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Subduction controls on the compositions of lavas from the Ecuadorian Andes

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Abstract

Three volcanoes of the Ecuadorian Andes, Atacazo, Antisana, and Sumaco, lie in a transect perpendicular to the trench and the main trend of the Andean arc. Each of the volcanoes lies on crust of substantially different age, composition, and thickness. Few compositional or isotopic features correspond in a straightforward way to the type of the crust through which the magmas have passed. Isotopic data limit assimilation to $<15\%$ at each of the volcanoes. Instead, a systematic relationship exists between the compositions of the lavas and the depth to the Benioff zone, suggesting that subduction imparts the principal control on the compositions of the magmas. Atacazo's lavas have low concentrations of the incompatible trace elements and very large LIL/HFS ratios. Sumaco's lavas are strongly enriched in the incompatible trace elements and have small LIL/HFS ratios. Antisana's lavas are intermediate in almost every respect. These features are consistent with devolatilization of the subducted slab controlling the extent of partial melting of a depleted mantle source. A mixing and melting model suggests the volcanic front magmas are made by large extent of partial melting ($\sim 15\%$) and include a large slab input (1.1% added to the depleted mantle). The magmas of the middle belt of volcanoes are made by smaller extent of partial melting (3%), induced by moderate amounts of slab-derived fluid (0.06%). The back arc magmas result from small degrees of melting (2%) and small slab input. © 1998 Elsevier Science B.V.

Keywords: Ecuador; Andes; subduction; andesites; assimilation

1. Introduction

A series of studies conducted on rocks from the southern and central Andes have demonstrated the important role of crustal assimilation in the genesis of magmas at an active continental margin [1–3]. The Chilean Andes provide an excellent setting to test for assimilation, because the crust thickens from about 30 to 60 km along the strike of the arc. In the areas underlain by the thinner crustal sections the geochemical characteristics of the lavas are thought to be mostly imparted by the subducted lithosphere and overlying mantle wedge[4,5], but compositional features that correspond to changing crustal thickness have been attributed to assimilation [1–3]. These

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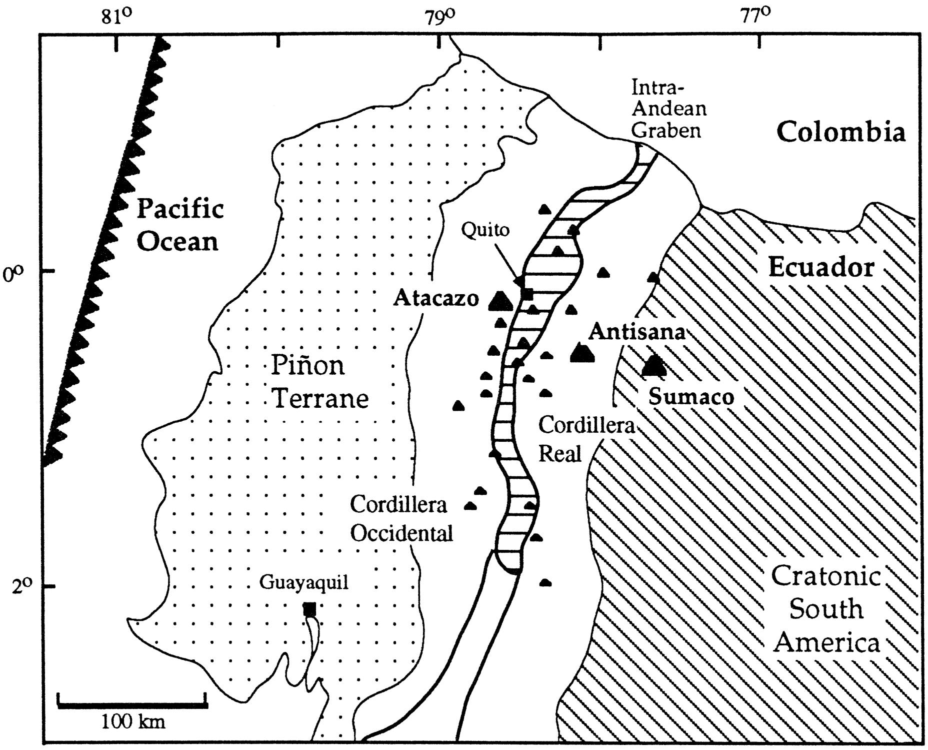

Fig. 1. Terrane map of northern Ecuador (adapted from [6,8]). *Closed triangles* are volcanoes. *Toothed line* indicates trench.

findings suggest that the crust at Andean-type margins may be dominated by recycling of older crustal material, thus only small amounts of juvenile crust are produced. The other important implication is that continental-arc magmas may be so strongly modified by crustal contamination that little can be discerned about their primary source in the subducted slab and upper mantle.

This paper reports the results of a study of three volcanoes, Atacazo, Antisana, and Sumaco, that lie perpendicular to the strike of the Ecuadorian Andes, representing a distance of ~100 km across an active volcanic arc (Fig. 1). The Ecuadorian Andes are fundamentally different from the southern Andes, especially in the geologic history of the upper plate. Specifically, several allochthonous terranes were accreted to the northwest part of the South American continent between the Middle Jurassic and Late Eocene [6–8]. Consequently, magmas of the Ecuadorian Andes have traversed crust of vastly different age, composition, and thickness. We have found that the compositions of these lavas are not related in any predictable way to the composition or thickness of the crust on which they sit. Instead, most of the geochemical features are simply related to the depth of the Benioff zone. We conclude that the composition of these lavas is mostly determined by processes occurring in the slab and mantle, and in fact neither crustal nor lithospheric-mantle interaction plays an important role.

2. Analytical techniques

Major-element and Ni, Cr, Sc, V, Ba, Rb, Sr, Zr, Y, and Nb analyses were by XRF in the Geoanalytical Laboratory at Washington State University (Peter Hooper, pers. commun., 1997). Precision was tested by multiple analyses of a single specimen. Major-element precision is < 2% of the absolute abundance; trace-element precision is < 5% except for Rb and Nb, which are 10% in low-abundance samples. Rare-earth elements (REE), Hf, Ta, Th, and U were analyzed by INAA at Oregon State University. Uncertainties are 7% for U and Ce, and < 5% for the other elements (M. Streck, pers. commun., 1994). Oxygen isotope analyses were performed using techniques reported in [9]; uncertainty is ±0.1‰. Sr and Nd isotopic analyses were performed by techniques reported in [10]. Internal precision is typically ±0.000020 for $^{86}Sr/^{87}Sr$ and ±0.000010 for $^{143}Nd/^{144}Nd$. Ratios are reported relative to 0.710240 for SRM987 for $^{86}Sr/^{87}Sr$ and relative to 0.511852 for the La Jolla standard.

3. Geologic setting

The Ecuadorian Andes result from the subduction of the Nazca plate beneath the South American plate. The active volcanic arc lies north of 2°S (Fig. 1). To the south of 2°S, the Nazca plate subducts at an angle of ~ 15°, creating an amagmatic convergent boundary. To the north, in the study area, the dip of the Benioff zone is between 25° and 30° [11]. The active composite volcanoes of Ecuador lie in two parallel chains called the Cordillera Occidental (west)

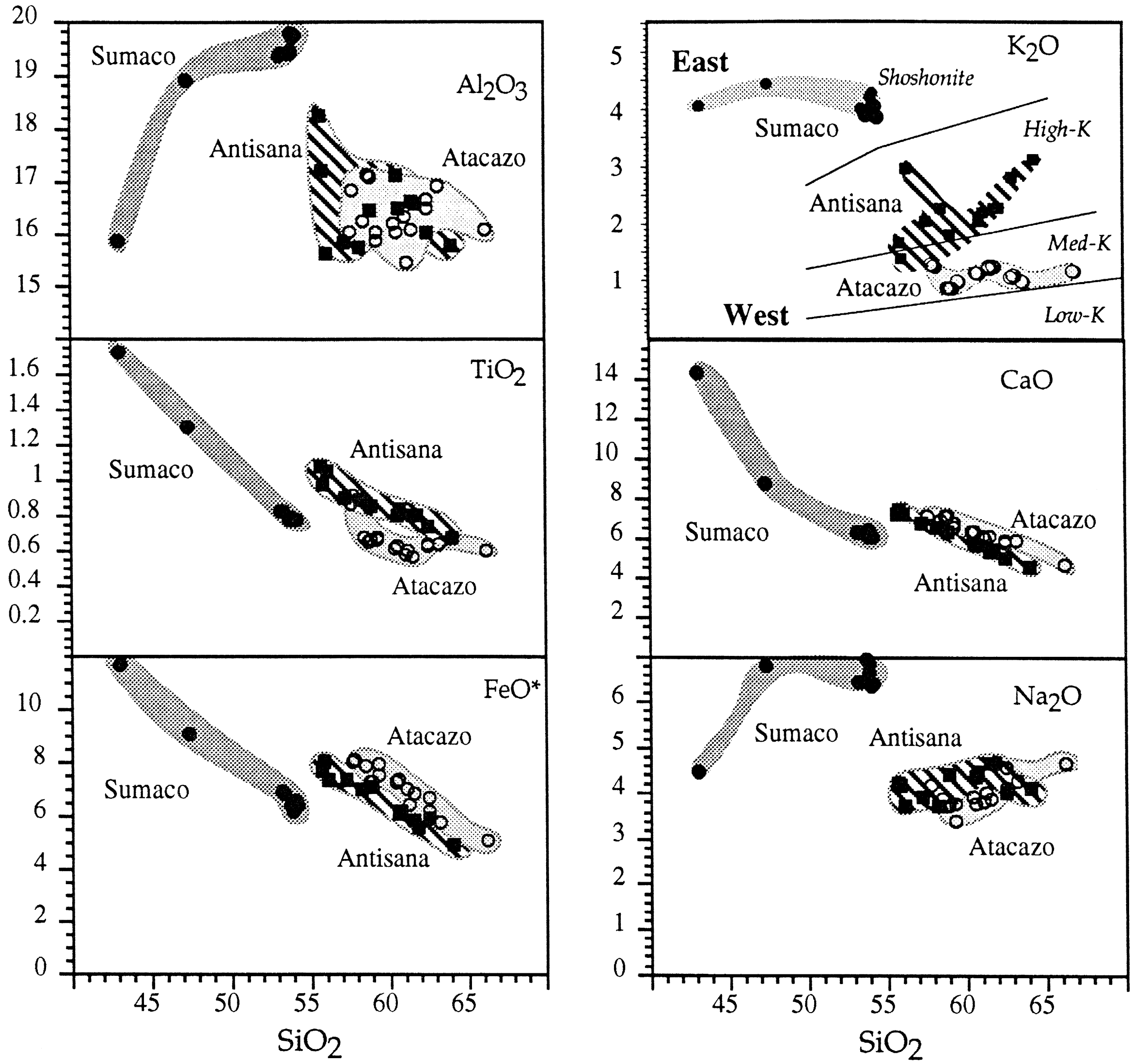

Fig. 2. Major-element Harker diagrams of lavas from Atacazo, Antisana, and Sumaco volcanoes. Fields on K_2O diagram from [16].

and the Cordillera Real (east). The two chains lie 40–50 km apart and are separated by the inter-Andean depression [12]. A third volcanic zone, consisting of back-arc volcanoes, lies in the Amazonian basin, east of the Andes.

A notable feature of these three volcanic zones is that each lies on a different crustal province, marked by differences in crustal age, composition, and thickness and separated by steeply-dipping shear zones [6–8]. The western part of Ecuador (north of 2.5°S) is made up of the Piñon terrane, an allochthonous terrane of basaltic basement of Cretaceous age overlain by younger arc rocks [13]. It is thought to have become sutured to South America in the Early Eocene [6]. Bouguer anomalies of up to +162 mGal indicate that the entire 30 km crustal section is mafic [14]. Paleocene to Early Eocene calc-alkaline arc rocks (called the ''Macuchi'' formation) are tectonically emplaced on the east side of the Piñon block. The eastern boundary of the Piñon terrane is the Cala-

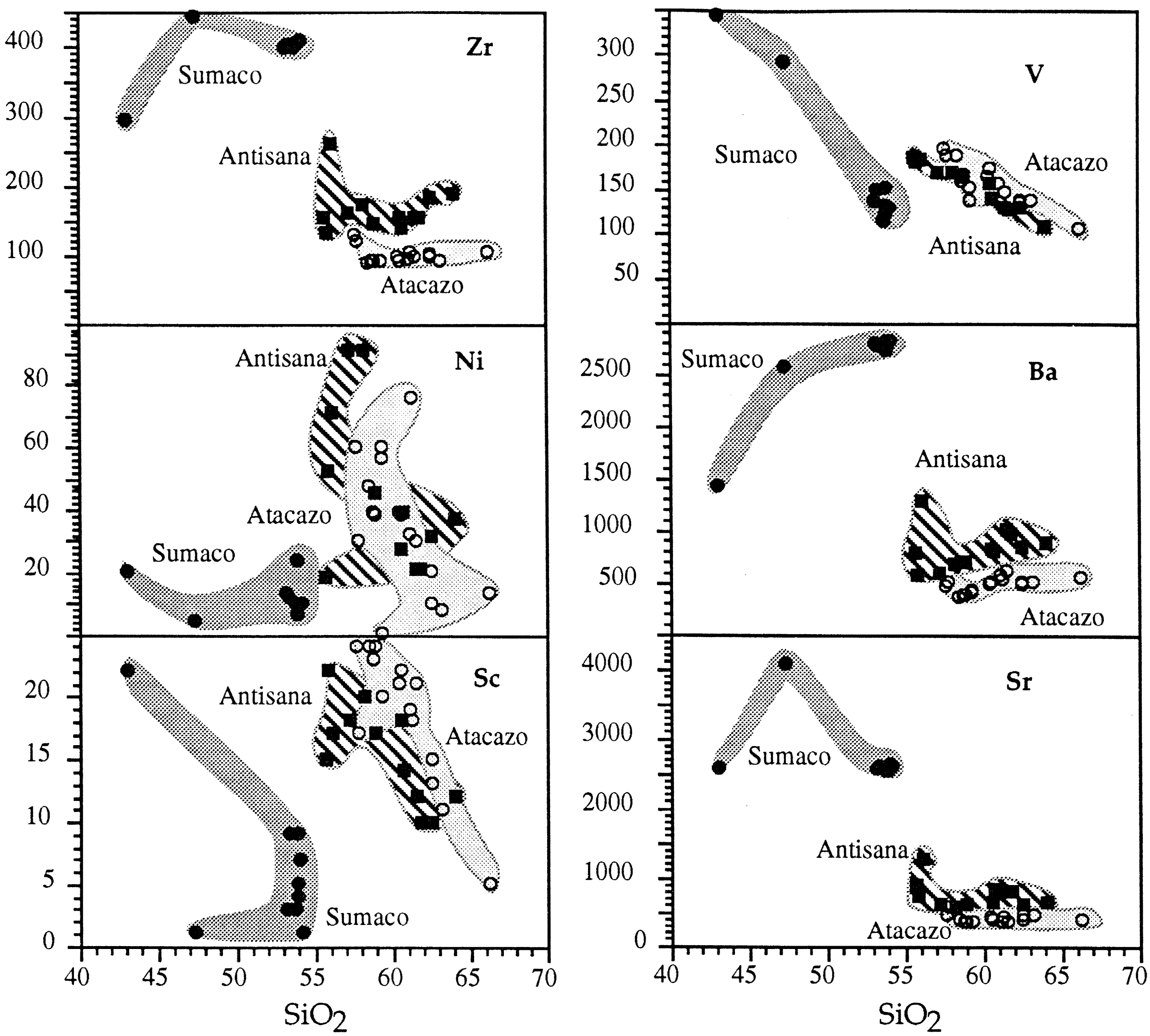

Fig. 3. Selected trace-element variation diagrams of lavas from Atacazo, Antisana, and Sumaco volcanoes.

cali–Pallatanga–Palenque (or ''Romeral'') fault, which bounds the west side of the inter-Andean depression in this region (Fig. 1).

The volcanoes of the Cordillera Real are underlain by metamorphosed Paleozoic and Mesozoic S-type granites and metasedimentary rocks of continental affinity [6,8]. The east margin of this terrane is defined by large-scale, steeply west-dipping faults that have thrust the metamorphic rocks of the Cordillera Real over unmetamorphosed continental-platform sedimentary rocks to the east. The Cordillera Real is characterized by negative Bouguer anomalies as great as −292 mGal, indicating low-density crust to depths of nearly 60 km [14].

The South American craton of the Amazon basin lies to the east of the Andes. Deep oil wells have penetrated granulites thought to be from the western part of the Guyana shield [6]. A thick sequence of Paleozoic and Mesozoic sedimentary rocks rests upon this basement, and is overlain in turn by a sedimentary fan of Late Jurassic to modern age whose source has been the Andes [7]. Bouguer gravity anomalies indicate that the crustal thickness in this area is a typical 35–40 km [14]. Abundant seismic reflection profiles reveal many thrust faults, of Late Cretaceous to Quaternary age, which are apparently related to transpression driven by plate convergence [7]. No young extensional structures have been identified that could conceivably be related to the back-arc setting and the alkaline volcanism.

3.1. Atacazo volcano

Atacazo volcano is located in the Cordillera Occidental ~25 km southwest of Quito and rises to 4455 m. An older, mid-Pliocene to Pleistocene (410,000 ± 10,000 to 300,000 ± 10,000 y) andesitic edifice is truncated by a large late Pleistocene–Holo-

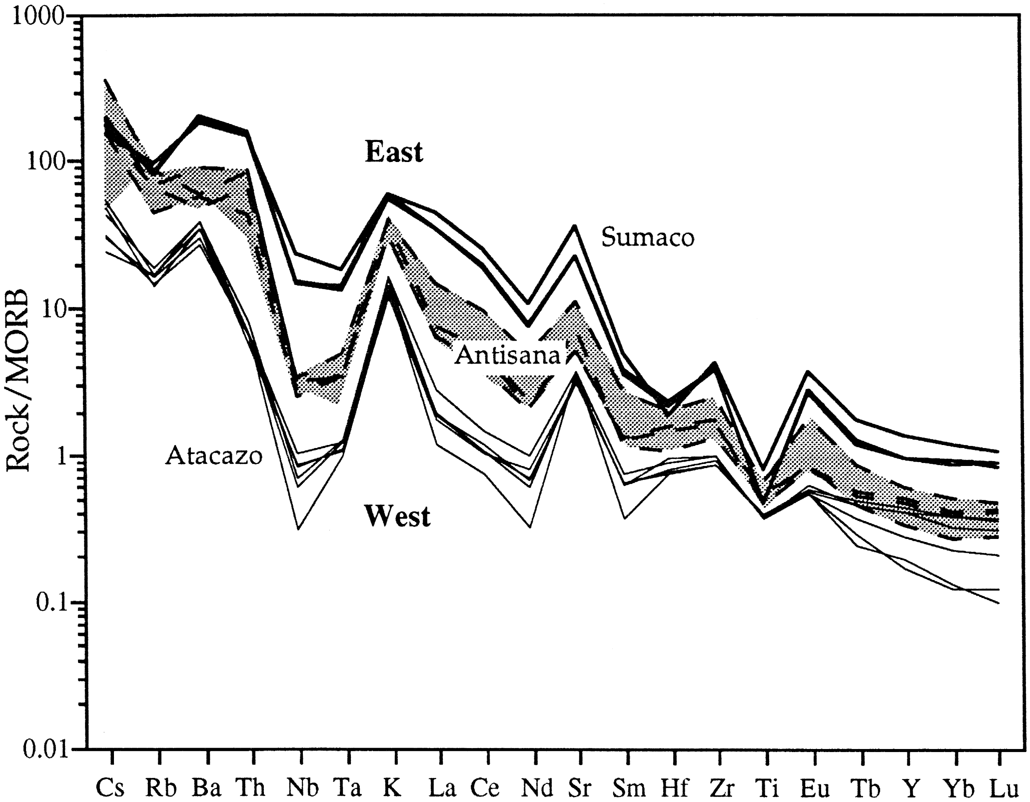

Fig. 4. MORB-normalized incompatible-element diagram of selected lavas from the three volcanoes. Normalization factors and element order from [29].

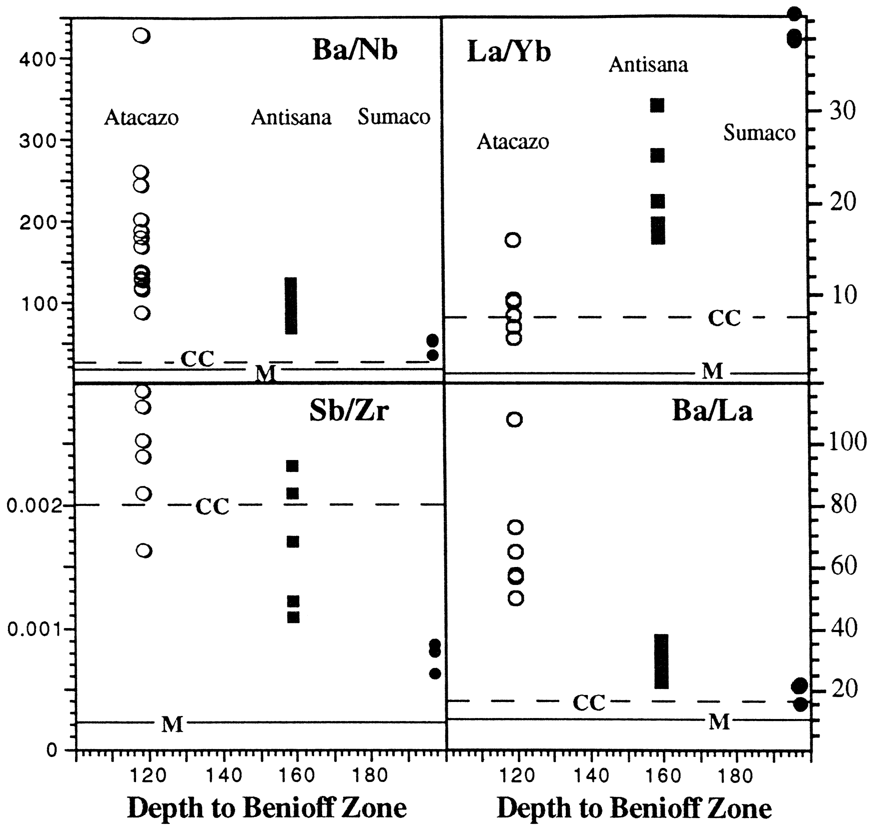

Fig. 5. Variation in element ratios with respect to the depth to the Benioff zone [11] for lavas from Atacazo, Antisana, and Sumaco. Numerators are elements that are abundant in slab-derived fluid and denominators are elements substantially less mobile [30–32]. Continental crust (CC) [27] and mantle (M) [29] values are also shown.

cene summit caldera that opens to the southwest [15]. The older lavas are dominantly porphyritic, two-pyroxene andesites. Two younger andesitic to dacitic domes are located on the outer southeastern flank of the caldera, and three dacitic domes lie within the 6 km wide, 900 m deep caldera. The youngest dome, Ninahuilca, erupted only 2370 ± 70 years ago [15]. The dome lavas are two-pyroxene andesites, hornblende andesites, and hornblende dacites.

The lavas of Atacazo belong to the medium-K calc-alkaline clan [16] (Fig. 2). Atacazo's lavas are notably poor in the incompatible trace elements, and the compatible elements (Ni, Sc, and V) decrease with increasing SiO_2 concentrations (Fig. 3). Atacazo's lavas are all light-REE enriched but have lower La/Yb than lavas from the other two volcanoes (Figs. 4 and 5). All of Atacazo's lavas have pronounced negative Nb and Ta anomalies on MORB-normalized diagrams (Fig. 4).

3.2. Antisana volcano

Antisana volcano, one of the highest mountains in Ecuador, rises to an altitude of 5735 m and is located in the Cordillera Real, 50 km southeast of Quito. It is surrounded by older volcanic rocks, but these in turn lie upon S-type granites and metasedimentary rocks of the Loja division [8]. An older edifice makes up the eastern half of the volcano and is truncated by several large amphitheaters that open to the inaccessible northeast, south, and east slopes. A younger composite cone grew upon the northwest part of the old edifice and constitutes the bulk of the volcano. In addition, two lava flows erupted from satellite fissures 15 km west of the base of the cone in the 18th century [17]. All Antisana lavas examined in this study contain 30–40% plagioclase (An_{34-46}), 10% hypersthene, 2% augite, and sparse olivine (Fo_{62-70}) phenocrysts. The satellite flows contain sparse resorbed quartz.

Antisana's lavas are of the high-K calc-alkaline type (Fig. 2). Most of the samples plot along simple linear trends on Harker diagrams. The incompatible elements are richer in Antisana lavas than those of Atacazo, especially the highly-incompatible trace elements (Figs. 3 and 4). Compatible-element trends are indiscernible from those of Atacazo (Fig. 3).

3.3. Sumaco volcano

Sumaco volcano rises from the Amazonian basin, to the east of the Andes and 105 km east of Quito [18]. The volcano is constructed upon a Phanerozoic sedimentary sequence that overlies cratonic South America [7]. Sumaco has a symmetrical composite morphology, and there are reports of three explosive eruptions, the most recent in 1933 [19]. The lavas of Sumaco are distinctly alkaline and are feldspathoid-bearing tephrites, basanites, and phonolites. The lavas are porphyritic and contain phenocrysts of hauyne and nosean (5–8%), leucite, sodic augite, and plagioclase (An_{33-53}). Olivine, apatite, and magnetite occur in most samples as well. Small crystals of nepheline occur in the groundmass. The alkaline mineral assemblage is reflected in the major-element compositions of the lavas, which shows their shoshonitic affinity (Fig. 2). Sumaco's lavas are rich in all of the incompatible elements and light-REE enriched (Figs. 3 and 4). Ta and Nb anomalies are much smaller than in the lavas of Antisana and Atacazo (Fig. 4). Despite their low silica contents and mafic appearance, Sumaco's lavas are strongly evolved, with lower MgO, Cr, and Ni abundances than the andesites of Atacazo and Antisana (Fig. 3).

4. Geochemical comparisons of the volcanoes

The outstanding feature of this transect across the Ecuadorian Andes is the systematic change in composition of the lavas away from the trench (Figs. 2–6). For nearly all of the analyzed elements (Table 1; for complete data see **EPSL Online Background Dataset** [2]), the differences among the volcanoes is overwhelmingly greater than the variation within the individual suites. Thus, the focus of this work is a comparison of the three volcanoes.

4.1. Isotopic tests of assimilation

The $^{87}Sr/^{86}Sr$ ratios of lavas from these volcanoes range from 0.70416 to 0.70428, only slightly higher than typical (or ''isotopically coherent'' [20]) island arc lavas, but well within the global range of island arcs (Fig. 7). Likewise, the $^{143}Nd/^{144}Nd$ ratios of the Ecuadorian lavas range from 0.51279 to 0.51289, slightly lower than typical island arc lavas (0.51297 to 0.51305) [20]. $\delta^{18}O$ values of the Ecuadorian lavas range from +6.1 to +8.1‰, with the highest values coming from Atacazo; $\delta^{18}O$ values from Antisana and Sumaco volcano fall within the island arc range of $+6.0 \pm 0.3$‰ [21].

Measurable assimilation of continental crust may be indicated by the higher $\delta^{18}O$ values of the Atacazo lavas and the lower $^{143}Nd/^{144}Nd$ of the Antisana lavas, but mass balance indicates that the amount of assimilation must be small. The high $\delta^{18}O$ values measured at Atacazo may be accounted for by ~15% assimilation of crustal rocks with a $\delta^{18}O$ value of +20‰, assuming a parental magma with a typical island-arc value of +6.0‰ (cf. [22]). If assimilation is responsible for increasing the $\delta^{18}O$ values of the Atacazo magmas, the likely assimilant would be altered Cretaceous mafic rocks of the Piñon terrane. Other considerations suggest that 15% assimilation is an overestimation. The very low Nb and Ta abundances in Atacazo lavas (some with Nb < 1.5 ppm and Ta < 0.20 ppm) preclude significant assimilation of crustal rocks. Also, the reported measurements are on whole-rock powders; recent work in our laboratories indicates that incipient weathering in optically-pristine oceanic basalts may raise the $\delta^{18}O$ value by ~0.5–1.0‰ [23]. It is also possible that the parental magmas of the Atacazo andesites have unusually high $\delta^{18}O$, but this cannot be tested until a thorough study of intra-suite variation of Atacazo is completed.

[2] http://www.elsevier.nl/locate/epsl, mirror site: http://www.elsevier.com/locate/epsl

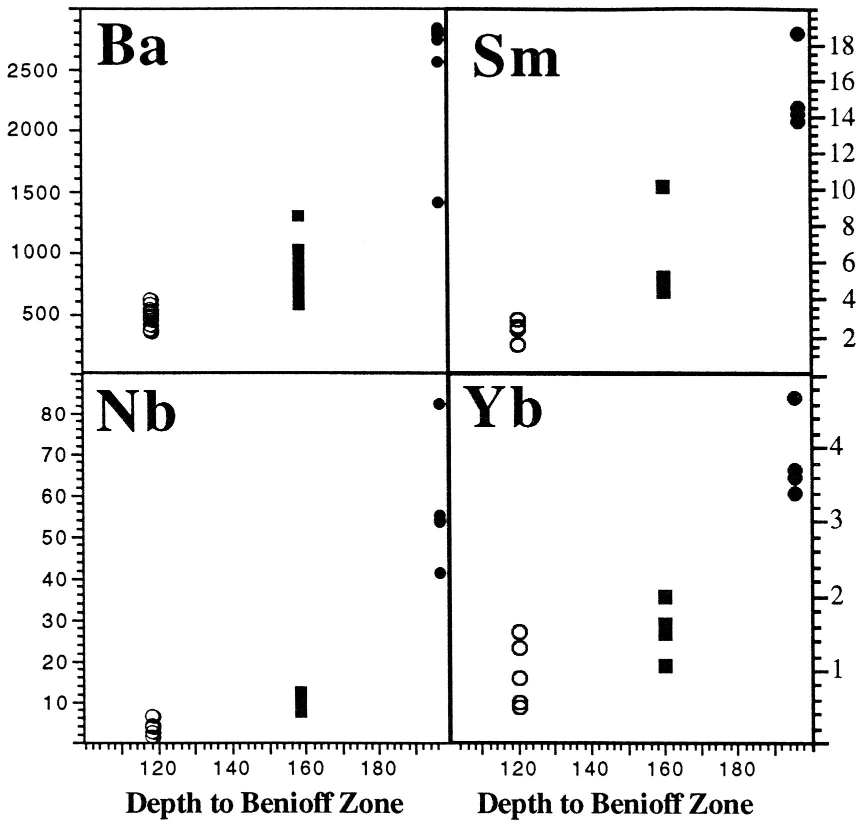

Fig. 6. Variation in the abundances of incompatible trace elements in lavas from the Ecuadorian Andes with distance above the Benioff zone.

The $^{143}Nd/^{144}Nd$ ratios of Antisana lavas are consistently lower than those of the other two volcanoes (Fig. 7). This probably relates to the fact that these magmas have ascended through an exceedingly thick section of continental crust and assimilated some of it. Nonetheless, the extent of assimilation is probably small. For example, simple assimilation of 8% continental crust with $^{143}Nd/^{144}Nd$ of 0.5120 is required to lower a magma's $^{143}Nd/^{144}Nd$ ratio from 0.51288 to 0.51279, assuming similar Nd concentrations in the basaltic to andesitic magma and the continental crustal materials.

Other than these two marginally-significant exceptions, none of the elements, elemental ratios, and isotopic ratios for which we have data change in a logical way in relation to the type or thickness of the crust on which the volcanoes sit, as would be the case if the magmas result from extensive assimilation of the lower crust [1]. The most obvious illustration is direct comparison of Atacazo, which lies on young, thin crust of oceanic affinity, to Sumaco, which lies on cratonic crust. Atacazo's lavas are much richer in SiO_2 than Sumaco's, a relation opposite that expected for assimilation of crustal material. Moreover, the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of lavas from the two volcanoes are virtually identical (Fig. 7). This is in striking contrast to the volcanoes of Chile, where the $^{87}Sr/^{86}Sr$ ratios correlate quite strongly with crustal thickness, increasing from 0.7036 to 0.7057 as the crust thickens from 30 to 60 km [1].

Sumaco's lavas are fundamentally different from other back-arc shoshonitic provinces of the Andes whose lavas have large contributions from the crust and lithospheric mantle. For example, lavas from the Pocho province in Argentina are believed to have assimilated large amounts of lithospheric mantle or lower-crustal granulites [24], because they are no-

Table 1
Representative analyses

	Atacazo volcano		Antisana volcano			
	At 01	8557 At	3.2 An	HHJ-An	GS-3	3D2
SiO_2	59.00	59.43	58.28	62.68	54.12	47.56
Al_2O_3	17.05	15.85	15.70	16.02	19.74	18.89
TiO_2	0.65	0.67	0.88	0.73	0.76	1.29
FeO^*	7.18	7.83	6.92	5.81	6.09	8.99
MnO	0.11	0.12	0.11	0.09	0.22	0.32
CaO	7.05	6.71	6.42	4.91	6.01	8.63
MgO	4.25	4.90	5.46	2.69	1.67	2.49
K_2O	0.89	0.98	2.30	2.84	4.31	4.43
Na_2O	3.68	3.38	3.72	4.01	6.61	6.77
P_2O_5	0.12	0.12	0.23	0.22	0.45	0.64
Zr	91	90	171	183	403	441
Ni	38	60	91	31	9	4
Sc	24	20	20	10	4	1
V	166	136	167	129	132	292
Ba	384	406	661	827	2806	2563
Rb	19	20	84	111	106	125
Sr	362	351	580	583	2542	4059
Zr	91	90	171	183	403	441
Y	16	13	18	17	35	49
Nb	2.9	3.4	9.8	11.8	54.0	82.0
$^{87}Sr/^{86}Sr$	0.704187	0.704304	0.704213	0.704194	0.704195	0.704243
$^{143}Nd/^{144}Nd$	0.512850	0.512890	0.512796	0.512799	0.512894	0.512893
$\delta^{18}O$	+8.1	+8.0	+6.7	+6.1	+6.2	+6.2
Sc	20.4	6.4	16.8	9.9	3.4	2.5
Cs	0.44	0.35	2.41	5.22	2.57	2.21
La	6.9	7.4	24.9	29.8	135.0	173.0
Ce	12.5	14.5	59.3	64.4	237.0	302.0
Nd	8.9	7.4	23.5	26.2	87.6	121.0
Sm	2.41	2.36	4.82	5.07	14.00	18.50
Eu	0.78	0.73	1.13	1.06	3.65	5.03
Tb	0.44	0.25	0.49	0.46	1.08	1.59
Yb	1.50	0.48	1.60	1.52	3.38	4.67
Lu	0.22	0.07	0.25	0.24	0.53	0.63
Hf	2.36	2.85	4.39	4.73	6.73	5.65
Ta	0.22	0.24	0.70	0.94	2.68	3.54
Th	1.2	1.3	12.2	16.1	29.1	27.8
U		0.73	5.19	6.39	10.70	7.26

Techniques are discussed in the text. Complete data set available from EPSL Online (http://www.elsevier.nl/locate/epsl, mirror site: http://www.elsevier.com/locate/epsl).

tably poor in Rb, U, and Th and have low La/Yb and $^{143}Nd/^{144}Nd$ ratios. Sumaco's lavas lack these features. Shoshonitic lavas from the Puna plateau [25] and Bolivian Altiplano [26] have even higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios ratios, reflecting substantial (> 20%) upper-crustal contributions and perhaps an origin in ancient lithospheric mantle. Sumaco's shoshonitic lavas are isotopically identical to the arc lavas, thus are likely related to similar sources without substantial contributions by the ancient lithospheric mantle that underlies the South American craton.

Much of the discussion that follows focuses on the trace-element ratios Ba/Nb and La/Yb. Assimi-

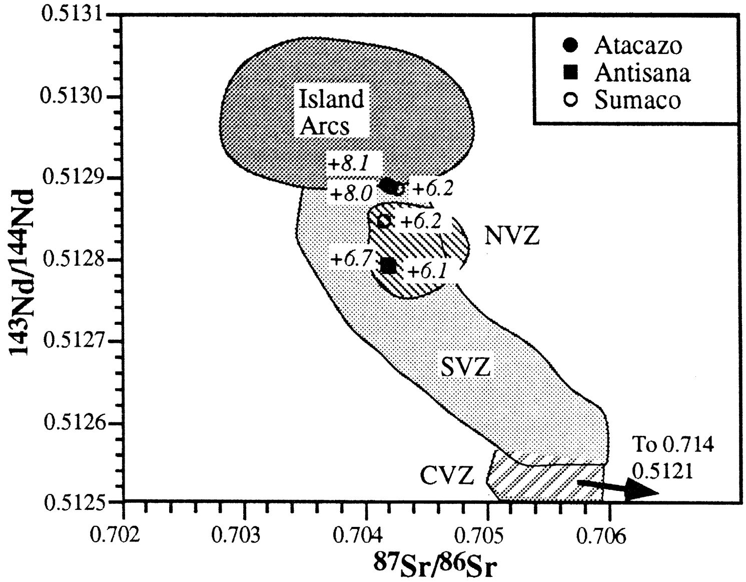

Fig. 7. Variation of Sr and Nd isotopes in lavas from the Atacazo, Antisana, and Sumaco volcanoes, showing fields from Andes Southern, Central, and Northern Volcanic Zones (SVZ, CVZ, NVZ; from [2] for comparison. $\delta^{18}O$ values indicated in *italics*.

lation of typical continental crustal material [27] in any proportion is unlikely to produce the systematic changes observed in the Ecuadorian lavas (Fig. 8). Even if atypical crustal materials are being assimilated, the < 15% of assimilation that is indicated by the Sr, Nd, and O isotopic ratios is unlikely to change markedly the La/Sm or Ba/Nb ratios of the magmas. Because the silica contents, incompatible-

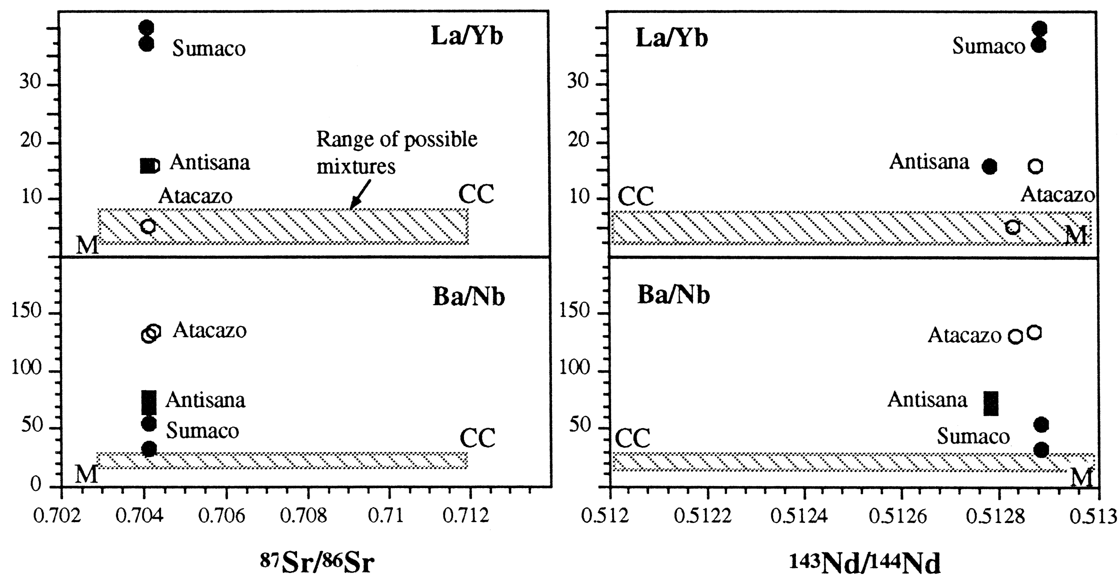

Fig. 8. Sr and Nd isotopic ratios compared to La/Yb and Ba/Nb ratios. *Rectangles* indicate extreme limits of mixing between typical mantle material (M) [29] and typical crustal materials (C) [27]. Most of the Ecuadorian lavas lie outside this limit.

element concentrations and ratios, and Sr, Nd and O isotopic ratios do not relate in a logical way to crustal thickness or the type of crust through which the magmas ascend, we conclude that assimilation is not important in bringing about the first-order differences in the compositions of these lavas.

4.2. Different slab contributions

It is well established that ratios of the large-ion lithophile elements (LIL; e.g., K, Rb, Cs, Ba) to high-field strength metals (HFS; e.g., Zr, Nb, Ta, Ti) and the REE are higher in island-arc lavas than they are in mid-ocean ridge and ocean-island basalts [28]. This fundamental difference has been attributed to mass transfer of a fluid (melt or volatile-rich phase) from the subducted slab to the overlying mantle wedge.

Lavas from Atacazo volcano have LIL/HFS and LIL/REE ratios similar to some island arc andesites. In stark contrast, lavas from Sumaco have much lower LIL/HFS and LIL/REE ratios, nearly as low as those typical of ocean-island lavas. Lavas from Antisana volcano have intermediate ratios. Overall, there is a clear relation between the depth to the Benioff zone and ratios of elements thought to be mobile in slab-derived fluids to those thought to be immobile (Fig. 5). This systematic change is not likely due to assimilation brought about by greater crustal thickness or in the type of crust, as the ratios are intermediate at Antisana (thickest crust) and lowest at Sumaco (mature continental crust). Instead, the systematic change in these ratios is likely due to a decreasing influence of slab-derived fluid into the mantle wedge as the Nazca plate descends further beneath South America (cf. [4,5]).

4.3. Different extents of melting

The concentrations of incompatible trace elements in the lavas steadily increase away from the trench as does the La/Yb ratio (Figs. 4 and 6). As noted above, this steady increase is not likely due to assimilation of crustal materials, as it is not accompanied by an systematic changes in $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $^{143}Nd/^{144}Nd$, and SiO_2. The most likely explanation for the increase in incompatible-element concentrations and La/Yb ratios away from the trench is that the magmas are the result of progressively lower degrees of partial melting of the mantle wedge (e.g., [4,5]).

4.4. Mixing calculations

The first-order compositional differences between the magmas from the three volcanoes are thought to be controlled by two parameters: the amount of slab-derived fluid and the extent of melting. These two parameters are directly related in that large fluid contributions correspond to large degrees of melting (cf. Figs. 5 and 6). All of the lavas considered here are evolved andesites, thus the absolute concentrations of the incompatible trace elements in the primary magmas are almost unconstrained. Therefore, we focus our modeling effort on ratios of incompatible trace elements that are unlikely to be strongly modified by crystal fractionation or small amounts of assimilation.

We have generated a melting and mixing model that mimics diagnostic trace-element ratios of the three suites (Fig. 9). The model assumes that the compositional differences in these lavas are due to two principal factors: (1) different degrees of partial melting of a depleted mantle source (as indicated by the Nd isotopic ratios); and (2) different contributions of a fluid or magma derived from the subducted lithosphere. These models are obviously not unique, but show that this explanation is workable with reasonable parameters. Batch modal melting of depleted MORB-producing mantle is assumed (source composition calculated from the parameters given in [29]), and bulk melt–solid distribution coefficients are assigned as La = 0.01, Yb = 0.8, Ba = 0.01, and Nb = 0.3. The relatively high distribution coefficient for Yb presumes a garnet-bearing source. The relatively high Nb distribution coefficient presumes a phase such as amphibole or rutile remains in the residuum. Nb concentrations as low as 1.1 ppm in Atacazo andesites (cf. nMORB concentrations of 3.5 ppm [29]) virtually require that a Nb-retentive phase was present during melting, no matter the source. The concentration of La and Ba in the slab-derived fluid is that calculated for Marianas back-arc basin basalts [30]: Ba = 1370 ppm and La = 99 ppm. Nb and Yb concentrations in the fluid are assigned to be 0 and 10 ppm, respectively (estimated from [31]).

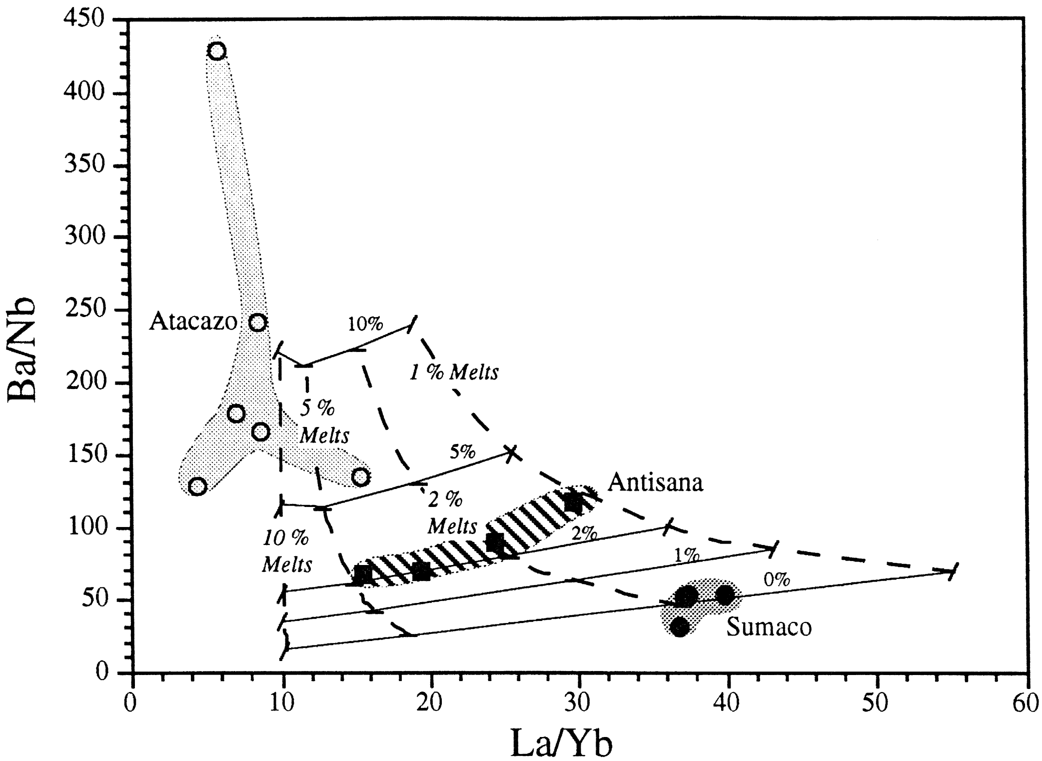

Fig. 9. Partial melting–slab fluid mixing model for Ba/Nb and La/Yb ratios in comparison to observed ratios in lavas; model parameters are discussed in the text. *Dashed curves* connect melts produced by equal degrees of partial melting; *solid curves* connect melts with equal proportions of slab-derived fluid.

Reasonably well-fitting models using the parameters above indicate that Atacazo's magmas may result from an average of 15% melting, Antisana's magmas from 3% melting and Sumaco's magmas from 2% melting (Fig. 9). Atacazo's magmas have an average of 7% fluid component (discounting the single sample with extremely high Ba/Nb), Antisana's magmas 2%, and Sumaco's nil. These fluid proportions are for the amount of slab-derived fluid in the melt; normalizing them by the extent of melting gives the proportion of fluid introduced into the mantle wedge, which results in 1.1%, 0.06%, and nil for the three volcanoes. We emphasize that the magnitude of these results depend strongly on the source composition, the bulk distribution coefficients, and especially the fluid composition, which are poorly constrained. For example, the composition of the introduced fluid no doubt changes as the slab descends, becomes progressively depleted in mobile species, undergoes different devolatilization reactions, and different residual phases are stable [32]. Nonetheless, the model demonstrates that these magmas may be produced by decreasing inputs of slab-derived fluids, which in turn cause decreasing extents of melting.

Nb/Ta ratios are in accord with the interpretation that the principal control on the compositions of the Ecuadorian andesites are imparted by a slab component and different extents of melting of a depleted mantle source. Plank and White [33] have demonstrated that mid-ocean ridge basalts and depleted arc lavas (those with low Nb concentrations) have Nb/Ta ratios ranging from ~ 6 to the chondritic ratio of 17 ± 1. The low ratios are attributed to derivation of both arc and mid-ocean ridge magmas from a source that had been previously depleted by partial melting. In contrast, arc lavas from the Bismark and Tongan arcs have Nb/Ta ratios ranging from 17 in lavas relatively depleted in incompatible elements to 33 in potassic lavas [34]. These higher ratios are attributed to enrichment of the mantle wedge by silicic melts that have left rutile in the residuum, as opposed to enrichment by a volatile-rich phase. The lavas from the three Ecuadorian volcanoes of this study have consistently increasing Nb/Ta ratios with increasing Nb concentrations, which in turn relates to the distance from the trench. Nb/Ta ranges from 6 to 15 at Atacazo, indicating derivation from a depleted, MORB-like source [33]. In contrast, Nb/Ta ratios at Sumaco are all higher than the chondritic ratio, ranging from 19 to 23, similar to other potassic arc lavas [34].

5. Conclusions: melt genesis and evolution

Trace-element concentrations and ratios and isotopic ratios in lavas from a transect across the Ecuadorian Andes indicate that assimilation does not play a fundamentally significant role in their genesis. Instead, the characteristic aspects of the magmas are principally controlled by the amount of fluid introduced into the mantle wedge by the subducted slab. The amount of fluid introduced in turn controls the extent of melting. At the arc front, a relatively large input of fluid causes large extents of melting. With successive devolatilization, decreasing amounts of fluid or magma are introduced into the mantle wedge from the subducted lithosphere, and the extent of melting becomes smaller.

These geochemical variations believed to link the amount of slab fluid to the extent of partial melting are common elsewhere in the Andes and in other continental arcs. Hickey and coworkers have described similar features in lavas in lavas of the Southern Volcanic Zone of the Andes [4,5]. A similar trend exists in a transect across the central Andes, although those lavas have a much larger crustal contribution [26]. Ryan and others [31] find almost exactly the same trends in a transect perpendicular to the Kurile island arc, which are also explained by a direct relation between the amount of slab-derived fluid and the extent of partial melting. A similar relation between slab input and degree of melting exists in the Central American arc, but the principal control there is changing dip of the subduction zone (which varies from 30° to 80°) along strike of the arc [35]. The reasons why some continental arc magmas undergo large amounts of assimilation and others do not remain elusive, but clearly crustal thickness is not the only control.

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