NEOGENE ANDEAN MAGMATIC EVOLUTION (22°-52°S LAT.)

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Summary
Late Oligocene to Recent Central and Southern Andean arc and backarc magmatism shows a strong link to changing slab geometry and Nazca-South America-Antarctica plate interactions. The character of Central Volcanic Zone (CVZ), flatslab, and Southern Volcanic Zone (SVZ) lavas reflects southward thickening of the frontal arc crust in association with a compressive tectonic regime. CVZ magmas in the Puna-Altiplano plateau from 22° to 25°S go from widespread small mid-Miocene stocks/domes to huge ~ 9 to 4 Ma ignimbrites to frontal centers as the arc narrows westward over a steepening slab. Persistent volcanism over an intermediately dipping slab from 25°to 28°S culminates with mafic lavas and dacitic ignimbrites as the arc front migrates ~ 50 km eastward and backarc lower crust and mantle lithosphere is delaminated. Miocene lavas over the non-volcanic flatslab from 28° to 33°S reflect initial broadening of the arc followed by extinction over a shallowing slab. SVZ lavas from 33° to 46°S, erupted over a relatively steep slab, reflect frontal arc migration and Late Miocene crustal thickening in the north. Young backarc lavas from 35° to 38°S reflect subduction of a relatively young slab into a hot mantle. Extensive 28 to 20 Ma backarc lavas near 40° to 42°S show the interaction of a transient "hotspot-like" anomaly with a remnant slab. Magmatic patterns from 46° to 52°S reflect the near approach and subduction of ocean ridges related to the northward migration of the Chile Triple Junction. Austral Volcanic Zone and 12 Ma Cerro Pampa adakites are linked to melting of hot young slabs and backarc lavas are related to the opening of an asthenospheric slab window.

Introduction
Temporal and spatial variations in central and southern Andean Miocene to Recent magmas are tied to changes in plate geometry and interactions between the South American, Nazca, and Antarctic plates. Below we present an overview of Late Oligocene to Recent Andean magmatic styles for arc and backarc volcanism in Argentina and Chile between 22° and 52°S latitude.

Central Andean Magmatism - 22°S to 33°S
The style of Late Oligocene to Recent Andean magmatism from 22°S to 33°S latitude reflects changes in dip of the subducting Nazca plate and thickness of the lithospheric mantle and crust. Correlation of magmatic events at ~ 18 to 16 Ma, ~10 Ma, ~ 7 to 5 Ma, and ~ 2 Ma with Andean-wide tectonic pulses supports external causes for major magmatic episodes and regional geometric controls on local events. Evolving magmatic patterns are consistent with the subducting slab steepening beneath the central Puna-Altiplano plateau (~ 22° to 25° S), remaining at an intermediate dip beneath the southern Puna (~25° to 28°S, and shallowing beneath the flatslab region (28° to 33°S). The region of interest is shown in Figure 1and a more complete discussion with further references can be found in Kay et al. (1999).

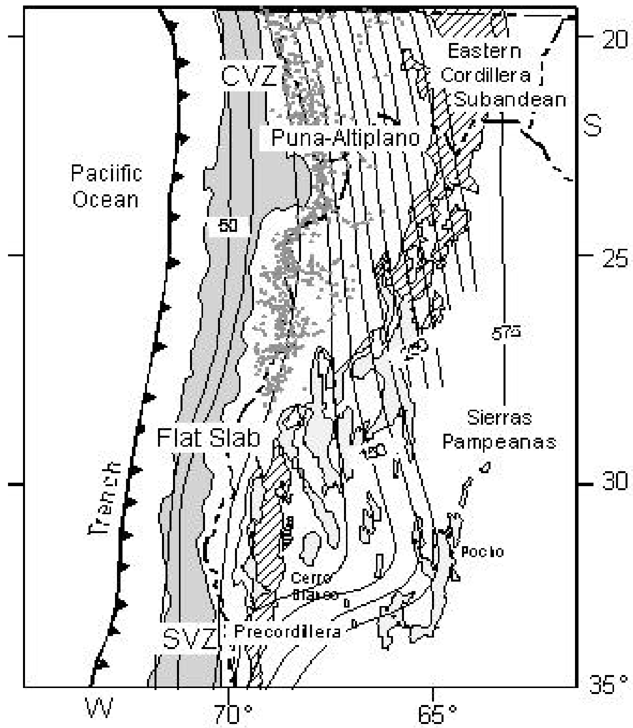

Figure 1. Central Andean map showing Neogene magmatic centers (circles, de Silva and Francis, 1991) relative to the Puna-Altiplano plateau, foreland fold and thrust belts, and contours to the Waditi-Benioff zone (Cahill and Isacks, 1992).

The Steepening Slab in the Central Puna-Altiplano Plateau
Steepening of the slab below the northern Puna is indicated by virtual Late Oligocene to Middle Miocene volcanic quiescence associated with widespread deformation and basin formation, subsequent widespread Middle to early Late Miocene volcanism, and then a Late Miocene to Recent period in which the arc narrowed as the easternmost centers were progressively concentrated to the west (Fig. 2). In detail, volcanism began with widespread ~ 14 to 10 Ma stocks and domes. By 10 to 7 Ma, voluminous ignimbrite sheets were erupting from huge calderas. Centers with ages from 11 to 6.5 Ma (e.g. Coranzuli, Panizos) erupted in both the Eastern Cordillera and on the plateau, whereas centers with ages from 6 to 3 Ma (e.g. Atana) were generally restricted to the western plateau and Cordillera. Young CVZ arc centers are concentrated in the Western Cordillera with only small shoshonitic and acidic centers occurring to the east. As shown in Figure 2, this magmatic pattern can be interpreted

as a response to a steepening subduction zone. As in the modern flatslab near 30°S , the crust over the Early Miocene shallow slab was thick and the lithosphere was thin and hydrous. A growing asthenospheric wedge over the steepening slab produced melts that caused extensive melting of the previously hydrated continental lithosphere. Intrusion of these magmas into the hot, thickened crust resulted in massive crustal melting producing the magmas that ponded in the crust before erupting as large ignimbrite sheets. Continued steepening of the slab pushed the zone of magma production eastward narrowing the arc. This effect along with underthrusting of the Brazilian shield promoted cooling and thickening of the continental lithospheric. A simultaneous eastward shift of th e major thrust front into the Subandean Belt can be explained by compressional collapse of the hot, ductile crust beneath the plateau..

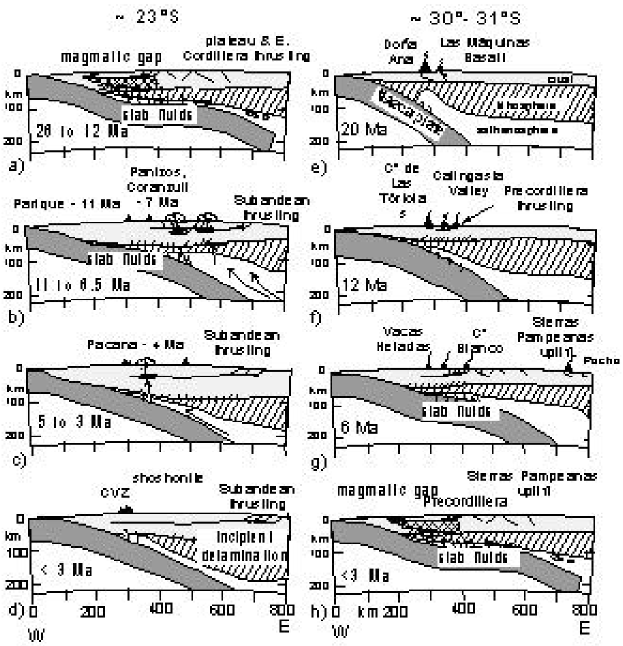

Figure 2. Temporal lithospheric cross-sections showing magmatic sequences in the central plateau near 23°S and modern flatslab near 30°S relative to slab dip, crustal and mantle thicknesses, and major faults. Figure modified from Kay et al. (1999).

Pleistocene to Recent activity is largely restricted to CVZ andesitic to dacitic centers in the Western Cordillera where seismic studies indicate a thin lithosphere. Back-arc activity beneath the thicker lithosphere further east is largely limited to Tuzgle region dacitic to basaltic andesite flows near 24°S, and small shoshonitic flows to the north. The shoshonitic magmas formed as asthenospheric melts above the slab produced small percentage melts of the underthrust Brazilian lithosphere that had been enriched by Neogene subduction processes. This backarc magmatism has been associated with the initial stages of delamination of the thickened backarc lithosphere.

The Transitional Slab in the Southern Puna

A nearly continuous Late Oligocene to Recent magmatic record in the Puna between ~ 28° to 25°S is associated with a slab that has retained a transitional dip between that to the south and north. Early Miocene andesitic to dacitic arc centers in this region have chemical characteristics consistent with an underlying crust of greater thickness than to the south. Back-arc mafic lavas (~ 24 Ma) occur in the Segerstrom belt near 27°S. Early Miocene back-arc domes and stratovolcanic complexes near ~ 25°-25°S (e.g., Aguilar) indicate a broadening volcanic arc over a slab with a progressively shallower dip to the south. Middle Miocene back-arc ignimbritic complexes erupted at ~ 15 to 13 Ma (e.g. Agua Escondida) along with large late Miocene back-arc stratovolcanic complexes (e.g., 11 to 7 Ma Antofalla and Beltrón centers) signal the advance of magmatism further into the backarc.

The magmatic style changed in this region in the latest Late Miocene as the arc front migrated ~ 50 km eastward from the ~ 26 to 7 Ma Maricunga belt to the post-3 Ma CVZ arc and an essentially bimodal suite of mafic andesitic lavas and dacitic/ rhyolitic flows erupted in the backarc. The mafic flows came from monogenetic cones and fissures associated with strike-slip and normal faults and from parasitic cones on stratovolcanoes (e.g. Incahausi). More voluminous flows with intraplate-like chemistry occur over a gap in intermediate level slab seismicity, whereas less voluminous back-arc calc-alkaline flows tend to be on the flanks of the seismic gap. The intraplate flows represent the highest percentage mantle melts. Associated glassy dacite flows along major Salar de Antofalla faults are consistent with partial melting of lower crustal basaltic eclogite. Dacitic ignimbrites erupted at ~ 6 and 4 Ma from the backarc Galán caldera are approximately contemporaneous with ~ 3 to 4 Ma eruptions of the Laguna Verde ignimbrite group behind the frontal arc. This magmatic episode ended at ~ 2 to 3 Ma with the termination of southernmost CVZ magmatism in the Bonete region (Fig. 3), establishment of the CVZ arc to the north, and the ~ 1000 km^3 Galán dacitic ignimbrite eruption at 2.7 to 2.2 Ma. Temporal variations in mantle-derived mafic magma chemistry indicate Neogene mantle enrichment by introduction of crustal material during the subduction process.

The concentration of Late Miocene to Recent backarc mafic flows and the Galán ignimbrite requires special explanation. Compressional shortening accompanying frontal arc migration from 7 to 4 Ma can be compensated by subduction erosion at the continental margin along with shortening in the forearc and arc crust and in the poorly developed fold-thrust belt to the east. Crustal thickening behind the arc facilitated lithospheric foundering (delamination) of overly thick eclogitic facies lower crust and underlying mantle. Loss of continental lithosphere increased the space for the asthenospheric wedge resulting in large scale lithospheric melting culminating in the Galán eruption. The resultant thin lithosphere and thick asthenospheric wedge is consistent with high average regional elevations, mafic magma production, and the gap in slab seismicity.

The Shallowing Slab in the Chilean-Argentine Flatslab Region

Miocene lavas over the non-volcanic flatslab from 28° to 33°S latitude reflect initial broadening of the arc followed by its extinction over a shallowing slab (see Figs. 2 and 3). The character of magmatism changed in time and space in concert with c rustal thickening particularly beneath the Main Cordillera, forearc tectonic erosion, lithospheric thinning and hydration above the shallowing slab, and a reduction in asthenospheric wedge volume which drove the andesitic front eastward (Fig. 2). Late Oligocene to Early Miocene magmatism began with the relatively voluminous Doña Ana basaltic andesitic to rhyolitic flows in the Main Cordilleran arc, and small volumes of Las Máquinas alkaline basalt in the back-arc. The subsequent eastward spread of volcanism was accompanied by a decrease in erupted volume and a trend towards a narrower and more silicic compositional range in Main Cordilleran flows. From ~ 18 to 9 Ma, hornblende-bearing andesitic and dacitic flows erupted from Main Cordilleran Cerro de Las Tórtolas group centers, and small andesitic to dacitic centers extended into the Frontal Cordillera, the Calingasta-Uspallata Valley, and the western Precordillera Fig. 3). By 7 to 5 Ma, the shallowing subduction zone caused volcanism to spread across the entire region with the small Vacas Heladas dacitic ignimbrite in the Main Cordillera, andesitic to dacitic Cerro Blanco type centers in the eastern Cordillera and Precordillera, and potassic basaltic andesitic to dacitic lavas in the Pocho volcanic field in the Sierras Pampeanas. The chemistry of the Pocho flows reflects their formation above a slab more than 175 km below. Volcanism ceased at ~ 5 Ma with the last eruptions in the Pocho field.

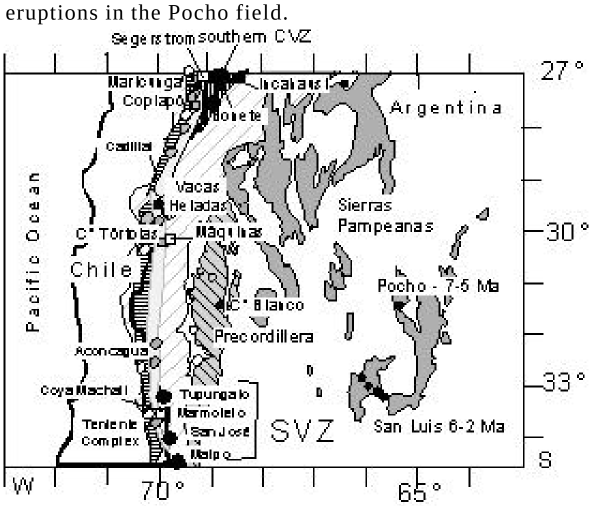

Figure 3. Map showing flatslab region and adjoining CVZ and SVZ with major geologic provinces and magmatic centers. White symbols and horizontal lined field represent Early Miocene centers, gray circles and light gray field represent mid to late Miocene centers, black symbols represent centers < 7 Ma.

Southern Andean Volcanic Zone (34° to 46°S)

Continuing south, Late Oligocene to Recent SVZ frontal arc lavas from 33°S to 46°S erupted have over a relatively steep slab that has progressively shallowed to the north. Parallels in chemistry and style between temporal changes in Late Oligocene to Pliocene lavas in the Andean forearc near 34-35°S (Kay et al. 1996, 1999) and north to south spatial changes in young SVZ arc lavas (e.g. Hildreth and Moorbath, 1988) suggest that the lavas groups erupted under similar conditions.

In detail, Early Miocene arc and backarc Coya Machali/Abanico group lavas, like young SVZ lavas south of 37°S, are characterized by low-pressure pyroxene-bearing assemblages, relatively primitive isotopic ratios (εNd = +5) and flat REE patterns (La/Yb < 9) consistent with eruption through a thin crust in a neutral to slightly extensional tectonic environment. Following compressional deformation and uplift at ~ 20 to 18 Ma, Miocene (16 to 7 Ma) Teniente Complex/Farellones group lavas north of ~36°S erupted east of the Early Miocene arc. These lavas are dominantly amphibole-bearing andesites with intermediate isotopic ratios (εNd = +3) and steeper REE slopes (La/Yb = 9-15 (TVC). Modern SVZ frontal arc lavas between ~ 36° and 34.5°S retain these characteristics. After uplift and a compressional event at ~7 to 5 Ma, amphibole-bearing andesitic to dacitic lavas erupted in the SVZ near 33°S to 34°S are characterized by enriched isotopic ratios (εNd = 0) and steep REE patterns (La/Yb > 25). Their trace element characteristics imply equilibration with high pressure garnet-bearing residual assemblages.

The spatial correlation of chemical signatures of modern SVZ lavas with northward crustal thickening and offsets in the arc at ~ 37° and 34.8°S has been discussed by many workers (e.g. Hildreth and Moorbath, 1988). The southward projection of the Miocene belts into the modern SVZ arc suggests eastward displacement of the volcanic front north of 37°S at ~ 20-18 Ma, and that north of 36.5°S again at ~ 7-5 Ma. If both younger and older centers were erupted at the same distance from the trench, the Early Miocene belt near 34°S is now ~ 50 km nearer the trench (Kay et al., 1996). Such a change in arc-trench distance requires horizontal shortening that may be explained by loss of forearc crust through subduction erosion (e.g. Stern and Skewes, 1995) as well as by thrusting. Evidence for a fore-arc crustal contaminant in Pliocene forearc lavas comes from their "enriched" isotopic signatures

Widespread Late Oligocene to Recent volcanism occurs in the backarc east of the SVZ, particularly south of 35°S. Extensive Late Pliocene to Recent backarc lavas between 35° and 38°S reflect subduction of a relatively young slab into a hot mantle. Their eruption postdates that of Late Miocene backarc andesitic to dacitic centers with arc-like chemical characteristics that formed up to 500 km east of the trench. Further south, extensive 28 to 20 Ma backarc lavas near 40° to 43°S in the Somuncura plateau reflect interaction of a transient "hotspot-like" anomaly with a remnant slab (Fig. 4). The widespread Late Oligocene to Pliocene Patagonian mafic backarc flows behind the SVZ seem to reflect perturbations of an already hot backarc mantle.

Southern SVZ and Austral Volcanic Zones (46° to 52°S)

Neogene magmatic patterns from 46° to 52°S reflect the near approach and subduction of ocean ridges related to northward migration of the Chile Triple Junction (see Fig. 4). Arc magmatism in this region occurs in the southernmost SVZ and Austral (AVZ) volcanic zones which are separated by a gap east of where the most recent collisions between segments of the Chile ridge and the Chile trench have occurred. AVZ frontal arc lavas are interpreted as melts of the hot young Antarctic plate (see Stern and Killian, 1996) which began to subduct after ridge collision. Miocene (~12 Ma) Cerro Pampa adakites east of the arc gap are linked to melting of the trailing edge of the subducting Nazca plate at the time of ridge collision (Kay et al., 1993). The Cerro Pampa adakites with their low $^{87}Sr/^{86}Sr$ (0.7028) and trace element signatures that are consistent with low percentage eclogite melts are among the clearest examples of slab melts in the Phanerozoic record.

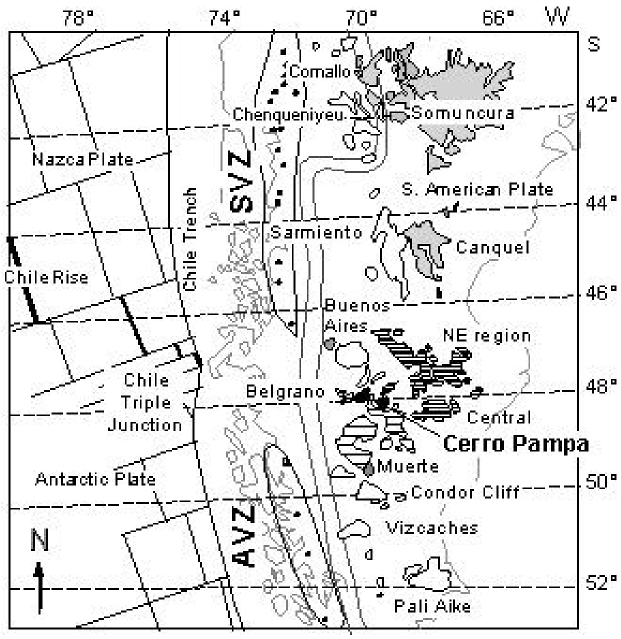

Figure 4. Map of central and southern Patagonia showing SVZ and AVZ centers relative to backarc flows (gray are Oligocene/Early Miocene, wide spaced lines are Late Miocene, narrow spaced lines are Pliocene, white are Pleistocene), oceanic magnetic anomalies, spreading center, and trench.

Extensive Miocene to Pleistocene mafic backarc plateau lavas east of the Chile triple junction have been related to the eastward progression of "slab windows" created by collisions of segments of the Chile rise with the Chile trench at ~ 12 and ~ 6 Ma. (see Gorring et al., 1997). The intraplate-like chemistry of these lavas and lack of similar slab window magmas erupted east of where ridge collision occurred at ~ 13 to 14 Ma can be explained by entrainment of a "weak" plume from the hot Patagonian mantle in the slab window.

Conclusions

The style and chemistry of Central Andean arc and backarc magmas from 22° to 33°S can be explained by changes in the dip of the subducting Nazca plate and the thickness of the continental mantle and lithosphere. The magmatic pattern between 22°S and 25°S reflects a steepening slab, that between 25°S and 28°S reflects a slab with a continuously intermediate dip, and that between 28°S and 33°S reflects a shallowin g slab. Distinctive backarc magmatism over the intermediately dipping slab reflects foundering (delamination) of over-thickened continental crust and lithosphere.

Miocene to Recent arc magmatism from 33°S to 46°S reflects eastward arc migration over a p rogressively shallower slab and a thicker crust to the north, forearc tectonic erosion and younging of the subducted slab to the south Extensive backarc lavas reflect the subduction of hot young oceanic crust and the presence of transient mantle thermal anomalies that are likely linked with mantle readjustments associated with changes in plate geometry.

Magmatism in the southernmost Andes and Patagonia reflects the close approach and collision of ridge segments with the Chile Trench. Young Austral Volcanic Zone and Miocene Cerro Pampa lavas are produced by melting of hot subducted slabs whereas backarc volcanism is produced by the interaction of mantle thermal anomalies with slab windows.

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