Geochemistry and tectonics of the Chilean Southern Andes basaltic Quaternary volcanism (37-46°S)

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ABSTRACT

Between latitudes 37° and 46°S of the Andes, the Nazca-South America Plate convergence is currently slightly oblique. Postglacial volcanism has been continuous and intense, being expressed as numerous composite stratovolcanoes (SV) and hundreds of minor eruptive centers (MEC). The overall trend of the volcanic arc is NNE (~ N10°E), and its main structural feature is the 1,000 km long, also NNE-trending, Liquiñe-Ofqui fault zone (LOFZ). Some MEC are spatially associated with the main NNE-trending lineaments of the LOFZ; others, such as the Carrán-Los Venados volcanic group (40.3°S), form N50-70°E clusters, oblique to the overall trend of the volcanic arc. Between 37° and 41.5°S, Central Southern Volcanic Zone (CSVZ), the SV form either N50-60°W or N50-70°E alignments. Between 41.5° and 46°S, South Southern Volcanic Zone (SSVZ), the distribution of SV is similar. The alignment of parasitic vents, MEC and SV suggests that the direction of σH_{max} in the CSVZ and SSVZ is roughly N50-70°E, which may reflect a transpressional tectonic regime, resulting from a combination of dextral strike-slip and shortening across the arc. Most young extensional NE-trending volcanic chains (Late Pleistocene-Holocene), including SV ± MEC contain mainly basaltic rocks. This is consistent with a short residence time of magmas in the crust. Older volcanic complexes (Early Pleistocene) and volcanic edifices controlled by NW-trending contractional fractures and faults present not only basaltic rocks, but also medium andesites, dacites and even rhyolites. This is probably the result of a longer,intracrustal magma residence, yielding a more mature and differentiated composition. Basaltic rocks from either N50-60°W and N50-70°E transverse fractures tend to increase their incompatible elements abundances, Ba/La, and $^{87}Sr/^{86}Sr$ ratios and decrease their La/Yb and $^{143}Nd/^{144}Nd$ ratios in going from west to east, suggesting that these geochemical features are mainly controlled by subcrustal features and processes; fractures and faults would only facilitate the ascent of magmas. Similar geochemical behaviours are observed between MEC basaltic rocks located at similar latitude, but different longitude.

Keywords: Arc basaltic magmas, Southern Andes, Tectonism, Geochemistry.

RESUMEN

Geoquímica y tectónica del volcanismo cuaternario basáltico de los Andes del Sur de Chile (37-46°S). Entre las latitudes 37° y 46°S de los Andes, la convergencia entre las placas de Nazca y Sudamericana es levemente oblicua. El volcanismo posglacial, que ha sido continuo e intenso, ha originado numerosos estratovolcanes compuestos (EV) y cientos de centros eruptivos menores (CEM). El arco volcánico tiene una orientación general NNE (~N10°E), y su principal característica estructural es la zona de Falla Liquiñe-Ofqui (ZFLO), de 1.000 km de longitud y orientación NNE. Algunos CEM están asociados espacialmente con los lineamientos NNE de la ZFLO; otros, como el grupo volcánico Carrán-Los Venados (40,3°S), están orientados oblicuamente (N50-70°E) con respecto a la orientación general del arco volcánico. Entre los 37° y 41,5°S, Zona Volcánica Sur Central (ZVSC), los EV presentan alineamientos N50-60°W o N50-70°E; algo similar acontece entre los 41,5° y 46°S, Zona Volcánica Sur Sur (ZVSS). El alineamiento de los conos parásitos, de los CEM y de los EV sugiere que la dirección de σH_{max} en las regiones central y sur de los Andes del Sur es aproximadamente N50-70°E, lo cual reflejaría un régimen tectónico transpresional, que resultaría de la combinación de una rotación dextral, tipo 'strike-slip', y un acortamiento del arco. La mayoría de las cadenas volcánicas jóvenes (Pleistoceno tardío-Holoceno), de orientación noreste, son extensionales y contienen principalmente rocas basálticas, lo cual es consistente con un tiempo de residencia cortical corto. Complejos volcánicos antiguos (Pleistoceno temprano) y edificios controlados por fracturas y fallas compresionales, de orientación noroeste, presentan basaltos y también rocas volcánicas más ácidas. Esto resultaría de un tiempo de residencia más prolongado en la corteza, lo que permitiría la generación de magmas más maduros y diferenciados. Las rocas basálticas, tanto de alineamiento de orientación N50-60°W como N50-70°E, tienden a aumentar su abundancia en elementos incompatibles y sus razones Ba/La y $^{87}Sr/^{86}Sr$ y a disminuir sus razones La/Yb y $^{143}Nd/^{144}Nd$ en dirección oeste-este, sugiriendo que estas características dependen fundamentalmente de procesos subcorticales; las fracturas y fallas sólo facilitarían el ascenso de los magmas.

Palabras claves: Magmas basálticos de arco, Andes del Sur, Tectonismo, Geoquímica.

INTRODUCTION

The Southern Volcanic Zone (SVZ) of the Andes is located along the western margin of the South America Plate, between latitudes 33°S and 46°S. At least four distinctive petrographic provinces have been recognized in this Quaternary volcanic arc: north (NSVZ=33-34.5°S), transitional (TSVZ=34.5-37°S), central (CSVZ=37-41.5°S) and south (SSVZ=41.5°-46°S) (López-Escobar and Moreno, 1994 and references therein; Fig. 1). The NSVZ province consists mainly of andesites and dacites with OH^- bearing ferromagnesian minerals, such as amphiboles and biotite. In this province, the volcanic centers exhibit a northsouth alignment. The TSVZ province ranges in composition from basalts to rhyolites, with a predominance of andesites and dacites. Pyroxenes±amphiboles±biotite is a common mineral association in most silicic products. In this province, northwest alignments of the volcanic centers predominate over northsouth and northeast alignments (Katsui and Katz, 1967; Katz, 1971; Nakamura, 1973; Moreno, 1974, 1976). The CSVZ province consists of a series of basalts to rhyolites, with a predominance of basalts and basaltic andesites. Two pyroxenes±Fe-olivine is a common mineralogy in the dacites and rhyolites. Northeast and northwest, but not northsouth, alignments of the composite stratovolcanoes (SV) are observed in this province; northsouth alignments are observed among minor eruptive centers (MEC=scoria cones ± lava flows and maars). Finally, the SSVZ province is less well known, but two types of basalts, 'normal' andesites+dacites, 'mixed' andesites+dacites and scarce rhyolites have been described (López-Escobar *et al.*, 1991, 1993). The intermediate to silicic members exhibit OH^- bearing ferromagnesian minerals. In this province, the alignment of the SV is mainly northeast.

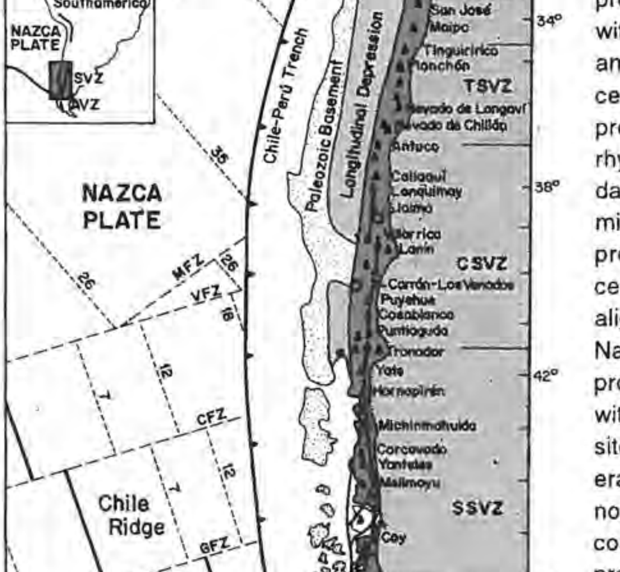


FIG.1. Geotectonic setting of the Southern Volcanic Zone (SVZ) of the Andes and its four main provinces (modified from López-Escobar *et al.*, 1993 and references therein). The trench is shown by a thick, barbed line; the Chile Ridge intersects the continental margin at the southern end of the SSVZ. Nazca-South America Plate convergence is slighlty dextral-oblique and occurs at 9 cm/yr (Cifuentes, 1989).

The CSVZ and SSVZ (37-46°S; Fig. 1), as the rest of the Southern Andes volcanic range, are the result of the subduction of the oceanic Nazca Plate beneath the continental South America Plate. The northern boundary of this Andean segment is the prolongation into the continent of the intersection of the Mocha Fracture Zone with the Chile-Perú Trench; its southern end is the intersection of the Chile Ridge with the continent. In this region of the Andes, the Nazca-South America Plate convergence is currently oblique (~25°) with respect to the orthogonal to the trench (Jarrard, 1986; Dewey and Lamb, 1992). Quaternary volcanism is intense and very active in both provinces (Moreno, 1974, 1976). Between 37° and 41.5°S (CSVZ), the width of the volcanic arc, whose axis is located about 270 km from the trench, is aproximately 80 km, with a maximum of 120 km and a minimum of 70 km; between 41.5°S and 46°S (SSVZ), the width of the volcanic arc reduces to about 40 km. The volcanic activity is expressed as numerous SV and hundreds of MEC. During postglacial times (last 15,000 years), volcanic activity has been continuous with eruptions in both kinds of volcanoes. Postglacial rocks of SV and MEC from the CSVZ and SSVZ are predominantly basalts and basaltic-andesites (Moreno, 1974, 1976; López-Escobar, 1984; Hickey *et al.*, 1986; Hickey-Vargas *et al.*, 1989; Tormey *et al.*, 1991a; López-Escobar *et al.*, 1991,1993), although the SV may also exhibit intermediate to silicic products (andesites, silicic-andesites, dacites and scarcely rhyolites).

NNE-trending regional lineaments correspond to the main basement structural feature of the CSVZ and SSVZ provinces, the 1,000 km long Liquiñe-Ofqui Fault Zone (LOFZ; Hervé, F. *et al.*, 1979; Fig. 2), previously designated as the Liquiñe-Reloncaví Fault Zone (Hervé, F. *et al.*, 1974). The LOFZ is represented in the field by northsouth trending ductile shear zones and brittle faults (Hervé, M. 1976; Cembrano, 1992; Pankhurst *et al.*. 1992; Cembrano and Hervé, F., 1993). Other regional-scale lineaments are oblique to the overall trend of the magmatic arc and show a predominant N50-60°W and N50-70°E orientation (Moreno, 1974, 1976). Some of the northeast trending lineaments are thought to join the two right-stepping NNE trending main lineaments of the LOFZ, giving rise to a strike-slip duplex (Cembrano and Hervé, 1993).

Geological, geochemical and petrological studies carried out in the CSVZ and SSVZ of the Andes have been mostly centered in the SV, although some MEC olivine basalts could represent some of the most primitive magmas erupted in this Andean region.

The aim of the present study is to discuss some geochemical characteristics of basalts erupted by SV and MEC, spatially associated with the LOFZ, in the 37- 46°S region of the SVZ, to critically evaluate these features as a function of their tectonic setting.

SPATIAL DISTRIBUTION OF VOLCANIC CENTERS

The spatial arrangement of individual SV and clusters of MEC within the SVZ arc, between 37° and 46°S, seems to define regular patterns at a regional scale (Fig. 2). Even parasitic volcanoes (vents) within individual SV show a systematic distribution, which is consistent with the regional pattern shown by SV and MEC (Katsui and Katz, 1967; Katz, 1971; Nakamura, 1973; Moreno, 1974, 1976; Moreno and Parada, 1976; Nakamura, 1977; Cembrano and Moreno, 1994; Figs. 2, 3).

In the CSVZ and SSVZ provinces, the distribution of some MEC is spatially associated with the main NNE-trending lineaments of the LOFZ, which are parallel to the overall trend of the volcanic arc. Such is the case of Lolco (38.5°S), Caburga (5 centers; 39.2°S), Huelemolle (3 centers; 39.2°S), Pichares (39.25°S), Huililco (39.5°S), Antcura (4 centers; 40.6°S), Cayutué (17 centers; 41.3°S), La Viguería (41.4°S), Pocoihuén (41.5°S), Palena (43.0°S), Río Frío (43.5°S) and Puyuhuapi (9 centers; 44.3°S). However, at a larger scale, other MEC, such as those of the Carrán-Los Venados volcanic group (70 centers; 40.3°S; Figs. 2, 3; Moreno, 1977, 1980), form clusters whose long axes are oriented in a N50-70°E direction (Fig. 3).

The distribution of the SV in the CSVZ (37-41.5°S) is mainly restricted to alignments whose trends are oblique with respect to the magmatic arc axis. In fact, the SV form either N50-60°W alignments (Tolhuaca-Lonquimay, Villarrica-Quetrupillán-Lanín, Puyehue-Cordón Caulle; Moreno, 1974, 1976, 1977) or, more commonly, N50-70°E alignments (Antuco-

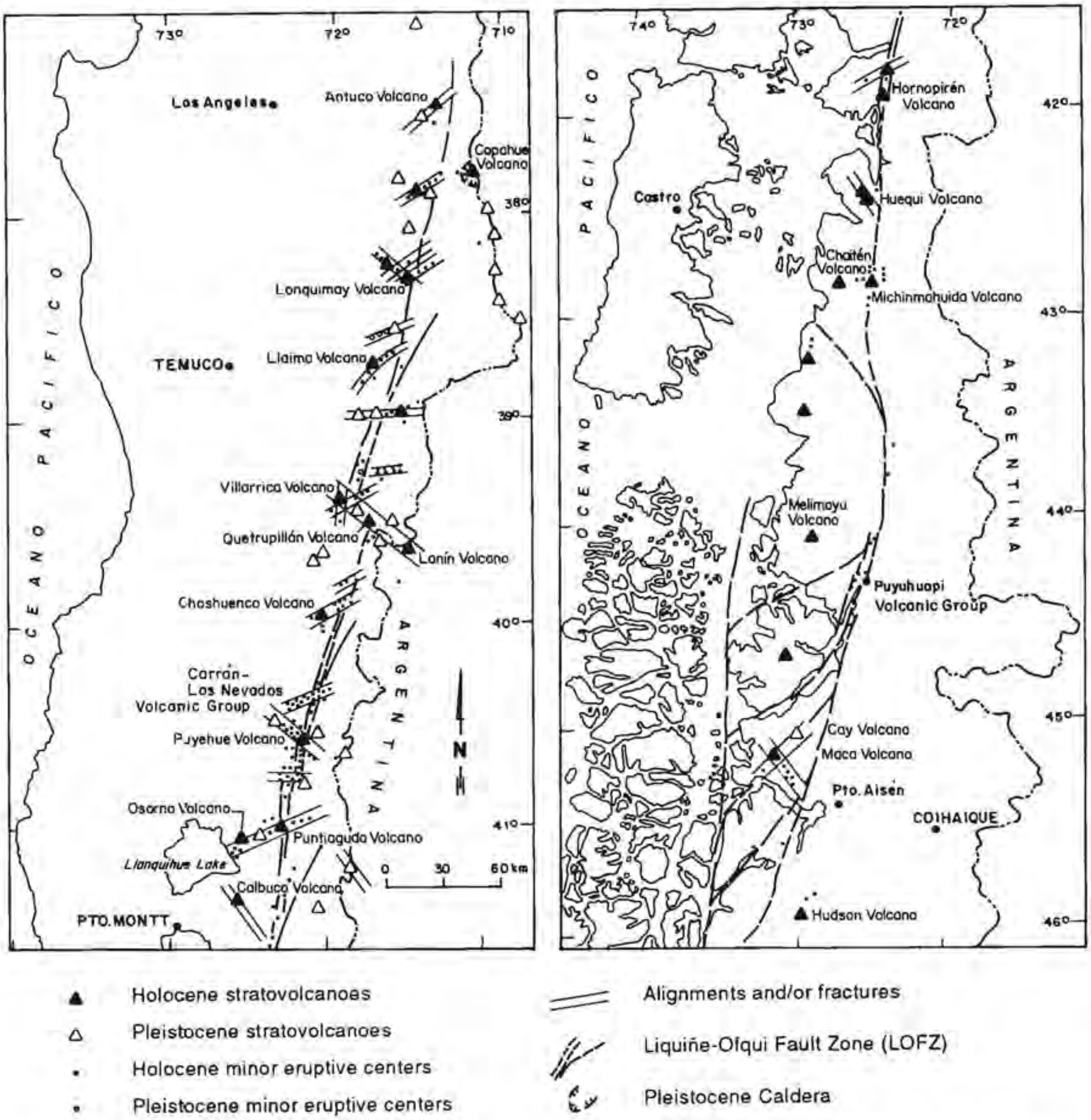
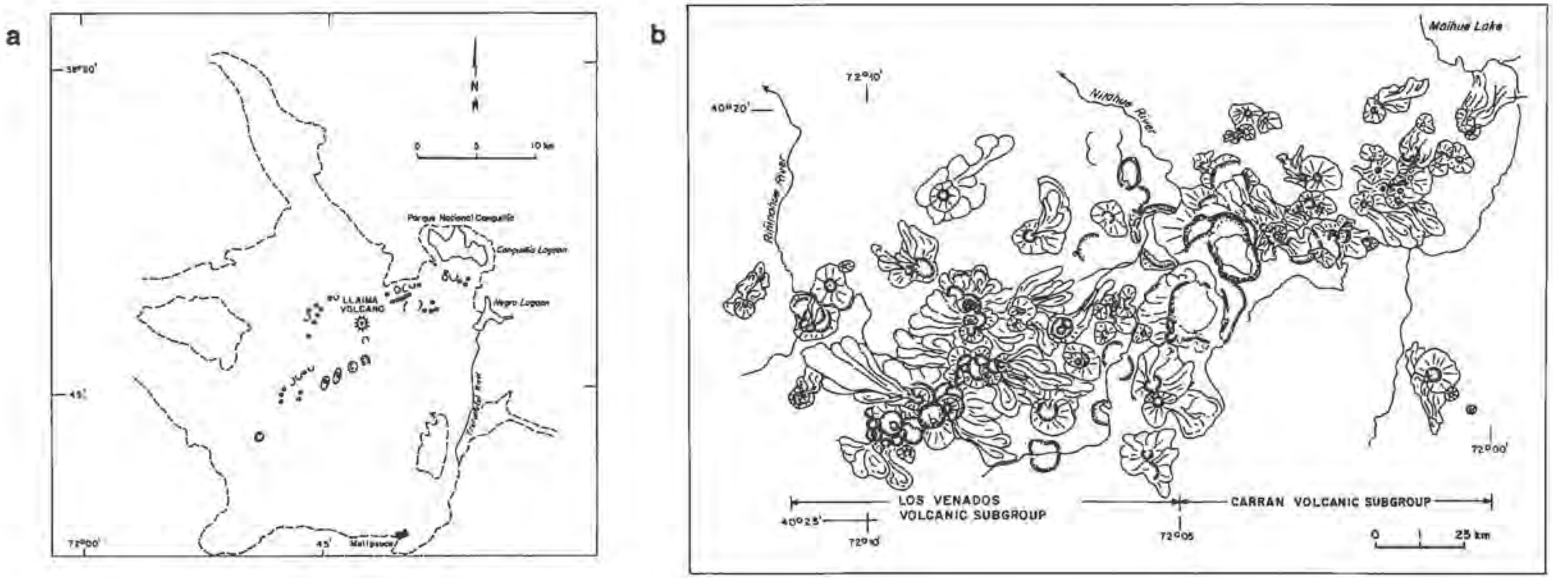


FIG. 2. Spatial distribution of stratovolcanoes (SV) and minor eruptive centers (MEC) of the CSVZ and SSVZ of the Andes. Stratovolcanoes form northeast and northwest-trending alignments. MEC form N50-70°E trending, en echelon, elongated clusters or lie along regional scale NNE trending lineaments of the Liquiñe-Ofqui Fault Zone. Modified from Katz (1971), Moreno (1976), Cembrano and Moreno (1994).

Sierra Velluda, Llaima-Sierra Nevada, Osorno-Puntiagudo-Cordón Cenizos). In the SSVZ (41.5-46°S), some SV lie along N50-70°E lineaments (Hualaihué-Yate, Michinmahuida, Maca-Cay), some lie within the LOFZ (Hornopirén), and finally, Corcovado, Yanteles, Melimoyu and Mentolat SV are located 30 km westward of the main lineament of the LOFZ. According to Cembrano and Hervé, F. (1993), the last four SV are distributed along N40°E lineaments that join the two N10°E branches of the LOFZ (Fig. 2), but LANDSAT images show a well-defined northsouth alignment of Chaitén, Corcovado, Yanteles and Melimoyu volcanoes.

a

b



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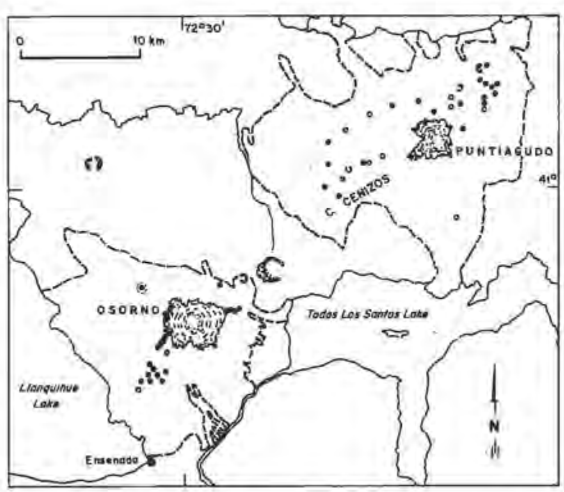

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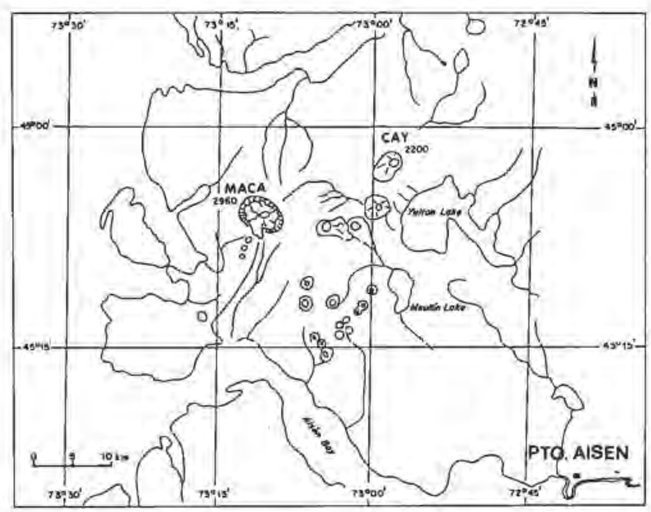

FIG. 3. Spatial distribution of parasitic cones (flank eruption sites) and MEC within the CSVZ and SSVZ of the Andes. The long axis of clusters of parasitic cones of the stratovolcanoes trends roughly N50-70°E; **a-** Llaima volcano (Naranjo and Moreno, 1991); **b-** Carrán-Los Venados volcanic group (Moreno,1977); **c-** Osorno-Puntiagudo-Cordón Cenizos volcanic chain (Moreno, 1976) and **d-** Maca-Cay volcanic region.

VOLCANISM AND TECTONICS: IS THERE A CAUSAL RELATIONSHIP?

Nakamura (1977) proposed that the systematic alignments of MEC and flank volcanoes (vents) within major SV in subduction zone margins may be used as a tool to determine the direction of the maximum horizontal stress (σH_{max}), at both local and regional scales. Both flank crater distribution within individual SV and the elongated distribution of MEC are believed to represent a natural analog of hydrofracture experiments resulting from magma overpressuring. In fact, the volcanic centers are supposed to be the surface expression of vertical feeder dykes located underneath (Nakamura, 1977). According to Lister and Kerr (1991) deviatoric stress plays a key role in the initiation and orientation of dykes. For low viscosity magmas, dykes are expected to be oriented perpendicular to the minimum principal stress axis at all depths within the lithosphere (Emerman and Marrett, 1990). Hence, spatially associated volcanic alignments would reflect the direction of the maximum horizontal stress, which may be either $\sigma1$ or $\sigma2$. Minor complications to this general model arise from: **1-** gravity forces acting on the volcano in addition to the regional tectonic stress. According to Nakamura (1977), gravity forces add up to the regional tectonic stress, and thus, may modify the trajectory of the principal stress axes, producing less well-defined, usually curved, volcanic center alignments, and **2-** pre-existing anisotropies in the basement rocks which may also serve as channelways for ascending magma (non-andersonian dikes). In this case, volcanic alignments will not indicate by themselves the orientation of the stressfield.

Nakamura's model, which can be extended to alignments of SV, has been succesfully tested in the Aleutians (Nakamura *et al.*, 1978). In this place, the expected direction of the σH_{max}, obtained by the inversion of fault-slip data, is consistent with that suggested by the systematic orientation of volcanic structures.

The fact that volcanic arcs occur along active convergent margins ('compressive' in a loose sense) led Nakamura (1977) to state that the overall tectonics of volcanic arcs should be strike-slip ($\sigma1$ and $\sigma3$ horizontal; $\sigma2$ vertical), instead of compressional (Fig. 3; $\sigma1$ and $\sigma2$ horizontal; $\sigma3$ vertical). This would allow magma to ascent through vertical dykes having a direction parallel to that of σH_{max} (Nakamura and Uyeda, 1980). More recent work on the causal relationship between tectonism and volcanism (Bellier and Sebrier, 1994; Ventura, 1994) have emphasized the close spatial and temporal relationship existing between volcanoes and pull-apart basins, releasing bends, tension fractures and Riedel shears, within and overall strike-slip deformation zone. In addition, focal mechanism studies of crustal earthquakes, occuring in many volcanic arcs, show that strike-slip deformation predominates over compression or extension (Mc Caffrey, 1992). The latter stress regimes are recorded in forearc and backarc regions, respectively. The hypothesis of magma ascending as dykes through a composite system of tensional and shear fractures, in an overall strike-slip deformation regime ($\sigma1$ and $\sigma3$ horizontal), is consistent with the dynamic models of fracture propagation proposed by Hill (1977) and Shaw (1980) for the crust and lithospheric mantle.

Following the model proposed by Nakamura (1977), the direction of σH_{max} in the CSVZ and SSVZ is roughly N50-70°E, as indicated by the alignment of most parasitic vents, MEC and SV. The fact that not all volcanic centers form northeast alignments can be explained as pre-existing crustal fractures of different orientations may also serve as channelways for magma ascent, regardless of the dominant tectonic stress field. Among these pre-existing discontinuities in the basement, the most important ones trend NNE and WNW. The NNE features correspond to crustal scale anisotropies related to Miocene-Pliocene ductile shear zones and brittle faults of the LOFZ. The WNW trending lineaments can be regional in scale and are thought to be pre-Andean in origin (Munizaga *et al.*, 1988). Although both NNE and WNW trending basement discontinuities may play an important role in magma ascent and emplacement, the predominant ENE alignments of MEC and CSV document the more likely pathways for low viscosity magma to ascent through the crust. This N50-70°E direction is oblique to the main trend of the volcanic arc (~N10°E), suggesting that the arc domain is not under an overall trench orthogonal shortening, as might be expected in a 'compressional', two-dimensional Chilean-type subduction model (*i.e.*, Uyeda and Kanamori, 1979).

As stated before, since feeder dikes of volcanic centers are thought to be vertical, $\sigma3$ has to be horizontal, and then σH_{max} corresponds either to $\sigma1$ or $\sigma2$. In the first case, the overall tectonics of the volcanic arc is strike-slip. In contrast, if σH_{max} corresponds to $\sigma2$, the volcanic arc tectonic is extensional.

Independent evidence of the geometry of the principal stress axes for the Quaternary is limited. However, structural studies in the Southern Chilean Andes show that the long-term (Ma) ductile-brittle kinematics, recorded in high-strain rocks and brittle faults underlying the Quaternary volcanoes along the Liquiñe-Ofqui Fault Zone (LOFZ), has been dextral strike-slip, for the late Miocene-Pliocene times (Hervé, M., 1984; Cembrano, 1992; Cembrano and Hervé, F., 1993; Nelson *et al.*, 1994). Inversion of fault slip data from 3.3 Ma ^{40}Ar-^{39}Ar age plutonic rocks, forming the basement of the volcanic arc at 42°S, is also consistent with a dextral strike-slip deformation (Lavenu and Cembrano, 1994).

The short-term kinematic picture is only poorly constrained by a single focal mechanism solution of a crustal earthquake, which occurred at ~46°S within the volcanic arc. The earthquake focal mechanism indicated dextral strike-slip deformation along a NNE-trending fault parallel to the surface expression of the LOFZ (Chinn and Isacks, 1983; Cifuentes, 1989).

Therefore, field and seismic evidences suggest that the tectonic regime within the volcanic arc has been dextral strike-slip for the last few million years (Pankhurst *et al.*, 1992; Cembrano, 1992). An overall ~N10°E-trending dextral strike-slip deformation zone, corresponding to the volcanic arc domain, should have a ~N55°E trending instantaneous shortening axis. This trend coincides closely with the direction of σH_{max} obtained from the volcanic alignments. The fact that the direction of σH_{max} is at a larger angle than expected, with respect to the deformation zone boundary may reflect a transpressional tectonic regime, resulting from a combination of dextral strike-slip and shortening across the arc. This tectonic regime is consistent with plate kinematic constraints as the Nazca-South America Plate convergence has been slightly dextral oblique for the last 20 Ma, producing deformation partitioning into forearc shortening and intra-arc transpressive dextral strike-slip deformation (Dewey and Lamb, 1992) (Fig. 4).

In the above scenario, and following the fracture propagation model of Shaw (1980), rapid ascent of magma should be expected along inherited or newly created northeast-trending tensional fractures and faults within the volcanic arc (Fig. 5). This agrees with geochemical interpretations based on U-Th disequilibrium considerations (Tormey *et al.*, 1991b).

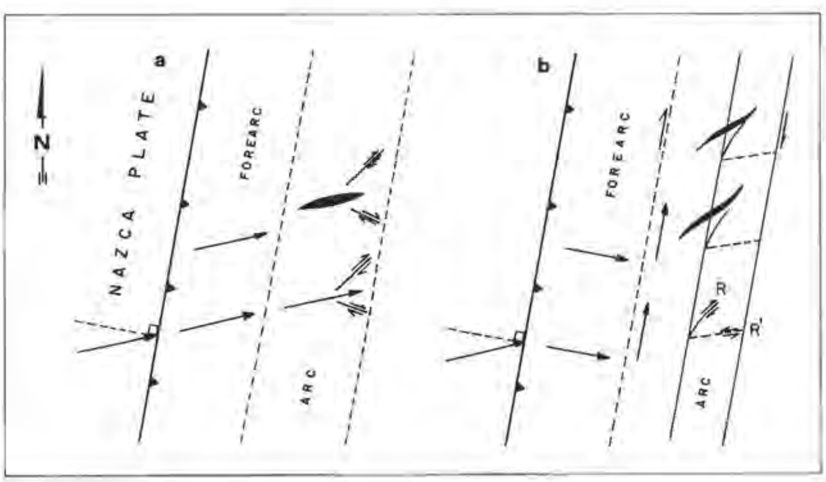

FIG. 4. Simplified model for the tectonic setting of the Southern Andes Vocanic Zone (modified from Dewey and Lamb, 1992; Cembrano and Moreno, 1994). The volcanic arc is seen as a N10°E trending broad zone of dextral strike-slip deformation resulting from different degrees of partitioning of oblique subduction into shortening in the forearc and intra-arc shear. Non-partitioning (a) and complete partitioning (b) scenarios are shown.

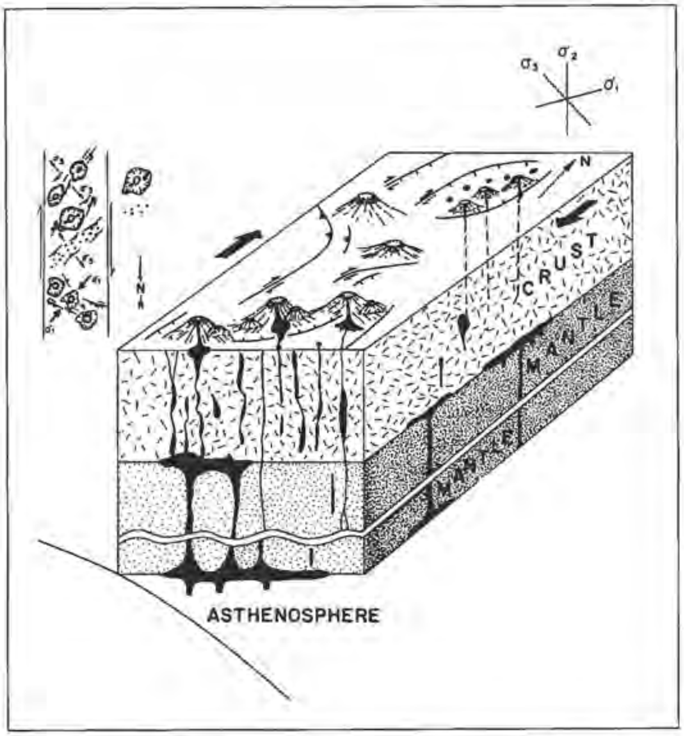

FIG. 5. Following Shaw's fracture propagation model (1980), rapid ascent of magmas is expected through inherited or newly created fractures which are close to parallelism with the instantaneous shortening direction or maximum principal stress axis. The present location of volcanic centers would reflect the subvertical position of underlying feeder dykes.

GEOCHEMISTRY

Most SV and MEC of the CSVZ and SSVZ, lying along northsouth-trending lineaments or forming N50-70°E trending-en echelon alignments, such as the Osorno-Puntiagudo-Cordón Cenizos volcanic chain, are fundamentally basaltic to basaltic andesite in composition (Moreno *et al.*, 1979; López-Escobar *et al.*, 1992; Tagiri *et al.*, 1993). However, N50-60°W trending volcanic chains, such as the Villarrica-Quetrupillán-Lanín and Puyehue-Cordón Caulle volcanic chains, include postglacial dacitic to rhyolitic rocks in addition to basaltic products (Moreno, 1977; Gerlach *et al.*, 1988; Hickey-Vargas *et al.*, 1989; López-Escobar *et al.*, 1993; Moreno *et al.*, 1994). Isolated young andesitic SV, like Calbuco and Huequi volcanoes, lie on northwest-trending lineaments, tens of kilometers long (Fig. 2). It is also worthwhile pointing out that Lanín (Lara and Moreno, 1994) and Tronador volcanoes are emplaced on an uplifted block, east of the LOFZ main trend. Calbuco volcano would be also emplaced on an uplifted block (Thiele *et al.*, 1986; Barrientos *et al.*, 1992; López-Escobar *et al.*, 1992; López-Escobar *et al.*, 1995). Unlike the other CSVZ and SSVZ centers, Mocho-Choshuenco, a basaltic andesite to dacitic SV, located at 40°S (Mc Millan *et al.*, 1989), is emplaced on a basement that, in addition to Jurassic igneous rocks and Triassic metasediments, also contains Paleozoic metasedimentary rocks of the coastal western series (Fig. 1).

Most SV and MEC basalts ($SiO_2 \leq 52\%$) and basaltic andesites (SiO_2=52-56%), from the CSVZ and SSVZ provinces of the Southern Andes, have MgO <11%, ranging from 3.0% to 10.5% (Fig. 6). These values are lower than those expected in magmas in equilibrium with mantle peridotite (MgO=11-15%). Only one basalt, from the SV Puyehue, has a MgO abundance equal to 14.32% (Gerlach *et al.*, 1988; Fig. 6). However, this particular basalt is olivine rich and its high MgO content could be the result of an olivine accumulation.

The two main types of basaltic rocks, depleted in K (K_2O < 1%) and enriched in this element (K_2O=1-

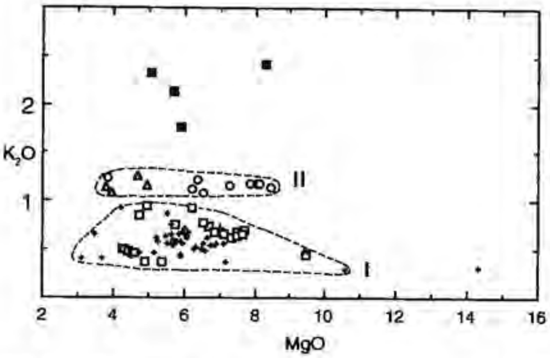

FIG. 6. K_2O *versus* MgO diagram for SV and MEC basaltic rocks from the CSVZ and SSVZ provinces of the SVZ of the Andes. Symbols are as follow: (I) K-poor basaltic rocks; (II) K-rich basaltic rocks; (+) K-poor SV basaltic rocks, (□) K-poor MEC basaltic rocks, (Δ) K-rich SV basaltic rocks, (o) K-rich MEC basaltic rocks, and (▪) Back-arc MEC basaltic rocks (Muñoz and Stern, 1989). The latter are shown for comparison. This figure and the following ones were built using the database shown in table 1.

1.5%), that were distinguished in the SSVZ (López-Escobar *et al.*, 1993), are also present in the CSVZ province of the SVZ of the Andes arc (Fig. 6). Both groups include SV as well as MEC basaltic rocks. In each one, K_2O variability is relatively narrow, even when MgO may vary from 3.5 to 10.5%. Only in the K-rich group, MEC basaltic rocks are significantly richer in MgO than SV basaltic rocks. Compared to K-rich basaltic rocks, K-poor ones are also depleted in other incompatible elements, such as Rb, La and Th (Fig. 7).

At latitute 39°S, where the SV Villarrica-Quetrupillán-Lanín are aligned in a N50-60°W direction and the LOFZ suffers a displacement of 18 km to the west (Fig. 2), the incompatible element abundances of the SV basaltic rocks increase from west to east, and MEC basaltic rocks related to the eastern branch of the LOFZ (Huililco and Pichares) are richer in these elements than those associated with the western branch (Caburga, La Barda and Huelemolle). Even more, the Rucapillán basalts that are the westernmost ones at this latitute tend to have lower incompatible element contents than the previous rocks (Moreno and López-Escobar, 1994). Similar west-east trends are observed in SV basaltic rocks belonging to N50-70°E volcanic alignments, such as the Osorno-Puntiagudo-Cordón Cenizos volcanic chain (Moreno *et al.*, 1979). At the Carrán-Los Venados MEC group, which has a N60-70°E orientation (Figs. 2, 3b) and cross the main trace of the LOFZ, those MEC located in the western part (Los Venados subgroup) are more depleted in incompatible trace elements than those located in the eastern part (Carrán subgroup; C. Rodríguez, personal communication). Farther south, the Puyuhuapi MEC basalts (45°S), located in the eastern branch of the LOFZ (like Huililco and Pichares centers), are also enriched in incompatible elements, being richer than those MEC basaltic rocks from Caburga-La Barda-Huelemolle (39°S), Los Venados (40.3°S) and Cayutué-La Viguería-Pocoihuén (41.5°S). Unfortunately, there are no data for MEC basaltic rocks associated with the western branch of the LOFZ at the latitude of the Puyuhuapi MEC group.

The behaviour of the incompatible trace elements suggests that their abundances in SV and MEC basaltic rocks of the Andean CSVZ and SSVZ is

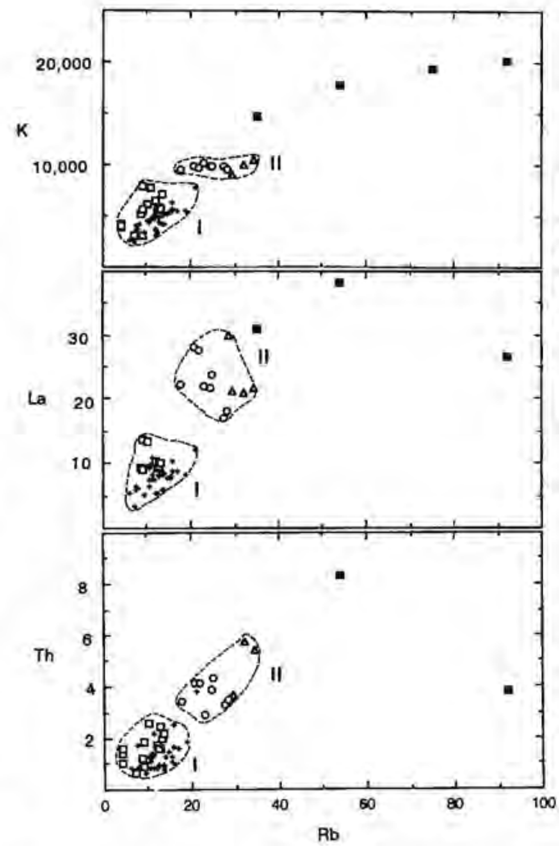

FIG. 7. K-Rb, La-Rb and Th-Rb (incompatible elements) diagrams for SV and MEC basaltic rocks from the CSVZ and SSVZ provinces of the SVZ of the Andes. Back-arc MEC basaltic rocks are shown for comparison. Symbols as in figure 6.

TABLE 1. NEW CHEMICAL ANALYSES OF BASALTIC ROCKS FROM THE SOUTHERN ANDES VOLCANIC ZONE.

	COMPOSITE STRATOVOLCANOES (SV)				MINOR ERUPTIVE CENTERS (MEC)			
	CASABLANCA	CASABLANCA	CASABLANCA	CASABLANCA	RUCAPILLAN PORPHYRITIC	RUCAPILLAN APHANITIC	MIRADOR	MIRADOR
Sample	280281-05	250483-02	120183-03	280281-03			120679-02	260479-03
Latitude	40.8°S	40.8°S	40.8°S	40.8°S	39.0°S	39.0°S	40.3°S	40.3°S
SiO_2	45.25	50.88	50.95	51.95	49.10	51.37	52.73	53.56
TiO_2	0.46	0.43	0.53	0.52	0.79	1.29	1.21	1.17
Al_2O_3	18.14	22.37	18.29	18.45	16.43	16.63	18.05	17.93
Fe_2O_3	9.54	8.50	10.13	9.83	9.67	11.57	11.64	11.19
MnO	0.14	0.12	0.14	0.15	0.14	0.16	0.18	0.19
MgO	4.21	4.51	7.16	6.34	9.44	5.73	4.57	4.29
CaO	7.70	10.43	9.11	9.76	10.35	8.15	8.42	8.50
Na_2O	3.98	2.93	3.09	3.49	2.93	3.66	3.93	3.88
K_2O	0.93	0.50	0.36	0.53	0.44	0.75	0.47	0.51
P_2O_5	0.22	0.15	0.23	0.15	0.14	0.29	0.19	0.18
Rb	21.2	8.4	12.0	10.6			9.8	8.5
Cs	1.5						1.0	1.0
Sr	444	534	514	441	528	495	478	478
Ba	324	140	232	158	154	266	185	192
Ga	19.2	18.5	18.0	17.9				
Pb	10.6	5.6	10.6	5.3				
Sc	25			30	36	35	27	27
V	198	180	196	220	231	305	241	224
Cr	44			100	320	125	5	3
Co	24			36	35	39	30	30
Ni	30	17	79	53	116	55	7	4
Cu					94	79		
Zn	81	70	81	80	86	117	95	96
Y	20.8	13.4	16.2	16.1	15.0	26.0		
Zr	107	57	88	62	53	114	72	78
Nb	3.5	1.8	3.8	1.5			1.6	1.8
Hf	2.6			1.6	1.7	3.8	1.9	1.7
Ta	0.21			0.13			0.10	0.10
Th	3.80			1.10			0.60	0.70
La	12.2			6.6	7.0	14.0	7.1	6.9
Ce	27.3			17.2	16.0	32.0	18.1	17.2
Nd	14.2			10.2	10.0	19.0	10.8	11.7
Sm	3.69			2.66	2.31	4.40	3.40	3.00
Eu	1.17			0.93	0.88	1.36	1.20	1.30
Gd					2.69	4.40		
Tb	0.54			0.48			0.60	0.70
Dy					2.53	4.35		
Ho					0.52	0.83		
Er					1.51	2.40		
Yb	2.14			1.64	1.50	2.41	2.20	2.20
Lu	0.33			0.24	0.23	0.35	0.30	0.40
$^{87/86}Sr$	0.70415						0.70410	0.70414
$^{143/144}Nd$	0.512842						0.512858	0.512850
$^{206/204}Pb$								
$^{207/204}Pb$								
$^{208/204}Pb$								

table 1 continued

MINOR ERUPTIVE CENTERS (MEC)								
	PICHIHUINCO	CAYUTUE	LA VIGUERIA	LA VIGUERIA	POCOIHUEN	PUYUHUAPI	PUYUHUAPI	PUYUHUAPI
Sample	220483-01	201282-01	040476-01	151284-04	160185-03	160390-01	160390-04	160390-05
Latitude	41.3°S	41.4°S	41.4°S	41.5°S	44.3°S	44.3°S	44.3°S	44.3°S
SiO_2	51.52	51.79	50.57	51.54	51.86	48.84	49.46	48.61
TiO_2	0.78	0.87	0.66	0.83	0.91	1.50	1.55	1.55
Al_2O_3	20.58	17.34	17.64	17.58	16.90	16.60	16.30	16.30
Fe_2O_3	8.25	8.52	10.81	8.93	9.19	9.73	10.13	10.53
MnO	0.14	0.17	0.16	0.15	0.16	0.15	0.15	0.15
MgO	4.88	6.54	7.33	7.47	7.67	8.06	7.30	8.12
CaO	10.45	9.90	10.05	9.86	9.83	10.46	10.36	10.10
Na_2O	2.94	2.91	2.86	2.80	2.69	3.29	3.25	3.15
K_2O	0.36	0.78	0.62	0.67	0.65	1.18	1.16	1.18
P_2O_5	0.10	0.14	0.20	0.19	0.18	0.38	0.35	0.39
Rb	9.0	11.7	8.8	8.9	11.5	22.2	21.4	21.4
Cs	0.6	0.7	0.5	0.3	0.5	0.6		
Sr	415	557	594	584	416	744	738	747
Ba	120	204	190	188	218	62	69	49
Ga	18.7	18.2		17.6	16.7			
Pb				8.3	8.8			
Sc	30	30	32	29	31	47	50	46
V	213	217		213	219			
Cr	79	156	200	177	277	180	159	180
Co	28	29	37			53	52	51
Ni	30	50	53	78	91			
Cu								
Zn	74	82		82	79			
Y	13.6	18.1		17.2	20.1			
Zr	40	95		76	82			
Nb	4.0	3.7		1.9	2.0			
Hf	1.2	2.1	2.0	1.8	2.0	2.9	3.1	2.9
Ta	0.06	0.21	0.13			0.86	0.99	1.20
Th	0.65	1.73	1.20	0.89	1.64	4.16	4.10	3.88
La	3.9	10.3	9.2	9.0	9.2	28.1	27.6	21.8
Ce	10.6	26.0	22.0	22.7	22.7	46.3	44.6	48.5
Nd	7.0	14.4	12.9	13.3	13.8	28.1	28.5	30.0
Sm	2.02	3.58	3.19	3.22	3.38	6.00	5.77	4.87
Eu	0.81	1.14	1.10	0.99	1.06	1.68	1.73	1.59
Gd								
Tb	0.33	0.41	0.53	0.44	0.50	0.72	0.62	0.61
Dy						3.49		
Ho								
Er								
Yb	1.50	1.74	1.70	1.63	2.03	1.84	1.98	1.84
Lu	0.23	0.28	0.26	0.26	0.27	0.30	0.37	0.31
$^{87/86}Sr$		0.703686			0.703912	0.704021	0.704001	0.703995
$^{143/144}Nd$		0.512828			0.512796	0.512762	0.512765	0.512770
$^{206/204}Pb$		18.575			18.516	18.447	18.457	18.462
$^{207/204}Pb$		15.627			15.570	15.580	15.580	15.579
$^{208/204}Pb$		38.513			38.337	38.459	38.443	38.420

The database for figures 6-10 are chemical analyses published in: Carrasco, 1995; Gerlach *et al.*, 1988; Hickey *et al.*, 1986; Hickey-Vargas *et al.*, 1989; Lahsen *et al.*, 1994; López-Escobar and Moreno, 1981; López-Escobar *et al.*, 1981, 1992, 1993, 1995; Moreno, 1977; Moreno and López-Escobar, 1994; Moreno *et al.*, 1979; plus the new analyses in table 1. The complete set is available upon request with the main author.

independent of the orientation of the faults and fractures where they are emplaced. In other words, the role of faults and fractures would be to allow the ascent of basaltic magmas, whose geochemical imprints are probably determined by subduction related processes.

The Ba/La and La/Yb ratios of Andean CSVZ and SSVZ basaltic rocks also seem to depend on sub-crustal features and processes. In fact, independently of the orientation of the volcanic alignments to which they belong, K-poor basaltic rocks tend to have higher Ba/La and lower La/Yb ratios than K-rich-ones (Fig. 8). One of the highest Ba/La and lowest La/Yb ratios are presented by basalts from the Pichihuinco maar (one of the westernmost MEC of this Andean region). On the other hand, one of the lowest Ba/La and highest La/Yb ratios are exhibited by the Puyuhuapi MEC basalts (Demant *et al.*, 1994; Lahsen *et al.*, 1994; López-Escobar and Moreno, 1994). 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) (López-Escobar, 1984; López-Escobar *et al.*, 1985), where the continental crust has a thickness of 55-60 km. The relatively low Ba/La ratios of the Puyuhuapi MEC basalts and, in general, of K-rich basaltic rocks have been explained by subduction related processes (López-Escobar *et al.*, 1993). These processes could also explain the enrichments of these magmas in incompatible elements and their relatively high La/Yb ratios. The extremely high La/Yb ratios of the Puyuhuapi basalts, which is mainly due to their low Yb contents, also suggest that their parental magmas were in equilibrium with garnet either at their mantle source or at lower crustal levels.

Andean CSVZ and SSVZ K-poor basaltic rocks are quite heterogeneous in Sr and Nd isotopic ratios ($^{87}Sr/^{86}Sr$=0.7036-0.7044; $^{143}Nd/^{144}Nd$=0.512700-0.512900; Fig. 9). However, K-rich ones have $^{87}Sr/^{86}Sr$ (0.7039-0.7044) and $^{143}Nd/^{144}Nd$ (0.51275-0.51283) ratios that are respectively concentrated in the uppermost and lowest parts of the range exhibited by K-poor basaltic rocks. In each group, MEC tend to have lower Sr-isotope ratios than SV. When MEC basalts of similar latitude are compared, their $^{87}Sr/^{86}Sr$ ratios tend to increase and their $^{143}Nd/^{144}Nd$ ratios tend to decrease with decreasing longitude. This is observed, for example, at ~39°S, where K-poor MEC basalts (Caburga) have significantly lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios than K-rich MEC basalts (Huililco and Pichares). Puyuhuapi MEC basalts (44.3°S), have similar $^{87}Sr/^{86}Sr$ ratios (about 0.70400; Table 1) than Huililco and Pichares basalts (Hickey-Vargas *et al.*, 1989), but their $^{143}Nd/^{144}Nd$ ratios are significantly lower (average 0.512766).

In K-rich as well as in K-poor basalts, high $^{87}Sr/^{86}Sr$ ratios are generally accompanied by low $^{143}Nd/^{144}Nd$ ratios. This trend is well defined in the former

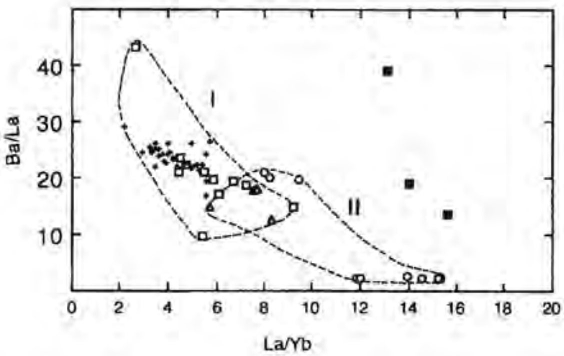

FIG. 8. Ba/La *versus* La/Yb diagram for SV and MEC basaltic rocks from the CSVZ and SSVZ provinces of the SVZ of the Andes. Back-arc MEC basaltic rocks are shown for comparison. Symbols as in figure 6.

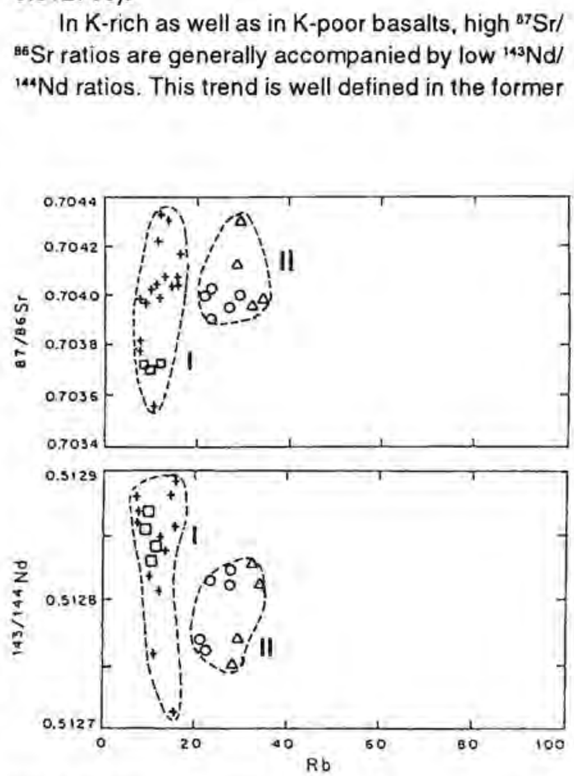

FIG. 9. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ *versus* Rb diagrams for SV and MEC basaltic rocks from the CSVZ and SSVZ provinces of the SVZ of the Andes. Symbols as in figure 6.

basaltic rocks. 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. At least at latitude 39°S, there is evidence that K-rich basalts (Lanín basalts) are emplaced on an uplifted block, so some influence of crustal material cannot be wholly denied.

In general, CSVZ and SSVZ basalts are quite heterogeneous in their incompatible element ratios (Fig. 10). Although this heterogeneity could reflect source heterogeneities, it may be also due to crystal fractionation processes, involving the principal minerals present in those basalts (olivine, pyroxenes and plagioclase). In fact, although K, Rb, La and Ba are incompatible with respect to olivine, pyroxenes and plagioclase, their degree of incompatibility, expressed by their crystal/liquid partition coefficients, is quite different in some cases. 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 coefficient for K is 0.002 and for La is 0.120. Petrographic and chemical evidences that crystal fractionation processes have affected CSVZ basalts are given by the Rucapillán MEC basalts (Moreno and López-Escobar, 1994). Samples from this MEC exhibit aphanitic lens of basaltic composition (SiO_2=51.37%; Table 1) immersed in a porphyritic basaltic mass (SiO_2=49.10%). In comparison with the porphyritic fraction, the aphanitic one is depleted in MgO, CaO, Sr, Cr and Ni, and has lower K/La and Sr/La ratios. These geochemical characteristics suggest that the aphanitic lenses represent melts derived, by crystal fractionation, from a parental basaltic magma similar to the porphyritic fraction. This is important because the geochemistry of some SV basaltic rocks from this Andean region resembles that of the aphanitic fraction of the Rucapillán samples.

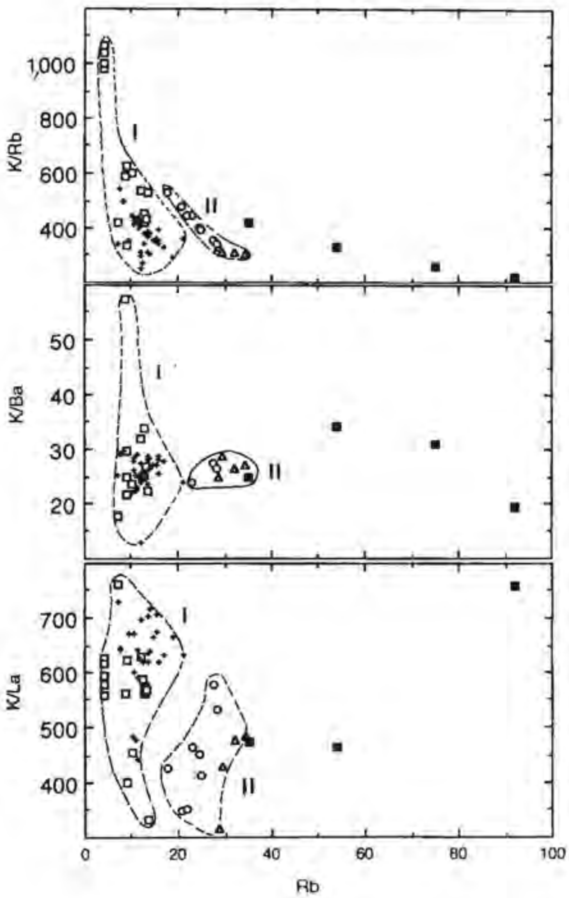

FIG. 10. Some Incompatible Element Ratios *versus* Rb diagrams for SV and MEC basaltic rocks from the CSVZ and SSVZ provinces of the SVZ of the Andes. Back-arc MEC basaltic rocks are shown for comparison. Symbols as in figure 6.

SUMMARY AND CONCLUSIONS

In summary, Andean CSVZ and SSVZ stratovolcanoes (SV) and minor eruptive centers (MEC) basaltic rocks, from either N50-60°W and N50-70°E transverse alignments tend to increase their incompatible elements abundances, Ba/La and $^{87}Sr/^{86}Sr$ ratios, and decrease their La/Yb and $^{143}Nd/^{144}Nd$ ratios in going from west to east. In other words, these geochemical characteristics seem to be independent of the orientation of fractures and faults where those centers are emplaced, suggesting that they are controlled mainly by subduction-related processes. Even the most primitive basalts of this Andean segment show evidences of undergoing fractional crystallization. Actually, they have MgO <

11%, and Ni and Cr abundances lower than those expected in mantle-derived primary magmas. Tectonism seems to control the possibility that basaltic magmas either reach the surface or evolve to more differentiated products at crustal levels. In fact, most young volcanic chains (Late Pleistocene-Holocene), including SV and/or MEC defining northeast-trending alignments are characterized mainly by basaltic to basaltic andesites rocks (*e.g.*, Osorno-Puntiagudo-Cordón Cenizos volcanic chain). This is consistent with a short residence time of magmas in the crust, resulting in a limited contamination and fractionation of mantle-derived magmas. On the other hand, volcanic edifices controlled by northwest-trending fractures and faults (*e.g.*, Villarrica-Quetrupillán-Lanín and Puyehue-Cordón Caulle volcanic chains) may be under a combination of shortening and strike-slip deformation, which would cause a longer intracrustal magma residence, yielding a more mature and differentiated composition. This could be a reason why the latter shows a wider rock suite, with the occurrence of not only basalts and basaltic andesites, but also medium andesites, dacites and even rhyolites erupted in historic times.

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