but with almost no contribution from the hemipelagic sediments (U ratios close to mantle values; Fig. 6). Noting that the AOC contributes significant amounts of boron to the magmas from the back-arc regions in Central America, we conclude that, indeed, the larger flux of boron in western Nicaragua can be related to a higher AOC/hemipelagic ratio in the slab component for this segment of the arc.

The larger contribution from the slab fluids in western Nicaragua coincides with distinctive geophysical features, i.e., thinner crust and steeper angle of subduction. Masson (1991) and references therein indicate that normal faulting in subducting slabs is ubiquitous and associated with the tensional stresses that result from bending the oceanic plate. Furthermore, Masson (1991) observes that the throw on these normal faults increases with the increasing bending of the subducting plate; the throw can vary from <35 m (Peru, where there is a shallow dip) to 115 m (Aleutian, steeper slab dip). Masson's (1991) results imply that the throw of the normal faults on the Cocos Plate would vary along the Middle American Trench because the dip of the slab changes along the arc. Thus, the throw would be greater in Nicaragua relative to other segments of the arc because the dip of the slab is steeper in this segment. Kirby (1995) suggests that fractures in the oceanic crust enhance the production of fluids because these areas would have larger concentrations of hydrous minerals. The larger displacement on faults underneath western Nicaragua would promote the generation of more fluids from the subducting oceanic crust. Therefore, the magmas from this segment of the arc would have a larger slab input, mainly from additional hydrous fluid derived from the altered oceanic crust.

The output/input models indicate the components of the subducted slab that take part in the magma generation processes. However, these models give few insights on the order in which these components were added to the mantle. Turner et al. (1997) suggest that for the Tonga–Kermadec arc the slab contribution is probably a multi-stage process due to lack of correlation between trace element isotope ratios. Reagan et al. (1994) has already proposed a multi-stage slab contribution for the Central American volcanic arc. Reagan et al. (1994) interpreted the U and Th isotopic composition of selected lavas from Nicaragua to represent different events of material transfer from the slab to the mantle wedge, similar to the physical–chemical model discussed earlier. The data presented in this paper can be interpreted so that the earlier contributions from the slab are dominated by material from the sediments "saturating" and modifying the mantle in elements like U, Ba, Sr, and ^{10}Be. A subsequent slab contribution, dominated by material from the AOC, will mostly affect the isotopic composition of the modified mantle (e.g., U and Sr isotopes). The addition of the AOC material will trigger the melting of the modified mantle.

Conclusions

The stratigraphic units of the Cocos Plate have significantly different geochemical characteristics that can be used to trace their input into the magma generation process along the Central American volcanic arc. The biogenic nature of the sedimentary sequence produces high Ba in both the carbonate and hemipelagic units, and the high organic matter of the hemipelagic sediments leads to uncharacteristically high U content.

In Central America, there are distinctive incompatible element heterogeneities in the magmas along-arc, across-arc, within segments of the arc, and within a single volcano. The nature of the heterogeneities is twofold. There are regional differences in the intensity of slab signature and local differences in the composition of slab input, both of which may be related to physical features of the arc. The most intense slab flux occurs in Nicaragua, where the dip of the subducting slab is also greatest. Higher slab flux may be produced by the release of larger amounts of fluids from the oceanic crust that is more highly fractured where the dip is steepest. These variations in flux then create the along-arc variation in trace element ratios associated with the slab, e.g., Ba/La and U/Th.

The local variation in Central American lavas implies binary mixing between two mafic basaltic magmas whose LILE contents are very different, but, whose major, compatible element, and REE contents are not obviously different. The simplest way to satisfy the LILE geochemistry is to randomly or alternately sequester the hemipelagic component from the rest of the subducting Cocos crust section. The horst–graben nature of the subducting Cocos Plate suggests a shallow mechanical solution, the scraping off of the soft upper sediments, the hemipelagics, from the horsts to the grabens. Alternatively, LIL elements from the hemipelagics may get sequestered via a two-stage flux. Initially, a silicic melt derived from hemipelagic sediment creates patches of LILE-enriched intrusives in the mantle adjacent to the slab. Subsequently, a hydrous flux is released from the downgoing slab. This flux generates basaltic magma either enriched in hemipelagic component (if the flux passes through silicic patches) or not (if the flux misses the silicic patches).

Output/input mass balance calculations are a useful approach to understanding the geochemical recycling in subduction. For Central America, the efficiency with which elements are recycled indicates that a hydrous fluid is the dominant process that transfers material from the slab to the mantle wedge. However, the composition of this fluid is not uniform along the arc. The fluid involved in the generation of lavas from western Nicaragua seems to have a larger contribution from the upper part of the altered oceanic crust. This could be the result of the steeper dip of the subducting slab in Nicaragua, which creates more fractures to facilitate the release of water.

Acknowledgements We would like to thank Richard Harwood for assistance in collecting the samples and T.N. Donnelly for providing splits of DSDP 495 sediments. T. Plank and C. Herzberg provided valuable comments. We also would like to thank J. Ryan and S. Turner for their reviews of the paper and A. Hofmann for his editorial help. This research was supported by grants from the National Science Foundation (NSF EAR 9406624).

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