ORIGIN AND EVOLUTION OF THE BACK ARC MAGMATISM OF ECUADOR (NORTHERN VOLCANIC ZONE, ANDES): EL REVENTADOR AND SUMACO ACTIVE VOLCANOES

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INTRODUCTION

The subduction of the Nazca and Antarctic plates under the continental west margin of South America is responsible for the Plio-Quaternary magmatic activity along the Andean Cordillera. This volcanism is divided into four separate provinces (Northern Volcanic Zone or NVZ, Central Volcanic Zone or CVZ, Southern Volcanic Zone or SVZ and Austral Volcanic Zone or AVZ), each one separated from the others by the presence of a volcanic gap, due to segments of flat slabs: the Peruvian, Pampean, and Southern Chile subduction, being this latter linked with the subduction of an active oceanic ridge.

Offshore of the Ecuador an aseismic Ridge is present, the Carnegie Ridge, which is interpreted to be the track of the Galàpagos hot spot on the Nazca plate. Unlike Perù or Chile, in Ecuador the volcanic gap is not present: the Ecuadorian volcanism is characterized by intense activity which is localized both trenchward and in the back arc direction (Bourdon *et al.*, 2003).

The Plio-Quaternary Ecuadorian volcanic arc (NVZ) is constituted by the Western Cordillera (fore-arc) and the Cordillera Real (main-arc). Other volcanoes, including El Reventador and Sumaco, are also present in the rear-arc zone (far from the trench). In this zone it is difficult to explain the occurrence of both calc-alkaline and alkaline products distinctively erupted by these two Quaternary volcanoes, located only 50 km far each other and over the same basement rocks: Jurassic granitoid intrusions covered by volcanoclastic formations (Misahuallì) and Cretaceous metamorphosed sedimentary sequences (Hollin, Napo and Tena formations; Fig. 1).

This study is going to deal with the processes responsible of such geochemical differences. In fact, simple subduction-related geodynamic models do not match with the presence, in the back-arc area and at the same distance from the trench, of both medium to high-K calc-alkaline (El Reventador) and alkaline (Sumaco) volcanic products. More than 300 rock samples were analysed in thin section (200 for El Reventador and 100 for Sumaco). On the basis of petrographic observations, selected samples were chosen for mineral chemistry and whole-rock chemistry (major-trace elements and Pb-Sr-Nd isotopic ratios).

VOLCANOLOGICAL BACKGROUND AND ERUPTIVE HISTORY

El Reventador is a stratovolcano of the Ecuadorian sub-Andean zone and it consists of a calderic amphitheatre (4 × 3 km), opened to the East, which accommodates the young active cone rising up approximately for 1300 m (Hall, 1977). The most recent eruption of El Reventador started on November 2002 (Hall *et al.*, 2004; Ridolfi *et al.*, 2008), with an explosive event (VEI = 4), followed by a sequence of lava flows which are discontinuously coming until now (May 2009).

The morphological, structural and chronologic evolution of El Reventador was characterised by a large stratocone (Old Volcanic Edifice, OVE) followed by a second stratovolcano which grew up

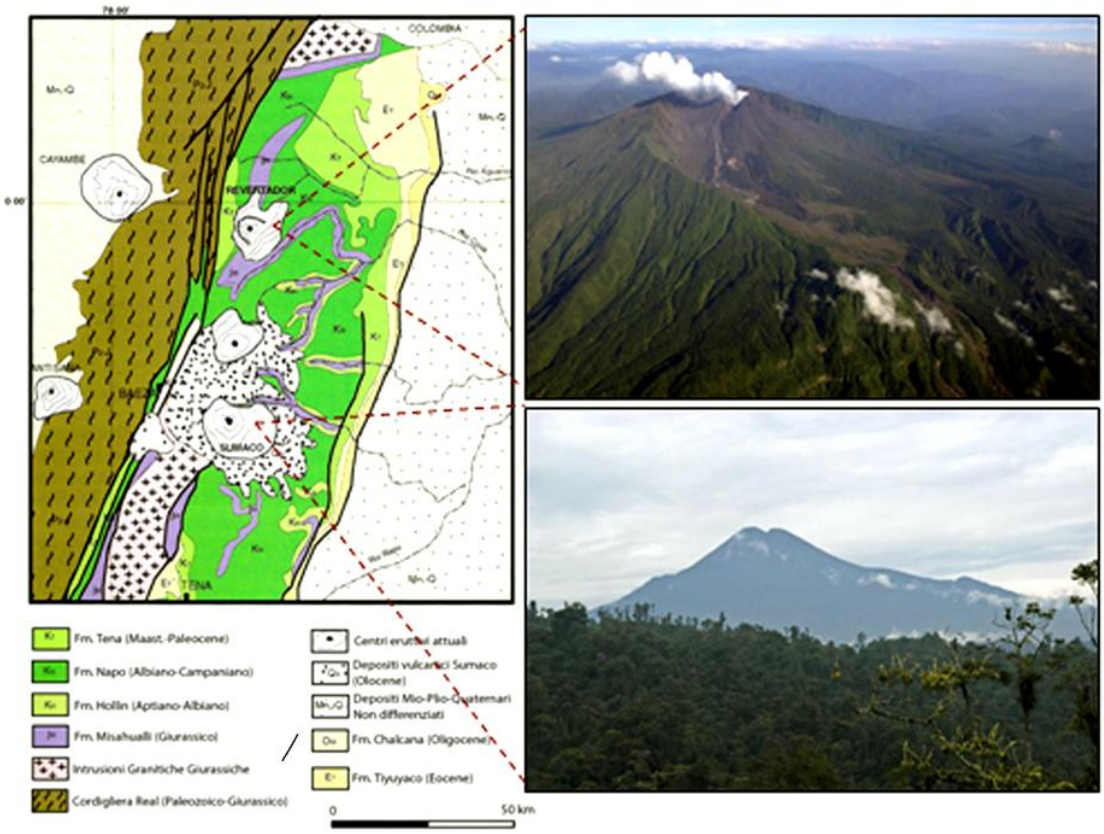

Fig. 1 - Geological sketch of the Ecuadorian sub-andean zone (from Barragàn & Baby, 2004); El Reventador (top) and Sumaco (bottom) volcanoes are also shown on the right.

asymmetrically with prevalent eastern development (Paleoreventador, PR). Paleoreventador underwent two major sector collapses with relative debris avalanche deposits. Currently, that is during the third stage of evolution, the activity is restricted to the young cone (Present Cone, PC) with an activity made of prevalent lavas and subordinate pyroclastic flows and ash fallouts.

Sumaco morphology is dominated by the presence of a conic structure with a basal radius of about 12 km, at the centre of which a symmetric stratocone, rising up for 2800 m, developed. This volcano is poorly known, with respect to the other Ecuadorian volcanoes, because of the difficulty to the access for the presence of the rain forest. The youngest eruptive activity may be ascribed at 1933 (Hantke & Parodi, 1966), although some local people eyewitnessed explosive activity in 1958 as well. The Sumaco structural evolution can be divided into two main stages: Paleosumaco (PS), the old edifice affected by an enormous sector collapse of the northeastern flank, and Neosumaco (NS), the youngest cone made of recent effusive and explosive products.

PETROGRAPHY AND MINERAL CHEMISTRY

The products of El Reventador are mainly represented by porphyritic lava, ranging from basalts to rhyolites (Aguilera *et al.*, 1988; Ridolfi *et al.*, 2008) and characterized by a phenocrysts assemblage made of plagioclase, clinopyroxene, opaque minerals, ± orthopyroxene, ± olivine, ± amphibole (± sanidine). Micro- to crypto-crystalline groundmass mainly consists of pyroxenes, plagioclases and Fe-Ti oxides.

Some gabbroic nodules, with cumulate texture, were found as cognate inclusions in the lavas. They are made of plagioclase, clinopyroxene, orthopyroxene, Ti-magnetite, amphibole and rare olivine.

One distinctive feature of El Reventador products is the presence of different kinds of amphibole breakdown coronas, which were well investigated and explained. The Al-in-amphibole geothermobarometry for the products erupted during November-December 2002 (Ridolfi *et al.*, 2008) was also discussed.

The products of Sumaco consist of porphyritic lavas with a common pilotaxitic groundmass and they vary from basanite to phonolite being characterized by the presence of modal feldspathoid (mostly haüyne and subordinate nepheline). The most common phenocrysts are represented by clinopyroxene and plagioclase. Olivine (in basanitic samples) apatite, amphibole, magnetite and K-feldspar may be also present among the investigated rocks. Titanite and pyrite are additional accessory phases (Colony & Sinclair, 1928; Barragàn *et al.*, 1998).

GEOCHEMISTRY

The oldest El Reventador products (OVE) are represented by the widest compositional range, from basalts to rhyolites with silica contents from 48.7 to 71.2%, and total alkali contents from 4.3 to 8.7%. Among all the products a small compositional gap is present between 63.0 and 66.0% of SiO_2. Al_2O_3 (21.9-15.8%), CaO (1.9-9.5%), MgO (0.4-6.7%), Fe_2O_3 (1.7-10.6%) and TiO_2 (0.2-1.2%) values show good negative linear correlations with SiO_2. P_2O_5 fix the apatite saturation at about 57.0% of silica. From PR to PC the most recent activity (PC), the most abundant products have intermediate composition: basaltic andesite and andesite. El Reventador volcano belong to a medium to high-K calc-alkaline series (Fig. 2).

By contrast, all the Sumaco products (from basanites to phonolites; Fig. 2) are characterized by an alkaline to high-K alkaline affinity (Fig. 3).

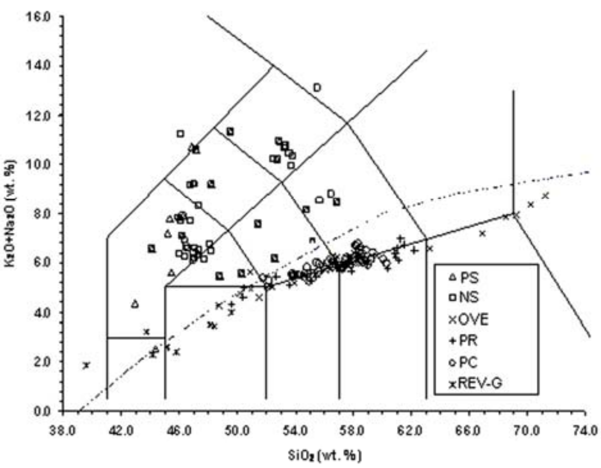

Fig. 2 - Total-alkali *vs.* Silica diagram; PS = Paleosumaco, NS = Neosumaco, OVE = El Reventador Old Volcanic Edifice, PR = Paleoreventador, PC = El Reventador Present Cone, REV-G = El Reventador cumulate gabbro nodules. Dashed line is from Irvine & Baragar (1971).

Basanites are the most common lavas of Sumaco (both for PS and NS) and their total alkali content ranges from 4.4 to 6.7%, whilst SiO_2 varies from 43.0 to 48.2%.

Some major elements concentrations, such as K_2O (2.1-5.0%), P_2O_5 (0.2-1.1%) and Na_2O (3.5-8.1%) are very high for lowest silica values (*i.e.* 45.2-56.5%) with respect to all volcanic products of the NVZ (Barragàn *et al.*, 1998; Bourdon *et al.*, 2003; Bryant *et al.*, 2006).

Although both volcanoes show the typical Nb-Ta-Ti negative anomaly as the result of a subduction-related environment, trace elements concentrations are markedly different between El Reventador and Sumaco. Small enrichment in incompatible trace elements with silica increase are typical of El Reventador lavas, especially for LREE (*i.e.* La = 20.5-38.6 ppm; Ce = 42.2-72.9 ppm; Pr = 5.4-8.8 ppm). By contrast, the Sumaco lavas are strongly enriched in all incompatible elements and show very low values of LILE/HFSE and LILE/REE ratios (*i.e.* Ba/Nb 35-105 and Ba/La 13-28). These ratios are close to those observed in some ocean island basalts (OIB, Barragàn *et al.*, 1998) even if some calcalkaline basalts (CAB) may also show similar ratios.

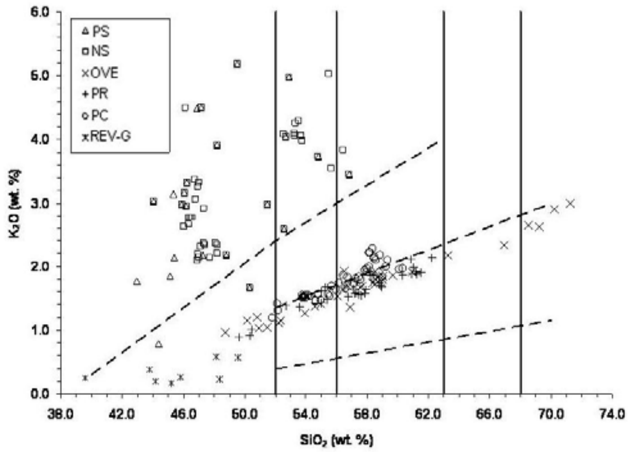

Fig. 3 - K_2O *vs.* Silica diagram; Symbols and abbreviations as in Fig. 2.

La/Yb ratios are higher for Sumaco samples than those for El Reventador, but both are similar to values observed by Hichey *et al.* (1986) in the SVZ of the Andes and interpreted as the result of low degree of partial melting of the mantle wedge. For both volcanoes La/Nb ratios are quite similar, although LREEs of Sumaco lavas are much higher with respect to those of El Reventador because the former is characterized by a very high abundance of Nb.

La/Sm_N ratios (up to 6.8 for Sumaco; 1.7-4.0 for El Reventador) point out the highest values for the Sumaco among all the lavas (with the same silica content) of the NVZ of the Andes. Sumaco geochemical affinity seems to be similar to some Nb-rich basalts which are associated to the adakitic magmatism of some volcanic arcs (Sajona *et al.*, 1996).

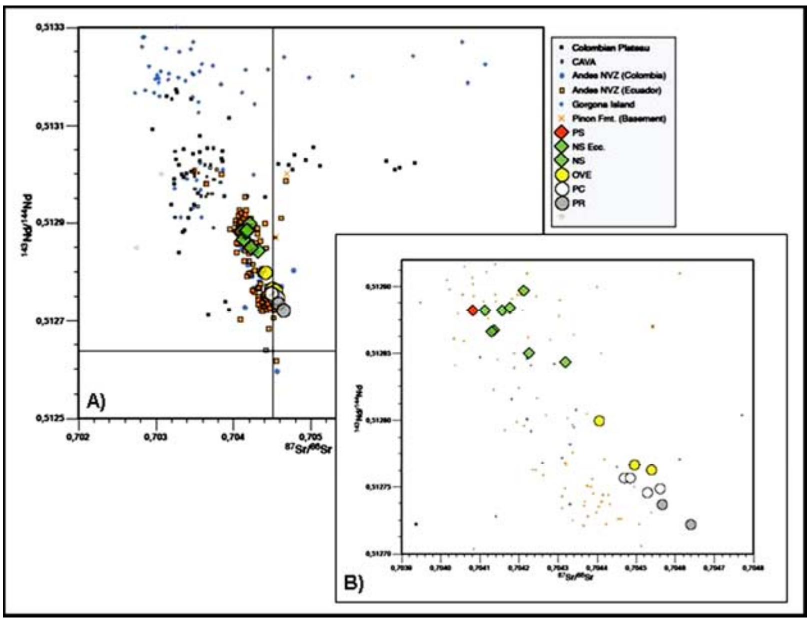

Fig. 4 - $^{87}Sr/^{86}Sr$ *vs.* $^{143}Nd/^{144}Nd$ isotopic ratios variation diagram (a), and relative inset (b) for El Reventador and Sumaco volcanic products; data from the literature are also shown (see legend). Symbols and abbreviations as in Fig. 2. The intersection of the horizontal and vertical lines in (a) represents the BSE (Bulk Solid Earth) composition, CAVA = Center America Volcanic Arc. NSecc = Neosumaco eccentric vents.

Radiogenic isotope data of El Reventador samples exhibit higher $^{87}Sr/^{86}Sr$ (0.70440-0.70464) and lower $^{143}Nd/^{144}Nd$ (0.51272-0.51280) with respect to Sumaco ($^{87}Sr/^{86}Sr$ from 0.70408 to 0.70432 and $^{143}Nd/^{144}Nd$ from 0.51284 to 0.51297; Fig. 4a). It is worth noting that the two distinct fields of El Reventador and Sumaco back-arc volcanoes are well within the Ecuadorian NVZ variation range ($0.7035 < {}^{87}Sr/^{86}Sr < 0.7047$; $0.5126 < {}^{143}Nd/^{144}Nd < 0.5130$). Nevertheless, El Reventador Sr isotopic ratios are among the highest values among the Ecuadorian volcanic rocks from the literature (Fig. 4b).

Lead isotope ratios show more complex variations. Whereas $^{207}Pb/^{204}Pb$ ratios are similar and almost constant, it is worth to note that El Reventador lavas have got lower values for $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$, which are clearly separated from all the other Ecuadorian volcanoes data from the literature (Fig. 5).

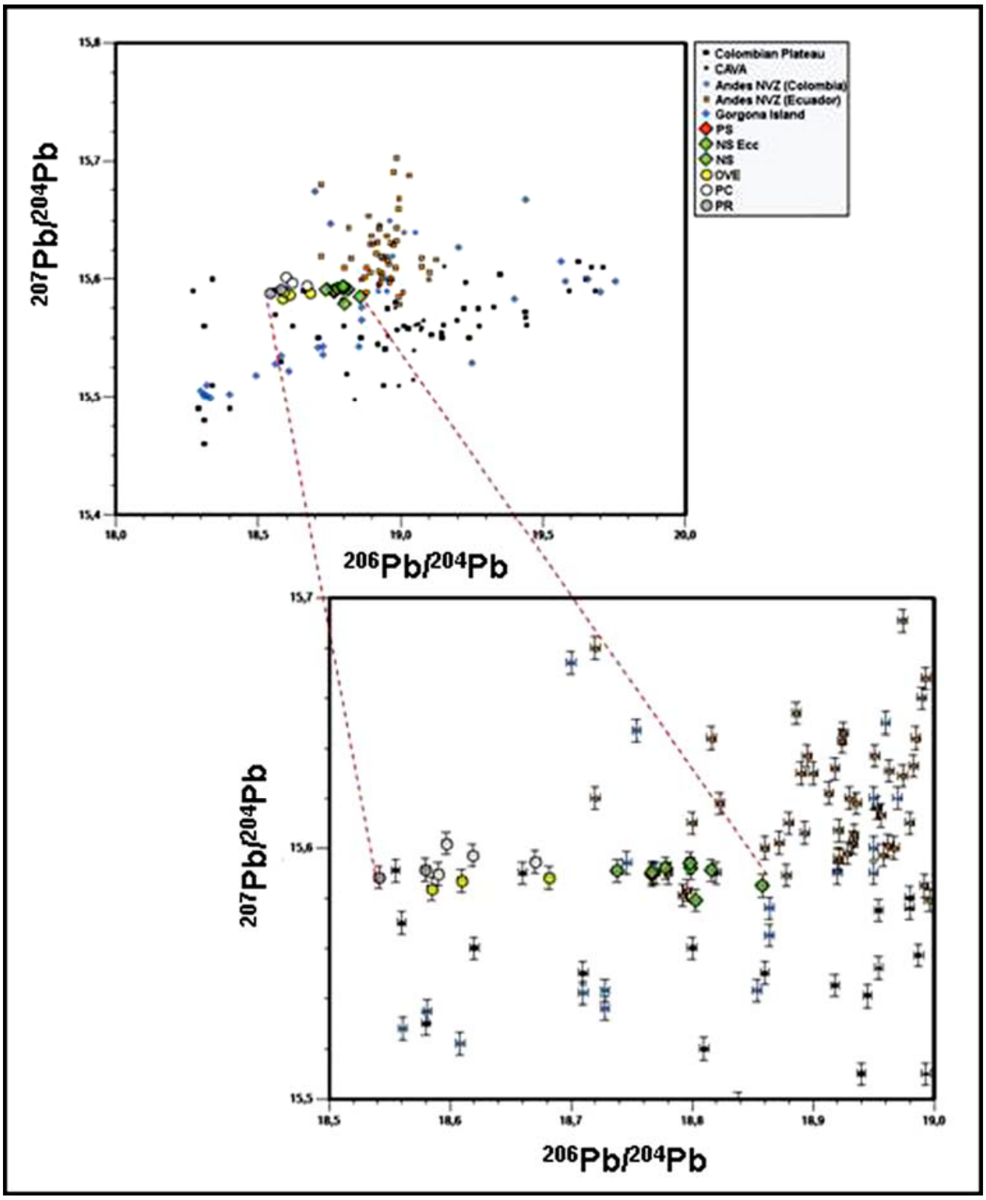

Fig. 5 - $^{207}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$ isotopic ratios variation diagram for El Reventador and Sumaco lavas (and relative inset). Symbols and abbreviations as in Fig. 4.

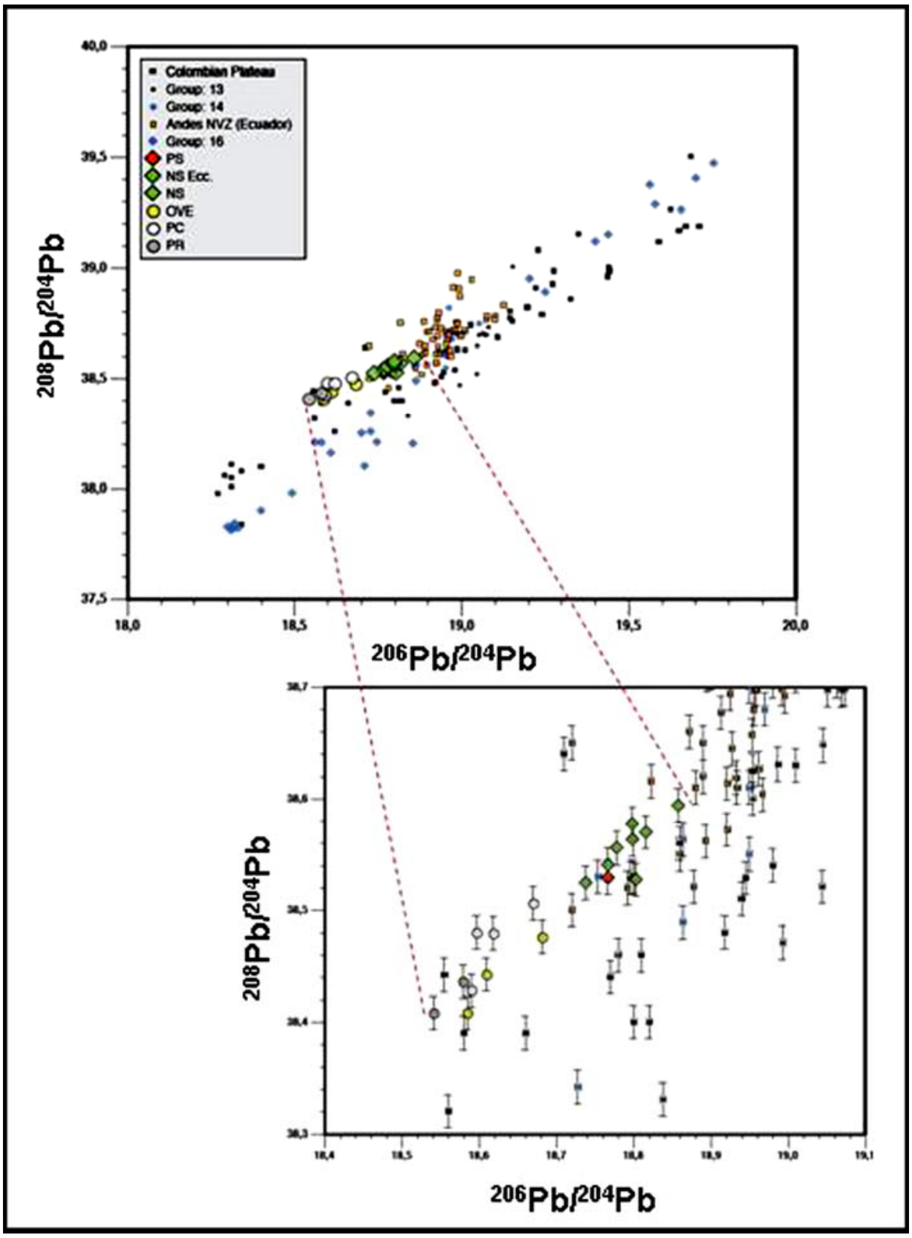

Fig. 6 - ^{208}Pb/^{204}Pb *vs.* ^{206}Pb/^{204}Pb isotopic ratios variation diagram for El Reventador and Sumaco lavas (and relative inset). Symbols and abbreviations as in Fig. 4.

In more detail, the studied rocks show a positive correlation between ^{208}Pb/^{204}Pb and ^{206}Pb/^{204}Pb for both volcanoes (Fig. 6). Lead isotope data for Sumaco ($18.738 < {}^{206}$Pb/^{204}Pb < 18.858; $15.579 < {}^{207}$Pb/^{204}Pb < 15.594; $38.525 < {}^{208}$Pb/^{204}Pb < 38.594) are comparable with the global Ecuadorian variation field ($18.700 < {}^{206}$Pb/^{204}Pb < 19.150; $15.575 < {}^{207}$Pb/^{204}Pb < 15.700; $38.450 < {}^{208}$Pb/^{204}Pb < 38.950) whereas those of El Reventador confirm different values from all the other Ecuadorian volcanoes and the lowest ^{208}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios ($18.541 < {}^{206}$Pb/^{204}Pb< 18.682; $15.584 < {}^{207}$Pb/^{204}Pb < 15.602; $38.408 < {}^{208}$Pb/^{204}Pb < 38.506; Figg. 5 and 6).

PETROGENETIC PROCESSES

Identification of magma sources in continental magmatic arcs, such as the Andean Cordillera, is a very complex geochemical task. This is more difficult when the subduction geometry (Benioff plane) is complex and not well defined by geophysical data because of the lacking or scarce seismicity of the subducted plate (Garrison & Davidson, 2003; Gutscher *et al.*, 1999). Physical structure of the Ecuadorian subduction zone suggests that different components may play a significant role in magma genesis: the mantle wedge, the subducted oceanic lithosphere, the physical-chemical characters of the slab, especially referring to the amount and type of the subducted sediments, and the nature and composition of the continental crust that the magmas pass through.

El Reventador and Sumaco volcanic products show completely different mineralogical and geochemical composition, even if they are located nearly at the same distance from the trench (360 km for Sumaco and 350 km for El Reventador), they grew upon the same basement rocks and they are located over mantle wedges with the same characters. The only geodynamic differences may be constituted by different subduction angles and, possibly, the occurrence of a subduction slab tearing close to Sumaco (Gutscher *et al*., 1999).

Erupted products from both volcanoes show Nb and Ta negative anomalies, which are slightly less marked in the Sumaco lavas. Fluid mobile elements are enriched with respect to the immobile ones: this is a peculiarity generally related to the release of the subduction fluids (Tatsumi & Eggins, 1995). El Reventador lavas, with their Sr/Y ratios between 40 and 75 and Y contents of 12-21 ppm, seems to have an adakitic-like signature (Barragàn & Baby, 2004) similar to the volcanoes of the Cordillera Real (*e.g.* Antisana and Cayambe; Monzier *et al.*, 1997) and the Western Cordillera (*e.g.* Pichincha; Bourdon *et al.*, 2002).

Differences in the geometry and/or age of the subducted slab may be responsible for heterogeneous kind of fluids ± melts which can "induce" different extent of metasomatism in the mantle wedge where the basic magmas of the active continental margin originate. In particular, metasomatism of the mantle wedge is usually stronger in correspondence of the main-arc.

The subduction of the slab may also generate some mantle wedge movement like "corner flows" (Tatsumi & Eggins, 1995) in which mantle metasomatized rocks are carried far from the trench.

New geochemical data collected during this work show different enrichments of the back-arc magmas of Ecuador, due to the subduction component. The subduction component may re-fertilize the mantle and normally triggers partial melting: trace elements and isotope data point out that the Sumaco Volcano is characterized by the smallest amount of this component and consequently by the lowest degree of partial melting of the mantle wedge among the Ecuadorian volcanoes. By contrast El Reventador lavas show geochemical peculiarities similar to other arc-lavas but with marked isotopic differences that are clearly visible considering lead isotopes, suggesting a carbonatic sediment signature (*e.g*. DSDP495 carbonatic sample; Plank & Langmuir, 1998; Pedersen & Furnes, 2001) as subduction-related melts which could have metasomatized the mantle wedge source.

We can summarize the origin and the evolution of the Sumaco magmas through the following steps:

(i) Small amounts of fluids, coming from both the subducted sediments and the alterated oceanic crust are added to the Sumaco mantle source;

(ii) Alkaline basic magmas are generated by low degrees of partial melting of the metasomatized mantle wedge. These primary melts are strongly enriched in incompatible elements, and have low

LILE/HREE and LILE/HFSE ratios, probably because of an OIB component coming up from the asthenosphere (maybe linked to the presence of a slab tearing; Gutscher *et al.*, 1999);

(iii) Partial melting of the subducted slab is not involved in the origin of the Sumaco primary magmas. Mantle-derived basic magmas rise through the continental crust without significant contamination processes and the evolution from basanite to phonolite is mainly driven by fractional crystallization.

On the other hand, El Reventador lavas may derive from the following petrogenetic processes:

(i) A role is played by the subducted slab-derived fluids (sediments, metamorphosed oceanic basalts and serpentinites) for the mantle wedge metasomatism;

(ii) Another component responsible for mantle wedge modification should be carbonatic sediment melts of the subducted slab. This latter component is the main responsible of the peculiar Pb isotopic composition (low $^{206}Pb/^{204}Pb$ and low $^{208}Pb/^{204}Pb$);

(iii) Basic magmas are generated by partial melting of the mantle wedge metasomatized as above. These magmas evolve by fractional crystallisation in crustal magma chambers, as testified by the abundant cognate gabbro cumulates, with negligible crustal contamination. Melts directly derived by partial melting of the oceanic lithosphere slab (adakite magmas *stricto sensu*) seem to be therefore absent.

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