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The link between volcanism and tectonics in the southern volcanic zone of the Chilean Andes: A review

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A B S T R A C T

The nature of the interplay between tectonics and volcanism is a major question in continental margin tectonics. The Southern Andes volcanic zone (SVZ), located at the obliquely convergent Nazca–South America plate margin between 33°S and 46°S, offers a unique opportunity to address this question because of along-strike changes in crustal thickness, tectonic style and well-constrained long-term and short-term kinematic history. The complex interaction between tectonic and magmatic processes is evidenced by both the architecture and geochemical signature of volcanic systems. Main first-order factors accounting for the along-strike variations in the nature and composition of volcanism are crustal thickness and the existence of a major, intra-arc fault system, the Liquiñe–Ofqui fault zone (LOFZ). Second order factors include the local nature of the volcanic arc basement.

Two main categories of volcano–tectonic associations have been identified, according to the spatial distribution and internal organization of individual volcanoes and clusters of volcanoes with respect to both the overall strike of the volcanic arc and the first and second-order active/inactive basement faults. Kinematically-coupled associations, those that are directly related to the current dextral transpressional tectonic regime, include NE-trending volcanic alignments of stratovolcanoes and/or monogenetic cones; kinematically uncoupled associations, in which coupling with the current regime is not required, include stratovolcanoes built on top of ancient reverse and strike–slip faults of the volcanic arc basement and monogenetic cones lying along master faults of the LOFZ. Whereas mostly primitive magmas are found in the first category, more evolved terms can occur genetically associated with the second category. We propose a simplified, three-dimensional model for the magma plumbing system along and across the SVZ that integrates kinematically-coupled and kinematically uncoupled volcano–tectonic associations within the framework of first- and second-order geological and structural constraints.

1. Introduction

1.1. Statement of the problem

One fundamental problem in continental margin tectonics is the nature of the interplay between deformation processes and magma transport through the lithosphere (*e.g.* Hutton, 1988; Vigneresse, 1999; Petford et al., 2000). Deformation-induced fault-fracture networks have been regarded as efficient pathways through which magma is transported, stored and eventually erupted at the earth surface (*e.g.* Hill, 1977; Shaw, 1980; Clemens and Mawer, 1992; Petford et al., 2000). Thus, the state of stress of the lithosphere at the time of magmatism should somehow control the spatial distribution of plutons, dikes swarms and volcanic centers (*e.g.* Nakamura, 1977; Nakamura et al., 1978; Delaney et al., 1986; Hutton, 1988; Takada, 1994; Glazner et al., 1999; Acocella et al., 2007). However, crustal deformation not only plays a significant role in magma migration. More importantly, it may exert a fundamental control on magma differentiation processes that, in turn, can determine the nature and composition of volcanism along and across continental margins (*e.g.* Cembrano and Moreno, 1994).

The Chilean Andes provides one of the best natural laboratories in the world to assess the link between tectonics and volcanism. Apart from its well-constrained plate kinematic history, there is a marked latitudinal segmentation in crustal thickness, upper plate deformation and a changing nature of the basement upon which the volcanic arc has developed (e.g. Jordan et al., 1983; Tassara and Yáñez, 2003). Then, the relative importance of present-day kinematics and inherited crustal composition and structure in the mechanisms of magma transport and in the nature and composition of volcanism can be successfully examined along the same orogenic belt. In this paper, we review and discuss all relevant tectonic, field and geochemical data on the Chilean volcanic arc from 33 to 46°S, a region encompassing the whole southern volcanic zone of the Andes. We hypothesize that one fundamental, usually overlooked factor controlling the wide variety of volcanic forms and rock compositions present along a single

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continental magmatic arc, is the contrasting kinematics of the fault-fracture networks under which they are transported within the same magmatic arc. Thus, magmas that migrate under crustal compression/ transpression would be significantly more evolved (differentiated) than those that have migrated under upper crustal extension/ transtension. Furthermore, as the Chilean volcanic arc shows a significant degree of strike–slip deformation, compression and extension can occur at the same time but in different orientation, both oblique to the magmatic arc trend.

1.2. The role of tectonics in magma transport through the lithosphere

Most early work regarding the origin of igneous rocks largely neglected the active role of deformation in the transport of magma. One notable exception is Cloos (1923), who suggested that magmas were squeezed upward by regional shortening. This early interpretation anticipated more elaborated models of intrusion within transpressional settings as recently postulated (*e.g.*, De Saint Blanquat et al., 1998]. Especially for plutonic rocks, the nature and transport of magma was traditionally viewed mostly from a petrological or geochemical point of view, almost completely separated from tectonics. Magma was assumed to migrate from the mantle to the upper crust as buoyant diapirs, by analogy with salt domes (*e.g.* Daly, 1903; Grout, 1945; Ramberg, 1967). The fact that the most common plan view of plutons is sub-circular to elliptical was taken as evidence to support this hypothesis. Later work, however, proved that it is almost impossible for a granitic diapir to reach the upper crust without crystallizing and stalling at deeper levels. This is because the country rock is required to flow around the diapir as it rises (Marsh, 1982). Over the last two decades, dike propagation, largely controlled by tectonics, has emerged as a more likely mechanism for magma transport in the lithosphere, mainly because it is consistent with the mechanics, nature and rates of geologic processes (e.g. Petford et al., 2000). These studies have emphasized that the final pluton shape is not necessarily indicative of the ascent mechanism but results from upper crustal emplacement of laccoliths fed by underlying vertical dikes. Dike propagation is then very common in the upper brittle crust whereas diapirism may be an important transport process in the lower ductile crust (*e.g.* Weinberg, 1996) In summary, with few exceptions (Paterson and Schmidt, 1999; Schmidt and Paterson, 2000), structural investigations and analog models have concluded that faults are closely related to magma transport and emplacement in space and time in any type of tectonic setting, either strike–slip (Hutton, 1982; Corti et al., 2005), extensional (Hutton, 1988), transtensional (Guineberteau et al., 1987), transpressive (D'Lemos et al., 1992; De Saint Blanquat et al., 1998) or compressive (Brown and Solar, 1998; Kalakay et al., 2001; Galland et al., 2003; Musumeci et al., 2005).

Regarding the interplay between crustal tectonics and volcanism, several authors have set examples of eruption centers and/or dikes that were formed in response to regional tectonic stresses in continental settings (e.g. Muller and Pollard, 1977; Nakamura, 1977; Delaney et al., 1986; Smith, 1987). For instance, Nakamura (1977) proposed that the systematic alignments of minor eruptive centers (MEC) and flank volcanoes (vents) within major stratovolcanoes (SV) in subduction zone margins can be used as a tool to determine the direction of the maximum horizontal stress ($\sigma H_{\max}$), 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 (Muller and Pollard, 1977; Nakamura, 1977).

More recently, Tibaldi (1995) extended Nakamura's model to isolated cones or clusters above gently slopes. Morphometric parameters of the pyroclastic cones such as the elongation of their base, elongation of the craters, or the strike of the two deep depressed points along the crater rim, are believed to reflect the geometry of the underlying faults and, in some cases, their kinematics. Further work by Adiyaman et al. (1998) and Dhont et al. (1998) has restricted the kinematic inference of tension cracks only for elongated cones or linear clusters with a major edifice in the middle.

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 $\sigma 1$ or $\sigma 2$. 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 may not indicate by themselves the orientation of the long-term stress field (*e.g.* Lara et al., 2004a,b).

Nakamura's model, which can be extended to alignments of SV, has been successfully tested in the Aleutians (Nakamura et al., 1978). For this volcanic arc, the expected direction of the σHmax, as obtained by the inversion of fault–slip data, is consistent with that suggested by the systematic orientation of volcanic structures. The same regional-scale scenario has been postulated for the southern Andes volcanic zone (Cembrano and Moreno, 1994; López-Escobar et al., 1995; Lavenu and Cembrano, 1999). 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 ($\sigma 1$ and $\sigma 3$ horizontal; $\sigma 2$ vertical), instead of compressional ($\sigma 1$ and $\sigma 2$ horizontal; $\sigma 3$ vertical). This would allow magma to ascent through vertical dykes having a direction parallel to that of σHmax (Nakamura and Uyeda, 1980). More recent work on the causal relationship between tectonism and volcanism (*e.g.* Tibaldi, 1992; Bellier and Sébrier, 1994; Ventura, 1994; Tibaldi, 1995; Dhont et al., 1998) 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, occurring in many volcanic arcs, show that strike–slip deformation predominates over compression or extension (*e.g.* McCaffrey, 1992; Barrientos and Acevedo, 1992). However, volcanism may indeed occur under purely compressional deformation as has been shown by both structural and seismic studies at present-day convergent margins, respectively (e.g. Tibaldi, 1995; Galland et al., 2007). Consistently, recent analog models have reproduced possible mechanisms of magma ascent and emplacement in the upper crust under compression (e.g. Galland et al., 2003), suggesting that thrust faults may act as pathways for magma ascent within a crust dominated by sub-horizontal, sill-like reservoirs.

The hypothesis of magma ascending as dykes through a composite system of tensional and shear fractures, in an overall strike–slip deformation regime ($\sigma 1$ and $\sigma 3$ horizontal), is consistent with the dynamic models of fracture propagation proposed by Hill (1977) and Shaw (1980) for the crust and lithospheric mantle.

Takada (1994) correlated volcano types (polygenetic or monogenetic), to the balance between magma input from the mantle source and differential stresses in the upper crust. Polygenetic volcanoes occur with large magma inputs and lower differential stresses. Monogenetic volcanoes, in contrast, are built with low input rates and higher differential stresses.

Last but not least, an important issue on magma transport throughout the continental lithosphere is the ascent through severely misoriented structures or bulk compressive settings. This case was widely explored for hydrothermal fluids in the classic papers by

Sibson (1985, 1987) and specially Sibson et al. (1988) where a critical reshearing angle is obtained from a relation between normal and shear stresses and the required magma overpressure.

At shallow levels, arrest of the dikes, volcanic unrest periods and subsequent eruptive cycles would be controlled by the local stresses, which finally are a composite of magma pressure around the conduit, regional stresses and mechanical properties of the host rocks (*e.g.*, Gudmundsson, 2006). Numerical modeling on the stress field around magma chambers and geothermal systems (Gudmundsson et al., 2002; Gudmundsson and Phillip, 2006) have quantified the boundary conditions for fluids reach the surface to fed volcanic eruptions.

2. Tectonic, geologic and kinematic framework of the volcanic arc between 33 and 46°S (southern volcanic zone)

The stretch of the Andean range examined here runs from 33°S to 46°S, encompassing the whole southern volcanic zone (SVZ). Its tectonic setting is characterized by slightly dextral-oblique convergence between the Nazca and South American plates at a rate of ca. 7–9 cm/year that has prevailed for the last 20 Ma (*e.g.* Pardo-Casas and Molnar, 1987; Somoza, 1998; Angermann et al., 1999). The active Chile Ridge collides with the continental margin a the Chile triple junction, where the Nazca, South American and Antarctic plate meet with the Peru–Chile trench, marking the end of the Central Andes (sensu Gansser, 1973) and the southern volcanic zone (Fig. 1).

Fig. 2 outlines the regional geology of central and southern Chile, as modified from the Chilean National Geological Survey 2002 map (SERNAGEOMIN, 2002 and references therein). Regional-scale rock units are organized into several margin–parallel belts, ranging from paleozoic plutonic and metamorphic rocks in the Coastal range to meso–cenozoic plutonic and volcanosedimentary units in the Main cordillera. The Central Depression, located in the middle, is characterized by Oligocene–Recent volcano–sedimentary rocks.

The basement of the volcanic arc between 33° and 37°S is made up of extensive outcrops of Meso–Cenozoic volcano–sedimentary rocks, only locally intruded by Mio–Pliocene plutons (e.g. Charrier et al., 2002; Farías, 2007). This setting changes markedly south of 38°S, where recent volcanoes are built directly onto Meso–Cenozoic plutonic rocks of the Patagonian Batholith (Fig. 2). Consistently, calculated cenozoic regional exhumation rates along the main range show a dramatic increase at 38°S, from less than 0,1 mm/year to the north to more than 1 mm/year to the south (e.g. Glodny et al., 2008). Furthermore, crustal thickness underneath the volcanic arc decreases steadily from *ca*. 50 km at 33°S to 35 km at 46°S, with an accompanying decrease in the average altitude of the main cordillera, from 5000 m to less than 2000 m (Tassara and Yáñez, 2003) (Figs. 3, 4).

The long-term regional-scale structure of the volcanic arc region between 33 and 35°S is characterized by east-verging margin–parallel folds and thrusts of Cenozoic age, representing the westernmost expression of the Aconcagua and Malargue foreland fold-and-thrust belts (*e.g.* Giambiagi, 2002). Main regional reverse faults affect both mesozoic and cenozoic volcano-sedimentary units and accommodate limited amounts of shortening when compared with the Central Andes of northern Chile.

The Neogene, El Agrio foreland fold-and-thrust belt is developed between 36 and 38°S in the Argentinian foreland (*e.g.*, Folguera et al., 2004). Recent papers document the active back-arc volcanism coeval with east–west compression along the Agrio belt (e.g. Tromen volcano, Kozlowski et al., 1996; Galland et al., 2007); a similar, current intra-arc compression is seismically documented for Central Chile (33–34°S) (Pardo et al., 2006) (Fig. 3). The volcanic arc region between 37°S and 38°S, in contrast, has undergone pleistocene-holocene arc-orthogonal extension, with a small component of dextral strike slip displacement (Melnick et al. 2006a). Right to the east of this area is the Antiñir-Copahue fault zone, an east-vergent, high-angle, dextral transpressive and dextral-transtensive faults, that constitute the orogenic front at these latitudes (Folguera et al. 2004). The Antiñir-Copahue fault zone merges southwestwards with the 1200 km-long Liquiñe–Ofqui fault zone (LOFZ), a major intra-arc fault system that dominates the region between 38° and 47°S (Cembrano et al., 1996; Folguera et al., 2002; Adriasola et al., 2006; Rosenau et al., 2006). Ductile-to-brittle shear zones document that the LOFZ has been active as a transpressional dextral strike–slip structure at least over the last 6 Ma, although geologic evidence suggests the LOFZ was probably a leaky transform fault at about 25 Ma (*e.g.* Hervé et al., 1994). The shortening component of Pliocene to Recent intra-arc deformation increases to the south, as the LOFZ approaches the Chile triple-Junction (*e.g.*, Lavenu and Cembrano, 1999; Cembrano et al., 2002; Thomson, 2002; Rosenau et al., 2006).

No significant Cenozoic foreland fold-and-thrust-belt is developed east of the LOFZ, where only limited pre-Quaternary evidence of dextral transpressional deformation has been described (Diraison et al., 1998).

The long-term Quaternary kinematics of the volcanic arc is given by fault–slip data for the central and southern Chilean Andes (*e.g.*, Lavenu and Cembrano, 1999; Arancibia et al., 1999; Cembrano et al., 2000; Potent and Reuther, 2001; Lara et al., 2006a). Inversion of these data for the stress tensor documents a NE-trending subhorizontal maximum compression axis (σ_1) throughout the southern volcanic zone between 37°S to 46°S (Fig. 3). The axis of the minimum compressional stress (σ_3) is mostly subhorizontal and trends NW. This is compatible with the margin–parallel, dextral strike–slip deformation along and across the SVZ during the Quaternary. Locally, especially towards the southern portion of the SVZ, σ_3 becomes vertical, suggesting a switch from strike–slip to compressional deformation.

The present-day kinematics of the volcanic arc is evidenced by several shallow crustal earthquakes recorded over the last thirty years (Fig. 3). Dextral strike–slip moment tensor solutions dominate the main cordillera between 34° and 46°S (e.g. Chinn and Isacks, 1983; Lange et al., 2008); compressional focal mechanisms only are recorded in the main cordillera between 33 and 34°S (*e.g.* Pardo et al., 2006; Farías et al., 2006). The along-strike switch from non-partitioned to partitioned deformation in this part of the Central Andes (*e.g.*, Lavenu and Cembrano, 1999; Folguera et al., 2004), coincides well with a significant increase in convergence obliquity south of 34°S, which in turn results from the abrupt change in trench orientation, from nearly NS to NNE. Dextral strike–slip deformation in the volcanic arc implies a northward motion of the forearc sliver, and concomitant margin–parallel shortening at its leading edge (buttress effect, Beck et al., 1993; Lavenu and Cembrano, 1999; Farías et al., 2006). One conspicuous upper crustal thrust-type earthquake close to Maipo volcano, right at the boundary zone between these two Cordilleran segments, is compatible with the expected margin–parallel shortening (Farías et al., 2006) (Figs. 3).

Although dextral strike–slip focal mechanisms prevail in most of the SVZ, field evidence of long-term strike–faulting at the surface can be observed only south of 38°S. As it will be discussed later, this has strong tectonic implications on the way deformation is accommodated in the overriding plate and also in the way magmas rise through the upper crust.

3. Key geochemical constraints

In this section we summarize only those geochemical data that have strong tectonic implications at the scale of the whole SVZ and within each of the segments in which this has traditionally been subdivided. A thorough review of the geochemistry and petrology of the SVZ rocks is beyond the scope of this paper; excellent reviews can be found elsewhere (e.g. Stern, 2004; Stern et al., 2007).

SVZ magmatism is mostly controlled by the dehydration of the Nazca plate and subsequent partial melting of the sub-arc mantle

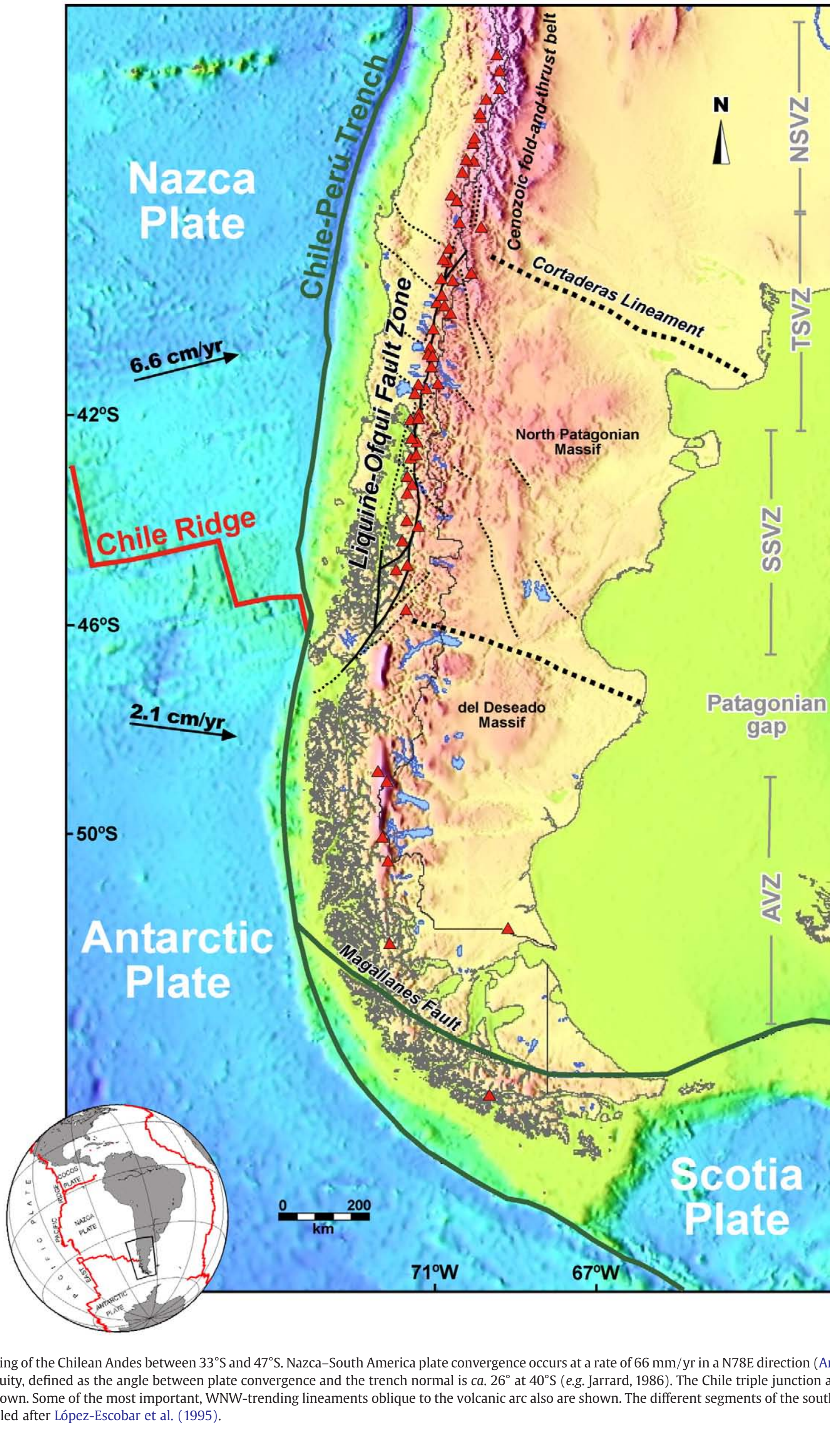


Fig. 1. Tectonic setting of the Chilean Andes between 33°S and 47°S. Nazca–South America plate convergence occurs at a rate of 66 mm/yr in a N78E direction (Angerman et al., 1999). Convergence obliquity, defined as the angle between plate convergence and the trench normal is *ca.* 26° at 40°S (*e.g.* Jarrard, 1986). The Chile triple junction and the Liquiñe Ofqui fault system are shown. Some of the most important, WNW-trending lineaments oblique to the volcanic arc also are shown. The different segments of the southern volcanic zone of the Andes are labeled after López-Escobar et al. (1995).

wedge. Along-arc variations in isotopic composition of volcanic rocks would indicate different amounts of participation of continental crust and/or mantle lithosphere in the magma genesis (Fig. 4). As widely accepted (see review by Stern, 2004), the incipient 'crustal signature' of the SVZ magmas could be acquired during interaction with the continental lithosphere (Rogers and Hawkesworth, 1989; Stern and Kilian, 1996; Hickey-Vargas et al., 2002), by intracrustal assimilation (Hildreth and Moorbath, 1988), and/or by source region contamination by subducted continental components (Stern, 1991; Kay et al., 2005). Relative roles of each process differ as a function of the thickness and composition of the continental crust, rates of subduction erosion of the continental margin, crustal rheology and tectonic regimes, which in turn would control the ascent pathways.

From a petrochemical point of view, a number of first order segmentations of the SVZ has been proposed (see review by Sellés et al., 2004). López-Escobar (1984) defined two major provinces: Province 1 (33°–37°S) and Province 2 (37°–46°S). Futa and Stern (1988) considered a similar scheme but placed the boundary at 36°S. Tormey et al. (1991) subdivided the northern segment with a limit at 34.5°S. López-Escobar et al. (1995) defined four subsegments: NSVZ (33°–34.5°S); TSVZ (34.5–37°S); CSVZ (37°–42°S) and SSVZ (42°–46°S). Finally, Dungan et al. (2001) considered the Tupungato–Maipo segment (33°–34.5°S), Palomo–Tatara segment (34.5°–36°S) and Longaví–Osorno segment (36°–42°S). As can be noted, discussion was mostly centered on the subdivision of the northern segments. South of 34.5°S, the arc front changes its strike from NS to NNE but following a sustained decrease in $^{87}Sr/^{86}Sr$ (Fig. 4). At 36°S, between Tatara and Longaví volcanoes, the arc front becomes NS and a remarkable change is observed on both the $^{87}Sr/^{86}Sr$ isotopic ratio, which remain roughly constant (0.7040) southward and the crustal thickness inferred from the Bouguer anomaly, that in turn reduces from *ca*. 50 to 35 km further south (Hildreth and Moorbath, 1988).

Quaternary rocks from the NSVZ (33°–34.5°S) are mostly intermediate in composition ranging from basaltic andesites to dacites. Basalts are absent and rhyolitic compositions are mostly recorded in large pyroclastic flows as the Pudahuel Ignimbrite (Stern et al., 1984). Compared to the southern segments at similar SiO_2 contents, NSVZ magmas have relatively high contents of incompatible trace elements (K, Rb, Sr, Ba, La, Th, U) and higher ratios of fluid-mobile to less fluid-mobile elements (Rb/Cs, La/Yb, K/La, Rb/La, Ba/La, Hf/Lu) as well as $^{87}Sr/^{86}Sr$ isotope ratios together with lower K/Rb and $^{143}Nd/^{144}Nd$. This 'crustal signature' could be acquired within intracrustal magma chambers, at the base of the crust throughout the MASH (mixing, assimilation, storage and homogenization) proceses (Hildreth and Moorbath, 1988) and/or by subduction erosion (Stern, 1991). Whatever the mechanism, the absence of primitive magmas suggests an advanced differentiation with a 'crustal filter' for basalts and probably a longer crustal residence. This is a plausible hypothesis with a thick crustal pile as inferred from the high La/Yb and lower Yb that suggest garnet in the source where both, the inherited structure of the crust and tectonic regimes could be driving factors.

The transitional segment from 34.5° to 36°S shows a wide variety of compositions ranging from tholeiitic basalts to high-K rhyolites. Andesites are the most abundant products, although the proportion of basalts increases southward and seems to be dominant in the older units. Large volumes of rhyolites were also erupted from the Pleistocene Calabozos caldera (Hildreth et al., 1984; Grunder, 1987) and Puelche volcanic field (Hildreth et al., 1999). Isotopic data indicate that the generation of these rhyolites involved significant contributions from crustal partial melts. Alkali-basalts appear in the back-arc scoria cones of Llancanelo and Payún Matru volcanic fields (Risso et al., 2008).

Nevado de Longaví (36.2°S) is a pivotal point at the northern edge of the central segment of the SVZ. Older units from this centre are formed by basalts to andesites, while the Holocene ones range from basaltic andesites to dacites (Sellés et al., 2004). Unexpected 'adakitic' signature is observed on Holocene dacites which has been interpreted as product of crustal evolution of uncommon hydrous primitive magmas (Rodríguez et al., 2007).

In the Central and Southern SVZ, tholeiitic and high-Al basalts and basaltic andesites are the dominant rock types that erupted from both stratovolcanoes and minor eruptive centers (López-Escobar et al., 1977; Hickey-Vargas et al., 1984, 1989; Hickey-Vargas et al., 1986; Gerlach et al., 1988; Futa and Stern, 1988; López-Escobar et al., 1993, 1995). Andesites, dacites and rhyolites also occur but they are scarce or restricted to some particular centers (e.g., Lara et al., 2006a).

At least an incipient deep fractional crystallization is inferred from the MgO, Ni and Cr contents of basalts, which are lower than those expected in mantle derived primary magmas. Rocks from CSVZ are characterized by dry mineral assemblages but growing evidence shows the presence of hornblende in some evolved magmas from Puyehue-Cordón Caulle and Antillanca volcanic complexes (40°S; Singer et al., 2008; Lara et al., 2007). The most silicic SSVZ rocks carry hydrous minerals like hornblende and even scarce biotite, the latter only in the Chaitén rhyolites which also have the highest $^{87}Sr/^{86}Sr$ ratios. Alkaline-basalts are restricted to monogenetic centers along the Liquiñe–Ofqui Fault Zone domain where tholeiitic basalts also occur.

At arc-scale, crustal tectonics would control whether basaltic magmas reach the surface or evolve to more differentiated products at crustal levels. NE-striking volcanic alignments contain mainly basaltic to basaltic andesite lithologies in either stratovolcanoes or minor eruptive centers (Fig. 5). NW-striking alignments, where only stratovolcanoes occur, include a wide range of compositions including centers that have erupted only rhyolites in historical times (*e.g.* Lara et al., 2004a,b). From radiogenic isotope contents, Tormey et al. (1991) inferred short residence times for SVZ basalts but recent estimations (Jicha et al., 2007) show that evolved magmas can also erupt so fast that eruptive ages are undistinguishable from U–Th disequilibria. Models of differentiation 'en route' compel to crustal tectonics to operate at more reduced time scales that previously thought.

Whatever the time framework, magmas from the most 'compressive' NW-trending domains show more advanced differentiation than those from 'extensional' ones as can be observed in a Cr–Rb plot (Fig. 5). Possible mixing model for intermediate compositions also suggests some crustal residence for the precursor magmas. LOFZ-related basalts appear as the most primitive products of the entire arc.

On the other hand, the increase of $^{87}Sr/^{86}Sr$ ratio around 42°S (Fig. 4) cannot be simply related to crustal thickness but to the nature of the uppermost crust. In fact, these stratovolcanoes, located on the western part of the volcanic arc, are built on top of structural blocks of differentially exhumed metamorphic basement.

4. Interplay between tectonics and volcanism in the SVZ

Individual stratovolcanoes and clusters of stratovolcanoes/monogenetic cones of the SVZ show several types of spatial distributions and internal organization with respect to both the overall strike of the volcanic arc and the first and second order active/inactive basement faults. These different overall geometries and associated volcano morphologies reflect the complexity of volcano–tectonic interactions and demand alternative explanations to those simple models postulated by earlier workers (*e.g.* López-Escobar et al., 1995). Thus, considering the along- and across-strike variations in the basement architecture and the superimposed present-day tectonic regime, the SVZ shows a variety of volcano–tectonic interactions that can be grouped into two main categories. Back arc volcanoes, although not the main topic of this contribution, are also included in our classification to emphasize their link with active compression. (Fig. 6).

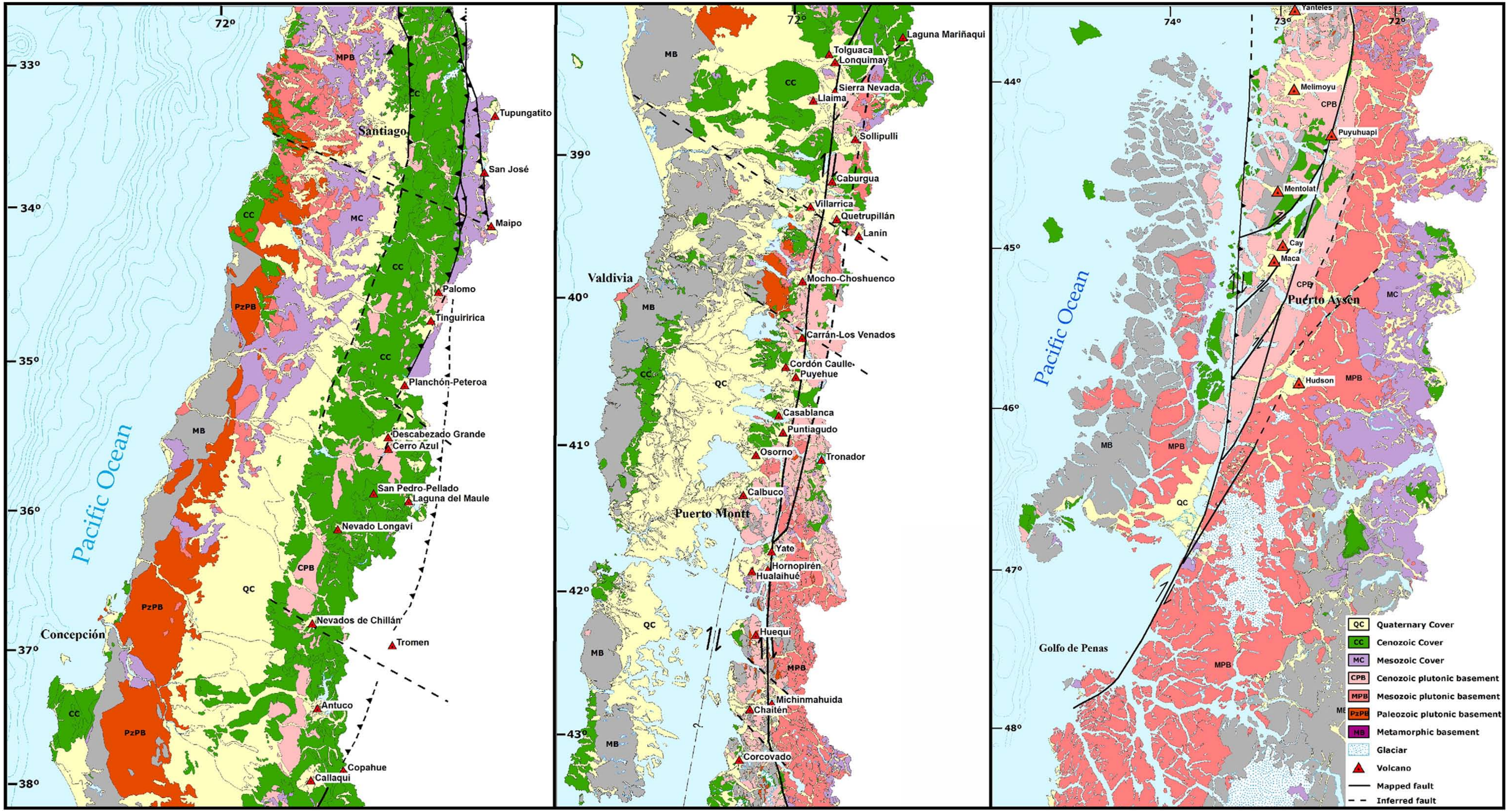
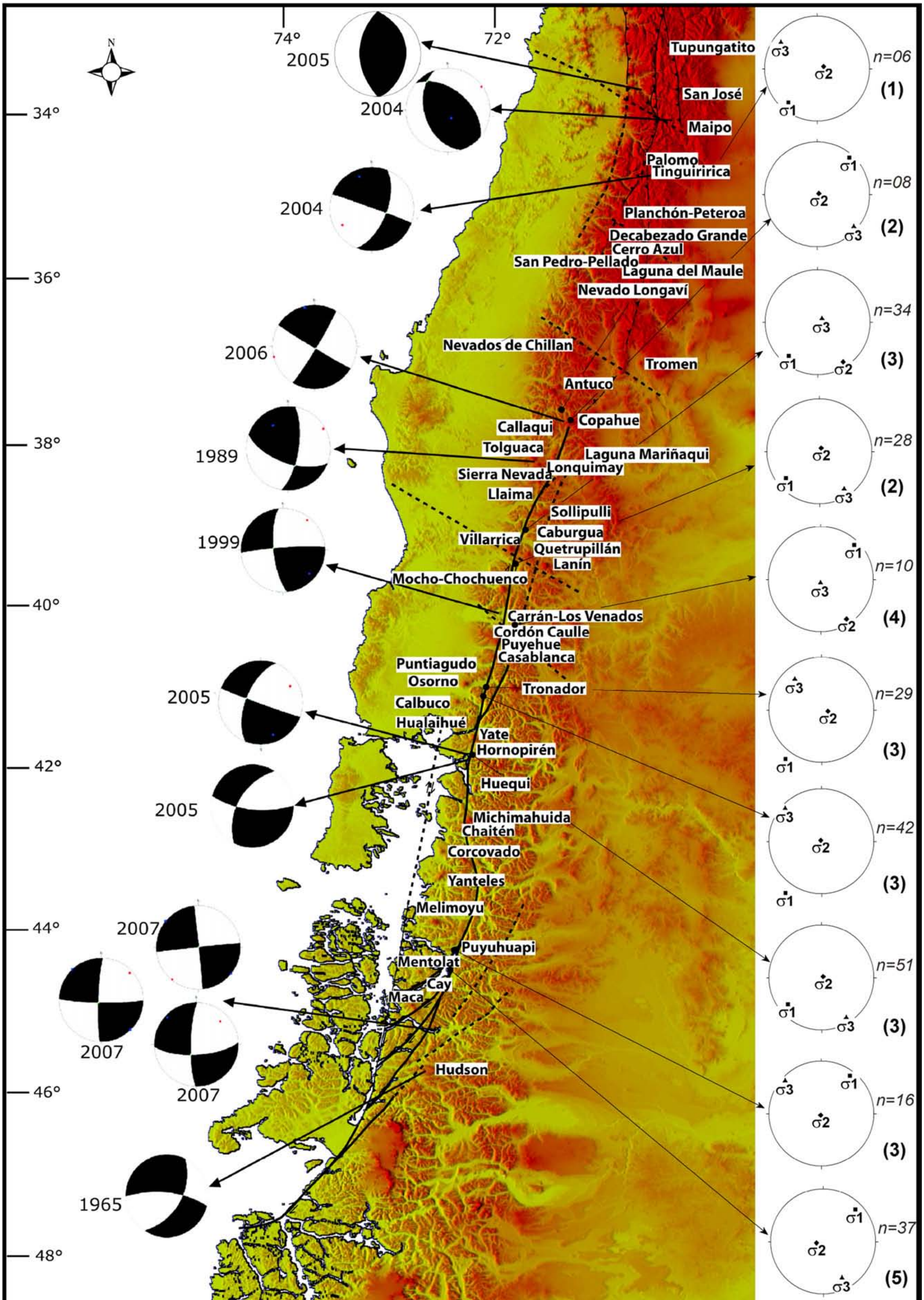


Fig. 2. Regional scale geology of the Chilean Andes between 33°S and 47°S, modified from 1:1.000.000 scale map, Servicio Nacional de Geología y Minería, Chile and previous compilations by various authors (Cembrano et al., 1996, 2002; Thomson, 2002; Farías, 2007). The present-day volcanic arc, located along the axis of the main cordillera, is built on top of the Meso–Cenozoic sedimentary cover north of 38°S. To the south, recent volcanoes lie directly on top of a Meso–Cenozoic plutonic basement of the Patagonian Batholith. Main regional neogene structures between 33 and 38°S are the Aconcagua, Malargue and El Agrio foreland fold-and-thrust belts, to the south, in contrast, the main tectonic element is the intra- dextral transpressional Liquiñe Ofqui fault system. The most important WNW-trending lineaments that crosscut the volcanic arc are shown with dashed lines. These have been interpreted by several authors as long-lived basement structures reactivated as sinistral-reverse strike-slip faults during arc development (e.g. Cembrano and Moreno, 1994; López-Escobar et al., 1995; Lara et al., 2006a; Melnick et al. 2006a; Lange et al., 2008).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74°
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34°
36°
38°
40°
42°
44°
46°
48°
2005
2004
2004
2006
1989
1999
2005
2005
2007
2007
2007
1965
Tupungatito
San José
Maipo
Palomo
Tinguiririca
Planchón-Peteroa
Decabezado Grande
Cerro Azul
San Pedro-Pellado
Laguna del Maule
Nevado Longaví
Nevados de Chillan
Tromen
Antuco
Copahue
Callaqui
Tolguaca
Laguna Mariñaqui
Lonquimay
Sierra Nevada
Llaima
Sollipulli
Caburgua
Villarrica
Quetrupillán
Lanín
Mocho-Chochuenco
Carrán-Los Venados
Cordón Caulle
Puyehue
Casablanca
Puntiagudo
Osorno
Tronador
Calbuco
Hualaihué
Yate
Hornopirén
Huequi
Michimahuida
Chaitén
Corcovado
Yanteles
Melimoyu
Puyuhuapi
Mentolat
Cay
Maca
Hudson
n=06
(1)
n=08
(2)
n=34
(3)
n=28
(2)
n=10
(4)
n=29
(3)
n=42
(3)
n=51
(3)
n=16
(3)
n=37
(5)
σ1
σ2
σ3

4.1. Kinematically-coupled volcano–tectonic associations:

In this category, the spatial distribution and overall morphology of individual volcanoes and groups of volcanoes is primarily controlled by the present-day compressional (33–34°30′) or dextral–transpressional (34°30′–46°S) tectonics of the volcanic arc, and compressional tectonics of the back arc (33°–38°S) which are in turn responsible for the geometry and kinematics of second-order structures such as tension cracks, shear factures and volcanic fissures.

a. Stratovolcanoes and monogenetic cones lying above active reverse faults. The first case is well-represented by the Tromen volcano, shown to be coeval with active thrusting in the backarc (e.g. Galland et al., 2007) (Fig. 6b). There is also the case of some pyroclastic cones located at the eastern Andean foothills of the northern SVZ segments. They appear as isolated cones related to active east-vergent thrusts that in turn would have triggered huge landslides (Folguera et al., 2004). This type is well represented by the Las Hoyadas cones (Naranjo et al., 1997).
b. Flank vents on stratovolcanoes: pyroclastic cones located on the flank of major stratovolcanoes. They follow NE–SW trends (*e.g.* Lonquimay, Callaqui) but also may show some curvature, even a sigmoidal pattern as the case of flank cones of Villarrica and Mocho–Choshuenco volcanoes (Melnick et al. 2006b; Rosenau, 2004; Moreno and Clavero, 2006; Rosenau et al., 2006; Moreno and Lara, 2007). Flank vents have evacuated mostly basalts although there are also andesitic lava flows. (Fig. 6f).
c. NE-striking clusters of monogenetic cones: pyroclastic cones and related lavas that form wide clusters or volcanic fields. Although the main trend is NE–SW, morphological analysis shows other second-order directions that suggest a shear component. Carrán-Los Venados (Lara et al., 2006a) and Fuy are archetypical examples. Products are basalts to basaltic andesites but Fuy group have erupted even dacites. (Fig. 6g).
d. NE-striking chains of stratovolcanoes and clusters of monogenetic cones: Stratovolcanoes and pyroclastic cones that form NE–SW alignments. Mostly basalts have been erupted from these arrays but stratovolcanoes evacuated also dacites or rhyolites. Antillanca Volcanic Complex (Lara et al., 2007) and Osorno–Puntiagudo–Cordón Cenizos are examples of this type (Fig. 6h).
e. Monogenetic cones in tail cracks: pyroclastic cones located at extensional splay faults of the LOFZ or inflections of master faults. No asymmetry of the base or craters can be observed. Mostly tholeiitic basalts have been erupted from these cones including the most primitive basalts recovered in the SVZ. Cones from the Aysén region (44°S) seem to meet this condition. The seismic swarm of 2007 in the Aysén fjord (Barrientos et al., 2007; Cembrano et al., 2007) is explained by the authors as a case of tail-crack with an 'aborted' eruptive cycle. (Fig. 6e).

4.2. Kinematically-uncoupled associations:

In this category, the spatial distribution and overall morphology of individual volcanoes and groups of volcanoes is primarily controlled by the inherited basement structures that underlie the volcanic arc. These basement structures may serve as passive channelways from magma ascent, reactivate independently of the present-day transpressional kinematics or episodically re-shear as highly misoriented structures within the prevailing dextral–transpressional regime. Within this category, the following volcano–tectonic associations can be identified.

a. Stratovolcanoes above ancient, now-inactive, margin–parallel thrust-belt faults: major stratovolcanoes or composite complexes built on top of reverse faults developed either within mesozoic units or at the boundary between cenozoic and mesozoic volcano-sedimentary sequences within the westernmost portion of the Tertiary fold-and-thrust belt between 34° and 36°S. Volcanic edifices show neither shape asymmetry of the base or craters nor flank vents in preferred orientations. Compositions are dominantly andesitic but range from basaltic to rhyolitic. This type is restricted to the northernmost SVZ segments and best represented by the Diamante–Maipo and Planchón–Peteroa volcanic complexes. (Fig. 6a).
b. Clusters of stratovolcanoes above ancient left–lateral–reverse strike–slip faults: major stratovolcanoes or composite complexes built on top of west–northwest-striking, pre-Andean, oblique–slip faults. Volcanic edifices show no asymmetry of the base but they can display flank vents in preferred orientation at a high angle to the basement fault. Compositions cover a wide range from basalts to rhyolites. This type is mostly observed in the central and southern SVZ segments where the LOFZ is present, but may also occur further north in the NSVZ. They are best represented by the Chillán volcanic chain, the Villarrica–Quetrupillán–Lanín chain and the Puyehue–Cordón Caulle volcanic complex (Gerlach et al., 1988; Naranjo et al. 1994; Radic, 2006; Lara et al., 2006b; Singer et al., 2008). (Fig. 6d). Note that the Villarrica volcano, although lying on top of a WNW-striking structure, exhibits NE-trending flank vents, suggesting that these are coupled with the present-day NE-trending maximum horizontal stress. (Fig. 6 f).
c. Monogenetic cones above strike–slip master faults: pyroclastic cones and their basal lavas organized in clusters or alignments right on top of the LOFZ master faults. No asymmetry of the base or craters can be observed. Mostly tholeiitic basalts have been erupted from these cones but some of them evacuated alkali–basalts. Caburgua, Ralún–Cayutue, Puyuhuapi and Aysén are the most representative examples of this type. (Fig. 6c).

The coexistence within the same volcanic arc of strike–slip NNE-striking faults, ENE-striking tension fractures and WNW-striking basement faults suggests that they have been episodically (alternatively) activated under different stress conditions. ENE-striking tension fractures likely form under relatively low differential stress, as a result of distributed, dextral shear within the volcanic arc. NNE-striking master faults, although favorably oriented for episodic reactivation in dextral shear, require higher differential stress. Lastly, the WNW-striking inherited basement faults are severely misoriented with respect to the prevailing stress field and therefore require supralithostatic magmatic pressures to become active.

5. Discussion

Feedbacks between tectonics and volcanism in the southern volcanic zone of the Chilean Andes can be understood as a complex set of interactions operating at different space and time scales, ranging from long-term regional to short-term local. First-order, long-term controls are largely modulated by crustal thickness, nature and structure of the lithosphere, presence of intra-arc fault systems and magma source. Second-order controls include the presence of a

Fig. 3. Digital elevation model of the Chilean Andes between 33°S and 47°S, showing the first-order morphostructural features: Coastal Cordillera, Central Depresión, Main Cordillera. The present-day volcanic arc varies in altitude from ca. 6000 masl at 33°S to ca. 2000 masl at 46°S. A major inflection of the trench and continental margin occurs at 34°30′S (Maipo orocline). Left panel: available focal mechanisms of shallow crustal earthquakes in the volcanic arc region, suggesting a change from partitioned to non-partitioned dextral strike–slip deformation south of 34°30′S (data compiled from the Harvard and NEIC catalogues, Farías et al., (2006), Pardo et al., (2006) and Lange et al., 2008). All earthquakes are of magnitude 5 or more, with the exception of the east-west compressional event at ca. 34ºS Pardo et al. (2006) and the two strike-slip events at ca. 42°S Lange et al., (2008). Right panel: long-term, Quaternary fault-slip data yielding principal stress axes (compiled and modified from Potent and Reuther (2001), (1); Rosenau et al. (2006), (2); Lavenu and Cembrano (1999), (3); Lara et al., (2006a), (4); and Arancibia et al., (1999), (5).

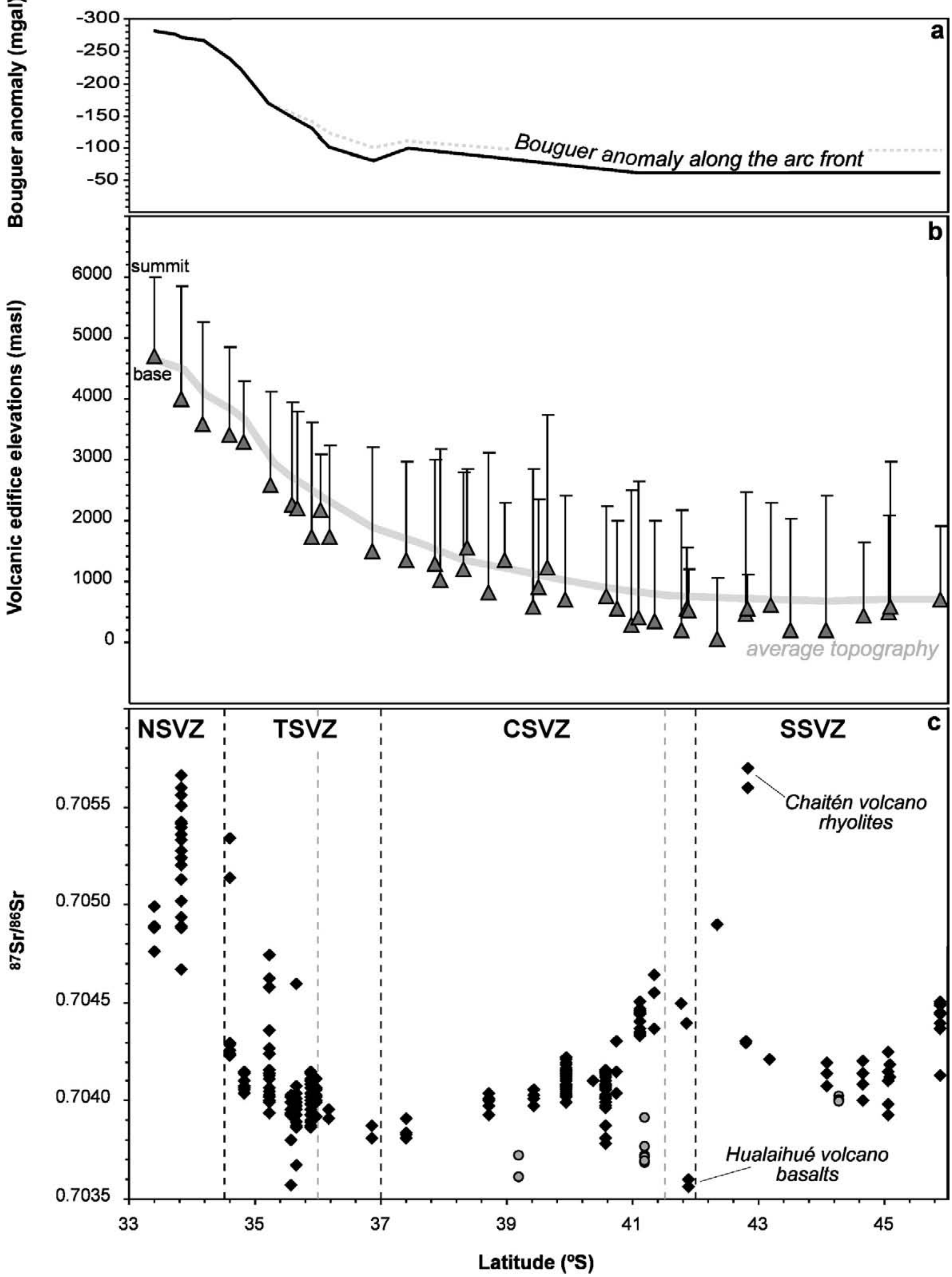

Fig. 4. (a) Along-arc front Bouguer gravity-anomaly profile that suggests increasing crustal thickness to the north (figure modified from the original of Hildreth and Moorbath (1988) that extends between 33° to 37.5°S). Grey line shows the Bouguer anomaly along the drainage divide. (b) Basal and summit elevations of volcanic centers along the arc front between 33° and 46°S together with average topographic relief. (c) $^{87}Sr/^{86}Sr$ isotopic ratio versus latitude (also modified from Hildreth and Moorbath, 1988). Data sources other than quoted in Hildreth and Moorbath (1988) are: Déruelle et al., 1983; Davidson et al., 1987; Gerlach et al., 1988; Futa and Stern, 1988; Hickey-Vargas et al., 1989; McMillan et al., 1989; López-Escobar et al., 1993; Tormey et al., 1995; Hickey-Vargas et al., 1995; Tassara and Yáñez, 2003. Grey filled circles indicate monogenetic cones above the Liquiñe–Ofqui fault zone.

temporally correlated with shallow magma migration and volcanic eruptions, either within the volcanic arc itself (e.g. LaFemina et al., 2004) or even in the subduction zone (e.g. Lara et al., 2004a,b). This reinforces the idea of tectonic and magmatic processes occurring at the same timescales favored by a positive feedback mechanism. On faulted volcano–sedimentary cover versus a relatively isotropic plutonic basement, the existence of deep-seated, seismically active or inactive faults cutting through the lithosphere and the balance between local tectonic rates and magma input rates. In particular, seismically active faults have been shown to be spatially and

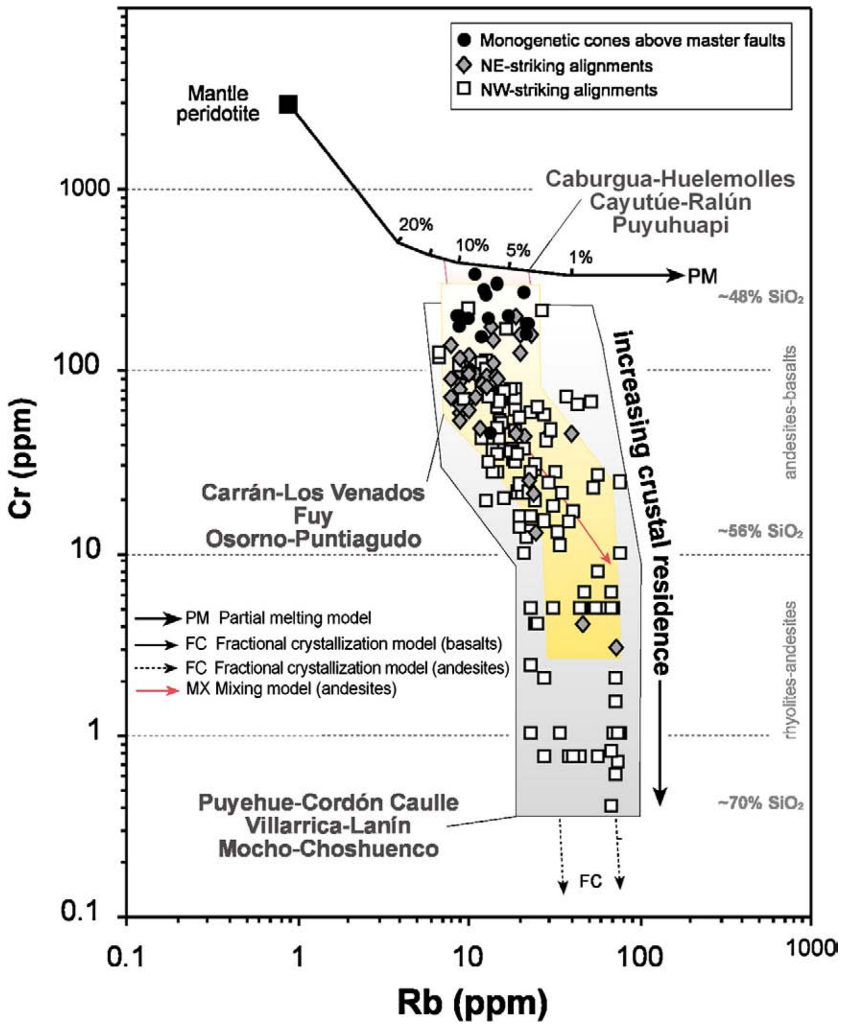

Fig. 5. Cr versus Rb plot (modified from Pearce, 1982 with Rb instead of Y as a more incompatible element). Mixing and Raleigh fractional crystallization vectors are indicated. Partial melting was calculated with a non-modal batch-melting model. Parental predictive contents are taken from McDonough et al. (1991). Note the transition from the monogenetic cones above the LOFZ-master faults related magmas to the more advanced differentiation observed in the most 'compressive' NW-trending domains.

one end, tectonics creates fractures where magma can be transported and/or emplaced, and other end, magma overpressure weakens the rock and triggers crack propagation.

As a first approximation, a thicker crust favors magma differentiation processes whereas a thinner crust tends to prevent it. Likewise, whereas bulk intra-arc compression (vertical $\sigma3$) would tend to enhance longer residence times, strike–slip deformation (horizontal $\sigma3$) would provide subvertical pathways for magma ascent and shorter residence times, which in turn prevents advanced magma differentiation (Fig. 7). However, looking more closely *within* a strike–slip deformation zone encompassing the whole magmatic arc, transtensional and transpressional domains can coexist in space and time. On one end of the spectrum, a plumbing system dominated by NNE-striking subvertical strike–slip faults and ENE-striking tension cracks will favor a rapid ascent of magmas from the asthenospheric wedge and/or Mash Zone with little crustal contamination (Figs. 5 and 7). On the other end, a plumbing system dominated by NW-striking interconnected, second-order reverse faults and subhorizontal cracks will favor longer residence times and episodic magma fractionation, which in turn allow eruption of evolved magmas (Figs. 5 and 7). Whereas the transtensional fault-fracture network does not require magma/fluid overpressures to operate, the transpressional does (e.g. Sibson et al., 1988; Sibson, 1996). This is consistent with the much higher presence of volatiles that accompanies magma fractionation and differentiation as documented in the more felsic rocks of the NW-trending chains (Hickey-Vargas et al., 1989). More precisely, one can speculate that under compression, during periods of low fluid pressure, magma is stalled at horizontal reservoir favoring in situ fractional crystallization (say, for instance at a neutral bouyancy level). Once fluid (magma) pressure builds up to nearly lithostatic values, a system of pre-existing or newly created reverse faults will connect the horizontal reservoir with another stagnation level, extracting only the portion of magma remaing after fractional crystallization. This processes of episodic fault-valve behaviour between subhorizontal reservoirs at different levels within the crust, similar to that proposed by Sibson et al., 1988 for hydrothermal fluids, provides a speculative, yet efficient mechanism to explain why compressional/transpressional domains will favor more differentiated magmas than those under extensional/transtensional domains.

On the other hand, pre-existing subvertical structures, especially those that cut through the lithosphere, may serve as channelways for magma transport regardless of the bulk kinematic regime of the volcanic arc. In particular, the LOFZ master faults are likely capable to connect the MASH zone or even the asthenospheric wedge with the surface, by seismic pumping and concomitant magma production by decompression. The fact that most, if not all volcanic systems that sit on top of the LOFZ are monogenetic strongly suggests that they were produced by single, geologically instantaneous events.

It is then likely that the architecture of the overall plumbing system is primarily controlled by the nature of the fault-fracture mesh as

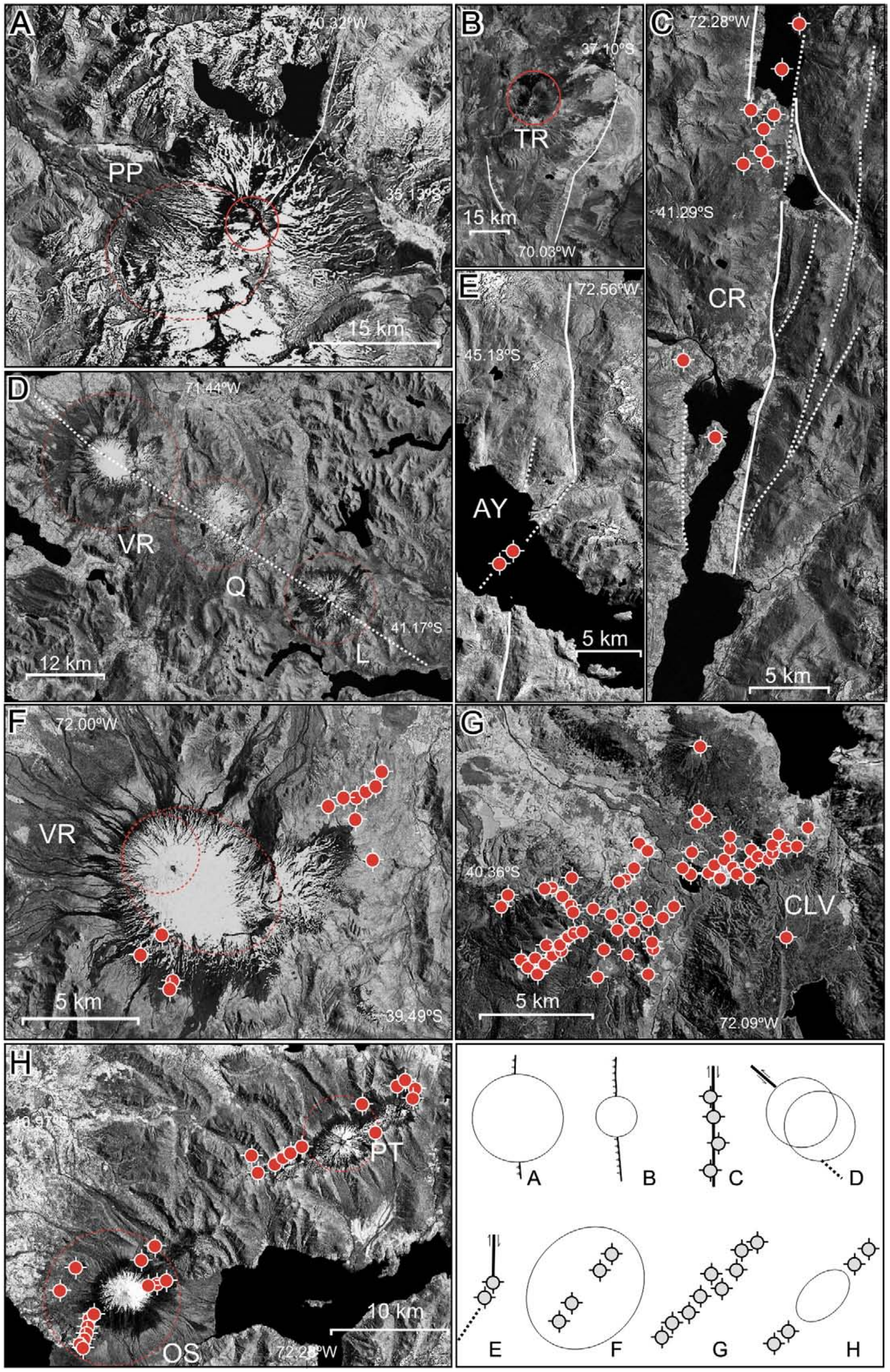

Fig. 6. Types of volcano–tectonic associations proposed for the Southern Andes based on selected examples. Two main categories are identified: (1) kinematically-coupled associations (b, e, f, g, and h) where the spatial distribution and overall morphology of individual volcanoes and groups of volcanoes are primarily controlled by the present-day compressional or dextral–transpressional tectonics of the volcanic arc, and compressional tectonics of the back arc, which are in turn responsible for the geometry and kinematics of second-order structures such as tension cracks, shear factures and volcanic fissures; and (2) kinematically-uncoupled associations (a, c, and d), where the spatial distribution and overall morphology of individual volcanoes and groups of volcanoes are primarily controlled by the inherited basement structures that underlie the volcanic arc, which may or may not be reactivated under the present-day dextral transpressional kinematics. Key: VR: Villarica; Q: Quetrupillán; L: Lanín; CLV: Carrán–Los Venados; OS: Osorno; PT: Puntiagudo; PP: Planchón–Peteroa; LH: Las Hoyadas; CR: Cayutue–Ralún; AY: Aysén Fjord. Cartoon on the lower right schematically shows the geometry of the different volcano–tectonic associations, as presented above.

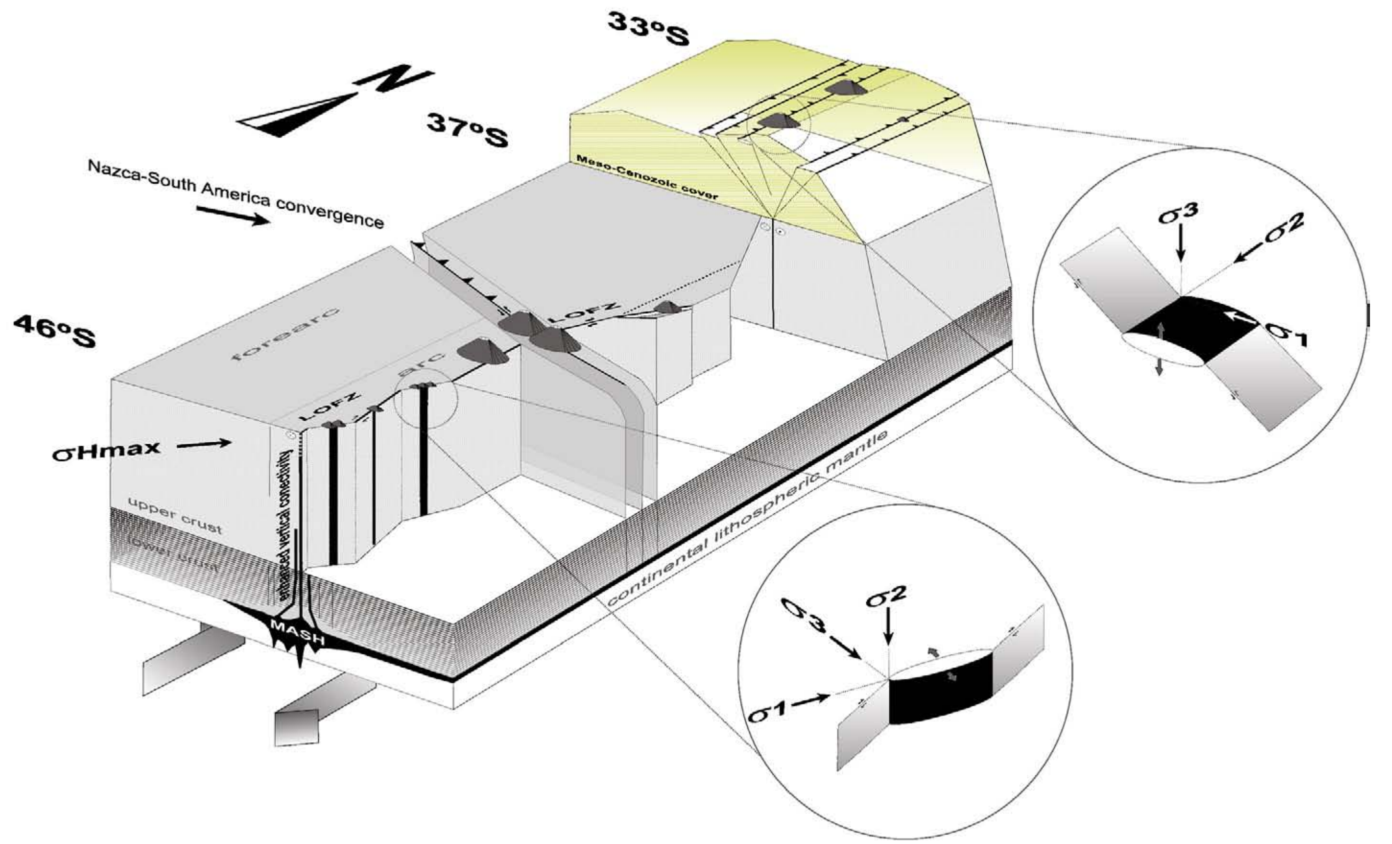

Fig. 7. Cartoon that summarizes the first- and second-order factors that control volcano–tectonic associations in the Southern Andes Volcanic Zone (not to scale). In Central Chile, between 33°S and 34°30′S, volcanism is coeval with current east–west compression; as indicated by upper-crustal seismicity. Magmas feeding stratovolcanoes are proposed to ascent through a composite system of subhorizontal reservoirs and ancient/active thrusts. Volcanoes between 34°30′S and 36°S sit on top of ancient reverse faults and/or WNW-striking basement faults that may connect downwards with tension cracks associated with a concealed dextral strike–slip fault zone as suggested by upper crustal seismicity. South of 37°S, stratovolcanoes are spatially associated with either NE-striking tension cracks or NW-striking basement structures. The most primitive minor eruptive centers of the Southern Volcanic Zone are those located on top of the NNE-striking master faults of the LOFZ.

formed from different stress regimes and by the inherited basement structure, but more importantly, these different architectures exert a first-order control in magma differentiation processes, which in turn account for different volcanic morphologies and rock composition along and across the same magmatic arc.

Another second-order factor controlling along–strike differences in the three-dimensional architecture of the plumbing system in the volcanic arc of central and southern Chile is the presence of a thick pre-Quaternary volcano–sedimentary cover, especially when this cover is folded and faulted (Fig. 7). Where such cover is present, between 34°S and 37°S, NE-striking tension cracks formed under upper crustal dextral strike–slip deformation, may not reach the surface but merge upwards with high angle presently inactive reverse faults marking major regional contacts between Mesozoic and Cenozoic sequences (Figs. 2, 6, and 7) as suggested by Diamante–Maipo and Planchón–Peteroa volcanic complexes. In contrast, south of 38°S, where volcanic systems are built directly on top of plutonic rocks, NE-trending tension cracks may reach the surface and then build either a stratovolcano or an elongated cluster of minor eruptive centers, depending on other factors such as the balance between magma input and strain rate.

Independent evidence for regional-scale, tectonically controlled magma ascent by diking underneath the volcanic arc in southern Chile is given by Soyer (2002). Induction vectors from a magnetotelluric survey in the region show a clear signature of continental mid to lower crustal horizontal electrical anisotropy, with anisotropy striking oblique to the arc trend. Although the modelled strike direction is not well constrained, it consistently falls in the NE quadrant (between N25°E and N70°E). According to Soyer (2002), one possible explanation for the proposed anisotropy would be NE-oriented dyke swarms below the surface, oriented parallel to the direction of maximum horizontal stress as already proposed by Cembrano and Moreno (1994) and López-Escobar et al. (1995).

6. Conclusions

1. The nature of the link between tectonics and volcanism in the southern volcanic zone of the Chilean Andes is controlled by first-order parameters such as crustal thickness and the presence (or not) of active intra-arc fault systems. The relatively thicker crust in the northern portion of the SVZ (~50 km) favors the operation of magma differentiation processes; the presence of an active, intra-arc fault system (the LOFZ) in the central and southern portion of the SVZ allows the existence of a number of second-order pathways which may or not favor magma differentiation processes.
2. Second-order factors such as the local nature of the volcanic system basement (a thick volcano–sedimentary cover versus metamorphic or plutonic rock) will have impact on the upper-crustal, three dimensional architecture of the plumbing system, even under the same bulk intra-arc kinematics. Whereas in the former, deep crustal tension cracks will connect with ancient, inactive reverse faults affecting the cover and feeding individual volcanic systems (such in the arc region between 34 and 36°S); in the latter, tension cracks can directly reach the surface (south of 38°S).

3. Two main categories of volcano–tectonic interactions are proposed in order to account for the many different spatial organizations of volcanoes and clusters of volcanoes observed along and across the SVZ: the kinematically-coupled and the kinematically-uncoupled associations. The former is represented by those cases in which there is an obvious spatial and temporal association with second-order structures as derived from the overall bulk dextral transpressional kinematics of the volcanic arc. Thus, NE- and ENE-trending clusters of flank vents, minor eruptive centers and/or of stratovolcanoes represent tension fractures, extensional-shear fractures or tail cracks oriented subparallel to the maximum horizontal stress. The kinematically-uncoupled associations in contrast, are represented by individual volcanoes and group of volcanoes spatially and temporally associated with ancient structures, some of them lithospheric, that may provide direct pathways for the ascent of magmas, in which a kinematic link with the prevailing intra-arc stress field is not required. The best example of such ancient structures is the WNW-striking Villarrica–Quetrupillán–Lanín volcanic chain, a deep-seated, structure, which is severely misoriented with respect to the present-day dextral transpressional kinematics of the volcanic arc.

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