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GEOCHEMICAL CHARACTERISTICS OF THE SOUTHERN ANDES BASALTIC VOLCANISM ASSOCIATED WITH THE LIQUIÑE-OFQUI FAULT ZONE BETWEEN 39° AND 46°S

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Introduction

The Southern Volcanic Zone (SVZ) of the Andes is located along the western margin of the South American plate between latitudes 33.0°S and 46.0°S. At least four remarkable petrographic provinces have been recognized in this volcanic arc: a) the northern province (NSVZ= 33.0°-34.5°S) has mainly andesites and dacites with $(OH)^-$ bearing ferromagnesian minerals, such as amphibole and biotite; b) the transition province (TSVZ= 34.5°-37.0°S) that has basalts to rhyolites, with 2 pyroxenes and/or amphibole + biotite in the most silicic products; c) the central province (CSVZ= 37.0°-41.5°S), with a series of basalts to rhyolites, with 2 pyroxenes and Fe-olivine bearing dacites and rhyolites, which would imply a generation under anhydrous conditions; d) finally, the southern province (SSVZ= 41.5°-46.0°S) is the most unknown, but two types of basalts, "normal" andesites + dacites, "mixed" andesites + dacites and scarce rhyolites, the latter with $(OH)^-$ bearing ferromagnesian minerals, have been described **(1)**.

The CSVZ and SSVZ (37.0°-46.0°S; Fig.1), as the rest of the Southern Andes volcanic range, is a result of the subduction of the oceanic Nazca plate beneath the continental South American plate. While the northern end of this Andean sector corresponds to the intersection of the Mocha Fracture Zone with the Chile-Perú trench, its southern end is the intersection of the Chile Rise with the continent. Quaternary volcanism in both provinces is intense and very active **(2,3)**. The width of the volcanic arc, whose axis is located about 270 km from the trench, is approximately 80 km between 37.0°S and 41.5°S (CSVZ), and about 40 km between 41.5°S and 46.0°S (SSVZ). The volcanic activity has produced numerous composite stratovolcanoes (CSV) and hundred of minor eruptive centers (MEC= pyroclastic cones ± lava flows and maars). During Postglacial times (last 15.000 years) **(4)**, the activity has been continuous with eruptions in both kinds of volcanoes. Rocks of CSV and MEC are predominantly basalts and basaltic-andesites **(1,2,3,5,6,7)**, although the composite stratovolcanoes also exhibit intermediate to acidic products (andesites, silicic-andesites, dacites and scarcely rhyolites) **(1,2,3,5,8)**.

One of the main structural features in these provinces is the Liquiñe-Ofqui fault zone (LOFZ; **9**; Fig.1), previously designated Liquiñe-Reloncaví fault zone **(10)**. This is a dextral transcurrent dislocation **(11,12,13)**, represented by a N-S trending belt of cataclastic and mylonitic rocks. This extends for about 1000 km between 38.0°S and 47.0°S, having a N10°E orientation **(9,11)**. The LOFZ is cut by transverse fractures having predominantly a N50°-60°W and N50°-70°E orientation **(2,3)**.

The distribution of most MEC are controlled mainly by the LOFZ. Such is the case of Lolco (38.5°S), Caburgua (5 centers; 39.2°S), Huelemolle (39.2°S), Pichares (39.25°S), Huililco (39.5°S), Anticura (4 centers; 40.6°S), Cayutué (17 centers; 41.3°S), La Viguería (41.4°S), Pocoihuén (41.5°S), Palena (43.0°S), Rio Frío (43.5°S) and Puyuhuapi (9 centers; 44.3°S). On the contrary, the MEC of the Carrán-Los Venados volcanic group (70 centers; 40.3°S; Fig. 1) are controlled by transverse fractures having a N60°-70°E direction **(14)**. However, some of them are located along the intersection of these fractures with the LOFZ. Three "monogenetic" centers of the Carrán-Los Venados volcanic group (Riñinahue, Carrán and Mirador) re-erupted in this century.

Contrary to most MEC, the distribution of the CSV are mainly controlled by transverse fractures. In the CSVZ (36.0°-41.5°S), the CSV are distributed either along N50°-60°W fractures (Nevados de Chillán, Tolhuaca-Lonquimay, Villarrica-Lanín, Puyehue-Cordón Caulle) **(2,3,14)** or along N50°-70°E fractures (Antuco-Sierra Velluda, Llaima-Sierra Nevada, Osorno-Puntiagudo). In the SSVZ (41.5°-46.0°S), some CSV are controlled by N50°-70°E fractures (Hualaihué-Yate, Chaitén-Michinmahuida, Macá-Cay), others by the intersection of transverse fractures with the LOFZ (Yate, Michinmahuida), others seems to be controlled by the LOFZ alone (Hornopirén), few of them by N50°-60°W (Huequi) and, finally, Corcovado, Yanteles, Melimoyu and Mentolat stratovolcanoes are located 30 km westward of the LOFZ, along inferred N40°E fractures that joints the two N10°E branches of the LOFZ **(15)**.

Most of the geological, geochemical and petrological studies carried out in the CSVZ and SSVZ of the Andes have been mostly centered in the CSV, in spite the fact that the MEC olivine bearing basalts may represent some of the most primitive magmas erupted in the whole Andean range.

The aim of the present study is to integrate the current knowledge of the main geochemical characteristics of basalts erupted by CSV and MEC, associated either directly or indirectly with the LOFZ, in the 39-46°S region of the SVZ to critically

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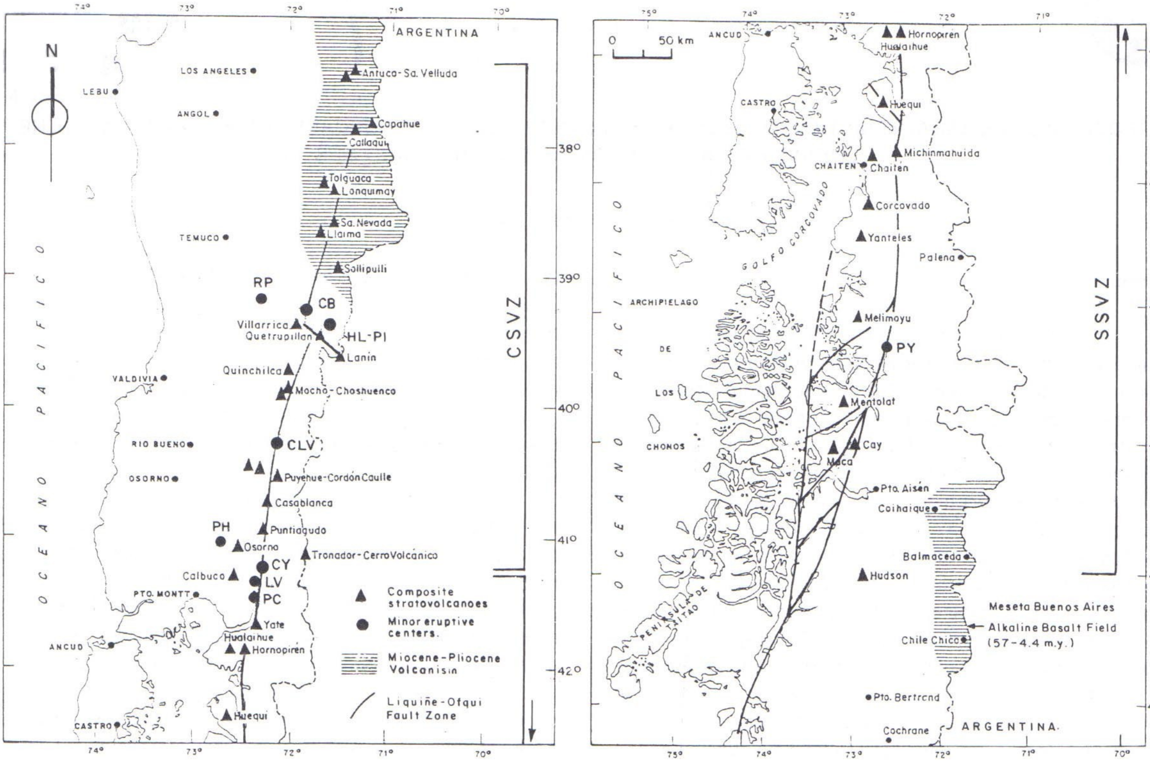

FIG. 1. Sketch map of the CSVZ (37°- 41.5°S) and SSVZ (41.5°-46°S) provinces of the SVZ of the Andes showing the location of the CVS, MEC and Liquiñe-Ofqui fault zone **(8 to 15)**. Symbols of MEC are: RP= Rucapillán, CB= Caburgua, HL-PI= Huililco and Pichares, CLV= Carrán-Los Venados, PH= Pichihuinco, CY= Cayutue, LV= La Viguería, PC= Pocoihuén, PY= Puyuhuapi.

evaluate their similarities and differences. The non-"monogenetic" quality of many MEC is also discussed.

Geochemistry

All samples discussed in this work are basalts (SiO_2 < 52%) from the CSVZ and SSVZ provinces of the Southern Andes (Fig. 1). The selected CSV basalts belong to the following stratovolcanoes: Villarrica (39.4°S), Lanín (39.7°S), Puyehue (40.5°S), Osorno (41.06°S), Hualuaihué (41.9°S), Michinmahuida (42.8°S), Corcovado (43.2°S), Cay (45.07°S), Maca (45.1°S) and Hudson (46.0°S). On the other hand, the selected MEC basalts are from the following centers: Rucapillán (39.0°S), Caburgua (39.2°S), Pichares (39.25°S), Huililco (39.5°S), Pichihuinco (41.0°S), Cayutue (41.3°S), La Viguería (41.4°S), Pocoihuén (41.5°S) and Puyuhuapi (44.3°S). For a comparison, alkaline basalts from back arc minor eruptive centers **(16)**, located eastward of the SVZ arc, between 38°S and 39°S, will also be discussed.

The MgO-K_2O diagram (Fig. 2) shows that: a) most CSVZ and SSVZ arc basalts, from CSV as well as from MEC, have MgO < 11%, ranging from 3.5% to 10.5%. Only one basalt, from the stratovolcano Puyehue, has a MgO content equal to 14.32% **(17)**, which is within the range expected in magmas in equilibrium with mantle peridotite (11-15%); b) two main types of basalts can be distinguished in these provinces of the SVZ arc: type-I, enriched in K_2O, and type-II, depleted in this element. Both types include CSV and MEC basalts. For example, basalts from the minor eruptive centers Huililco, Pichares and Puyuhuapi are K-rich, those from the Caburgua, Cayutue, La Viguería and Pocoihuén are K-poor. The poorest in K, within type-I group, are those basalts from the Rucapillán and Pichihuinco maars, which are the westernmost basalts from the CSVZ province; c) in spite of the large range in MgO content, the K_2O variability in both groups is relatively narrow; d) on the basis of the current data, only in type-II group MEC basalts are significantly richer in MgO than CSV basalts; e) for similar MgO contents, MEC basalts from the SVZ back arc are notably richer in K than basalts from the SVZ arc.

Those basalts which are depleted in K (type-I) are also depleted in other incompatible elements such as Rb, La and Th (Fig. 3), and those that are K-rich (type-II) are also rich in incompatible elements. In general, while type-I basalts belong to volcanic centers located in the western part of the SVZ arc, type-II belong to centers located in the eastern part. On this basis, the abundance of incompatible elements in CSVZ and

SSVZ basalts increases from west to east, regardless of whether they are either CSV or MEC basalts.

Although there are overlaps, type-I basalts tend to have higher Ba/La and lower La/Yb ratios than type-II basalts (Fig. 4). The highest Ba/La and lowest La/Yb ratios are presented by basalts from the Pichihuinco maar and some basalts from the Puyehue CSV. On the other hand, one of the lowest Ba/La ratios and the highest La/Yb ratios are exhibited by the Puyuhuapi MEC basalts. In fact, the latter basalts have La/Yb ratios as high as those presented by andesites from the northernmost part of the SVZ (33°-34.5°S) **(5,18)**, where the continental crust has a thickness of 55-60 km. The relatively low Ba/La ratios of the Puyuhuapi and, in general, of type-II basalts suggests that the mantle source of their primary magmas experienced low degrees of aqueous influx from the subducted oceanic crust, suffering low degrees of melting. These subduction related processes could also explain the enrichments of these magmas in incompatible elements and their relatively high La/Yb ratios. Nevertheless, the extremely high La/Yb ratios of the Puyuhuapi basalts suggests that their magmas could also undergo contamination with crustal material in equilibrium with garnet.

Type-I and -II basalts are quite heterogeneous in their incompatible element ratios (Fig. 5). Although this heterogeneity could reflects source heterogeneities, it also may be due to different degrees of contamination of subcrustal magmas with crustal material. It is expected that subcrustal magmas decrease their K/Rb ratios and increase their K/Ba, K/La, Rb/Ba and Rb/La when become contaminated with crustal material enriched in K and Rb respect to Ba and La **(19)** and enriched in Rb respect to K. In fact, the most primitive basalt of the SVZ, that of Puyehue with 14.32% MgO, has one of the lowest K/Ba, K/La, Rb/Ba and Rb/La ratios among all SVZ basalts however, its K/Rb ratio is only 430. According to this criteria, most of the CSVZ and SSVZ basalts would be contaminated with crustal material, regardless of whether they are either CSV or MEC basalts. Nevertheless, the variability may be also partially due to crystal fractionation processes involving the principal minerals (olivine, pyroxenes and plagioclase) present in those basalts. Although K, Rb, La and Ba are incompatible with respect to olivine, pyroxenes and plagioclase, their degree of incompatibility in some cases is quite different. For example, the plagioclase/basaltic liquid partition coefficient for K is 0.20 and for Rb is 0.05 and the clinopyroxene/basaltic liquid partition for K is 0.002 and for La is 0.120. In addition, at Rucapillán MEC it has been observed aphanitic lens of basaltic composition (SiO_2= 51.37%) inmersed in a basaltic porphyritic mass (SiO_2= 49.10%) **(20)**. The aphanitic fraction has geochemical characteristics (lower MgO, CaO, Sr, Cr, Ni, K/La, Sr/La than the porphyritic fraction) that are consistent with a derivation by crystal fractionation from a parental basaltic magma with the characteristics of the porphyritic fraction.

The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ versus Rb diagrams (Fig. 6) shows that: a) type-I basalts are quite heterogeneous in both kind of isotopic ratios; ($^{87}Sr/^{86}Sr$= 0.7036-0.7044; $^{143}Nd/^{144}Nd$= 0.512700-0.512900); b) the $87Sr/^{86}Sr$ ratios of type-II basalts are concentrated in the upper part of the range exhibited by type-I basalts (0.7039-0.7044), and their $^{143}Nd/^{144}Nd$ ratios are concentrated in the lowest part of the range presented by type-I basalts (0.51275-0.51283); c) when MEC basalts of similar latitude are compared, their $^{87}Sr/^{86}Sr$ ratios increase and their $^{143}Nd/^{144}Nd$ ratios decrease in going from west to east. For example, at *ca.* 39°S, type-I MEC basalts (Caburgua) have significantly lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios than type-II MEC basalts (Huililco and Pichares). The highest $^{87}Sr/^{86}Sr$ ratios are exhibited by back arc basalts **(16)**; d) Puyuhuapi and Huililco-Pichares (type-II MEC basalts) have similar $^{87}Sr/^{86}Sr$ ratios (about 0.70400), but differ significantly in their $^{143}Nd/^{144}Nd$ ratios; the latter are much lower in the Puyuhuapi basalts (average 0.512766); e) within each group of basalts, high $^{87}Sr/^{86}Sr$ ratios are generally accompanied by low $^{143}Nd/^{144}Nd$ ratios; this trend is better observed in type-II basalts. The isotopic trend of decreasing $^{143}Nd/^{144}Nd$ as $^{87}Sr/^{86}Sr$ increases is commonly interpreted as evidence of contamination with crustal material. In this sence, type-II basalts tend to be more contaminated than type-I.

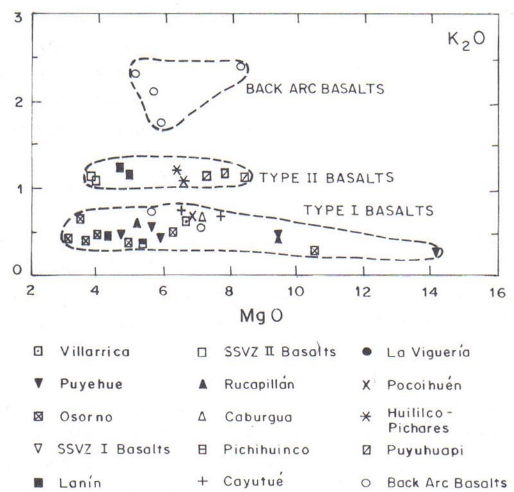

FIG. 2. K_2O versus MgO diagram for CSV and MEC basalts from the CSVZ and SSVZ provinces of the SVZ of the Andes. Two groups of basalts can be distinguished: one depleted in K_2O (type-I) and other enriched in this element (type-II). Type-I is represented by basalts from the MEC Rucapillán, Caburgua, Pichihuinco, Cayutue, La Viguería and Pocoihuén and the CSV Villarrica, Puyehue, Osorno, and SSVZ-I (Hualaihué, Corcovado, Cay and Maca). Type-II basalts are represented by basalts from the MEC Huililco, Pichares and Puyuhuapi and the CSV Lanín and SSVZ-II (Michinmahuida and Hudson). In general, type-I basaltic centers are located closer to the trench than type-II. Back arc basalts **(16)** are significantly more rich in K_2O than arc basalts with similar MgO contents.

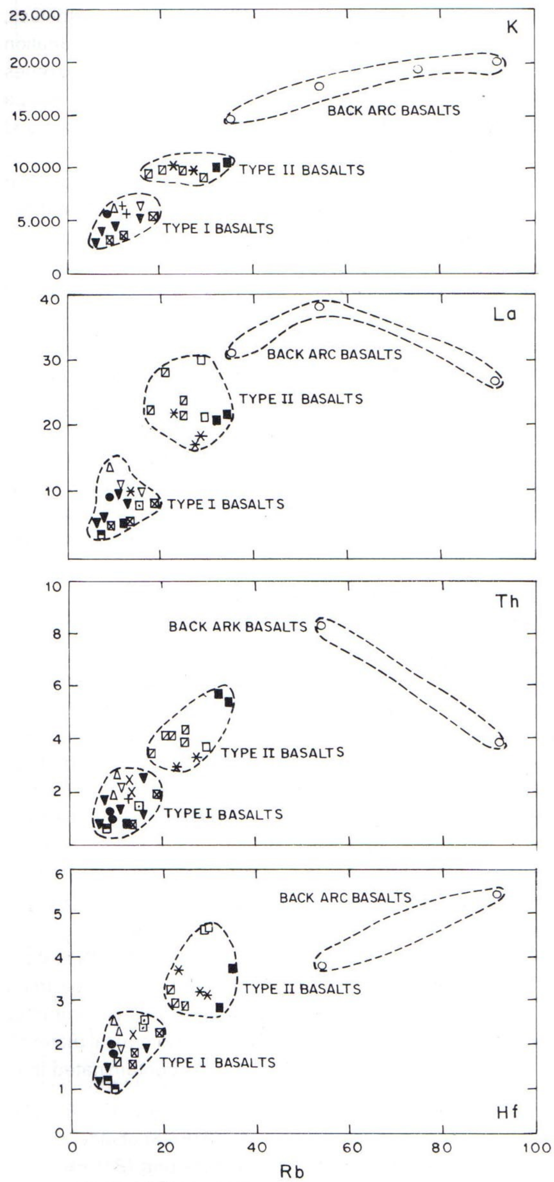

FIG. 3. K, Rb, La and Hf versus Rb diagrams for CSV and MEC basalts from the CSVZ and SSVZ provinces of the SVZ of the Andes. These diagrams show that type-I basalts are depleted with respect to type-II basalts not only in K, but also in other incompatible elements. Symbols are the same as in figure 2.

Some considerations on the Carrán-Los Venados Volcanic Group

The Carrán-Los Venados volcanic group (40.3°S; Fig. 1)

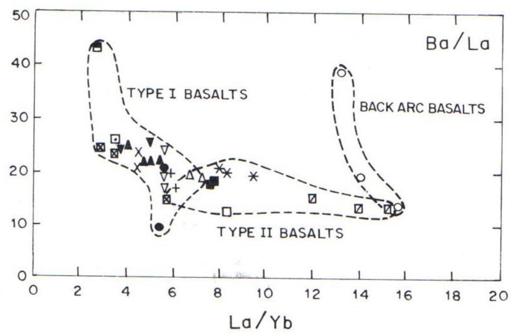

FIG. 4. Ba/La versus La/Yb diagram for CSV and MEC basalts from the CSVZ and SSVZ provinces of the SVZ of the Andes. Type-I basalts tend to have higher Ba/La and lower La/Yb ratios than type-II basalts. The highest La/Yb ratios and one of the lowest Ba/La ratios are presented by the Puyuhuapi basalts. On the other hand, the lowest La/Yb and highest Ba/La ratios are exhibited by the Pichihuinco maar basalts. Symbols are the same as in figure 2.

have geochemical features that make them different from other MEC associated with the LOFZ. In fact, some analyzed samples from this volcanic group are basaltic andesites, have significantly lower MgO, Ni and Cr contents, and have lower La/Yb and higher K/La ratios **(21,22)**. In these characteristics, those samples are similar to CSV basaltic andesites from the CSVZ arc of the Andes.

The Carrán-Los Venados volcanic group not only differs from the other MEC associated with the LOFZ in the geochemical characteristics of its products, but also: **(a)** it represents the largest group of MEC within the SVZ of the Andes, being formed by about 70 centers consisting of pyroclastic cones and maars, distributed in an area of about 100 km² **(14,23)**; **(b)** the center of this group is located along the intersection of the LOFZ with an important N60°-70°E fracture zone **(14,23)**; **(c)** in this intersection, three volcanic eruptions have occurred during this century (1907 at Riñinahue maar, 1955 at Carrán maar and 1979 at Mirador pyroclastic cone + lava flow) **(21,23)**; **(d)** these eruptions constitute the only reactivations of minor eruptive centers (MEC) during historic times in Chile; **(f)** two of these eruptions, occurred at maars, with an eruptive style (phreatomagmatic) that commonly generates pyroclastic surges.

Considering that within the SSVZ the major volcanic centers are commonly separated by 20 to 55 km, it is noticeable the large distance (75 km) between the northern (Mocho-Choshuenco) and southern (Puyehue-Cordón Caulle) neighbours of the Carrán-Los Venados volcanic group. This fact, together with the geological and geochemical features, already mentioned, suggest the hypothesis that the Carrán-Los Venados volcanic group could represent the initial step in the formation of a magma chamber that could develop a poligenetic CSV. Hence, not all the MEC tha belong to the CSVZ a really "monogenetic". In addition, other MEC, like La Viguería, have

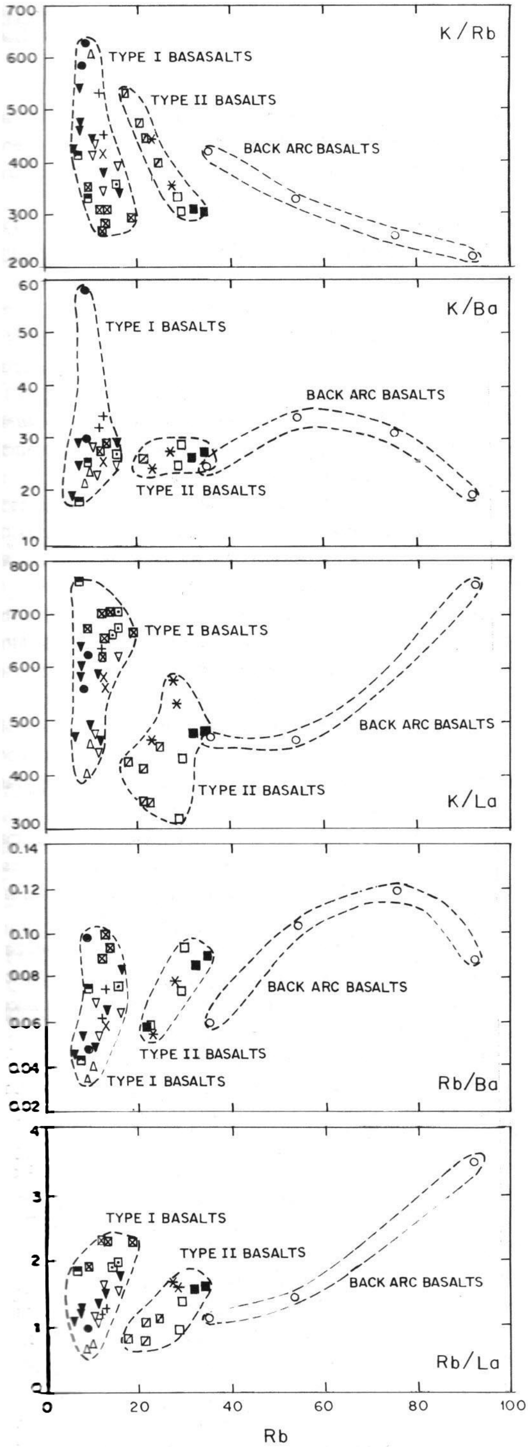

FIG. 5. Some Incompatible Element Ratios versus Rb diagrams for CSV and MEC basalts from the CSVZ and SSVZ provinces of the SVZ of the Andes. These ratios are quite heterogeneous in both type-I and -II basalts. The most primitive basalt of the SVZ, that of Puyehue with 14.32% MgO, has one of the lowest K/Ba, K/La, Rb/Ba and Rb/La ratios among all SVZ basalts; however, its K/Rb ratio is only 430. Symbols are the same as in figure 2.

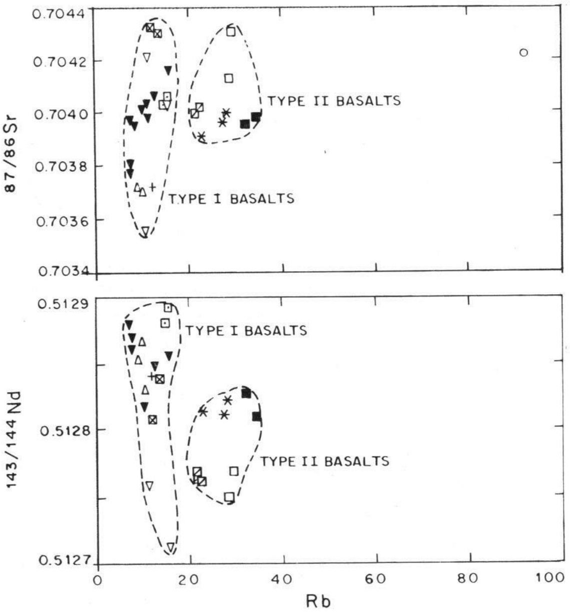

FIG. 6. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ versus Rb diagrams showing that: a) type-I basalts are quite heterogeneous in both kind of isotopic ratios; b) while the $^{87}Sr/^{86}Sr$ ratios of type-II basalts are concentrated in the upper part of the range exhibited by type-I basalts, their $^{143}Nd/^{144}Nd$ ratios are concentrated in the lowest part of the respective range presented by type-I basalts; c) at a given latitude, the $^{87}Sr/^{86}Sr$ ratios of MEC basalts tend to increase and the $^{143}Nd/^{144}Nd$ ratios to decrease in going from west to east; d) within each group of basalts, high $^{87}Sr/^{86}Sr$ ratios are generally accompanied by low $^{143}Nd/^{144}Nd$ ratios; this trend is better observed in type-II basalts. Symbols are the same as in figure 2.

two eruptive phases with two distinctive magma composition, another criteria that defines the monogenetic quality of an eruptive centers. This hypothesis is being currently evaluated through a FONDECYT project.

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