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MIOCENE 'FLAT-SLAB' VOLCANIC ROCKS AS GUIDES TO LITHOSPHERIC PROCESSES IN THE CENTRAL ANDES (25-33°S)

S.M. Kay*

Crustal components in Miocene to Recent intermediate to silicic volcanic rocks from the Andean 'flat-slab' (33-28°S) and the southern Central Volcanic Zone (CVZ) (28-24°S) (Fig. 1) can be used as a guide to contemporaneous lithospheric proceses. These components can be characterized as 'upper crustal' and 'lower crustal'. 'Upper crustal' components are most clearly seen in 'flat-slab' Main Cordillera and CVZ volcanic rocks, while 'lower crustal' components are most clearly seen in back-arc 'flat-slab' volcanic rocks.

The distribution of these volcanic rocks can be explained by regional tectonic processes that reflect the geometry of the subducting and overriding plates. Volcanic rocks with an 'upper crustal' component erupted through a crust thickened by eastward wedging of crustal rocks from beneath shortened foreland thrust belts to the east. Crustal rocks trenchward of the wedge tip are translated into the ductile lower crust and subsequently provide the 'upper crustal' component that contaminates mantle-derived arc magmas. An additional component derived from the west by subcrustal erosion cannot be ruled out. Volcanic rocks with a strong 'lower crustal' signature erupted over the shortened foreland in the 'back-arc' can be related to contamination of mantle melts by original lower crust. An additional component from delaminated lithosphere carried to the east is also possible in backarc 'flat-slab' volcanic rocks. Both a temporal and spatial prospective is used to evaluate these processes.

'Upper' and 'Lower Crustal' Geochemical Signatures in Time and Space

Miocene Main Cordillera 'flat-slab' andesites and dacites in the modern non-volcanic zone (28-33°S) are characterized by an 'upper crustal' component whose intensity increases from the early Miocene until volcanism ends in the late Miocene (≈6 Ma). This signature is indicated by a changing range of increasingly higher $^{87}Sr/^{86}Sr$ ratios and lower εNd (Fig. 2). An 'upper crustal' component is also indicated by high normalized concentrations of Th,U, Ba and K relative to light REE (Fig.3). This 'upper crustal' component appears to have been added at progressively greater depth through time as the trace element chemistry suggests a contemporaneous progression to a higher pressure and more anhydrous residual crustal mineral assemblage[8, 9]. Equilibrium with a garnet-bearing and plagioclase- poor source is required by steep REE patterns in mid to late Miocene andesite (Fig. 3).

In contrast, 'flat-slab' Miocene to Pliocene backarc volcanic rocks (28-33°S; see figure 1) in the Calingasta-Iglesia Valley behind the Main Cordillera (R), in the Precordillera (G and C) and in the Sierras Pampeanas (Pocho) are characterized by a 'lower crustal' component. This 'lower crustal' signature is shown by low $^{87}Sr/^{86}Sr$ ratios at a given εNd (Fig.2), low Rb/Sr and high Na_2O/K_2O ratios, and low Th, U and REE (Fig. 3) and high Sr contents. The combination of low Rb/Sr and $^{87}Sr/^{86}Sr$ ratios and low U, Th and REE contents reflect a depleted source region, not fractionation of accessory phases. Positive Eu anomalies and high Sr contents in some samples suggest that excess plagioclase was once present in the source of these samples. The correlation of decreasing εNd with decreasing (and low) Nd concentrations suggest that εNd values could reflect some upper crustal contamination. As in the 'flat-slab' arc rocks, normalized concentrations of Ba and K are high relative to light REE.

Some spatial and temporal patterns are seen in the 'flat-slab' back-arc rocks. In the Precordillera, the 'lower

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* INSTOC, Snee Hall, Cornell University, Ithaca, NY 14853, U.S.A.

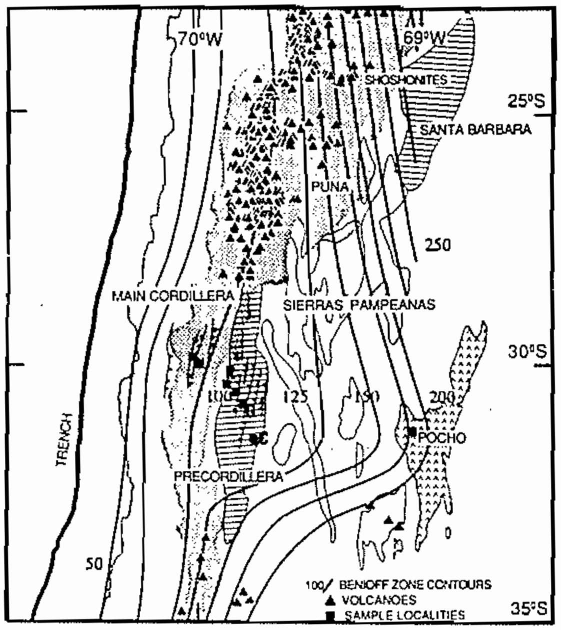

FIG. 1. Central Andean map for the 'flat-slab' (33-28°S) and southern Central Volcanic Zone (north of 28°S) with geologic provinces, Benioff zone contours and late Miocene to Recent volcanoes. Shaded area labeled Main Cordillera and Puna includes region with elevations above 3 km. Ranges in the Sierras Pampeanas are shown as unpatterned and patterned (Sierra de Córdoba). Figure is modifies from Isacks[3]. Generalized thrust faults near 30°S are from Allmendinger *et al.*[1]. Squares represent samples for which data is presented in figures 2 and 3.

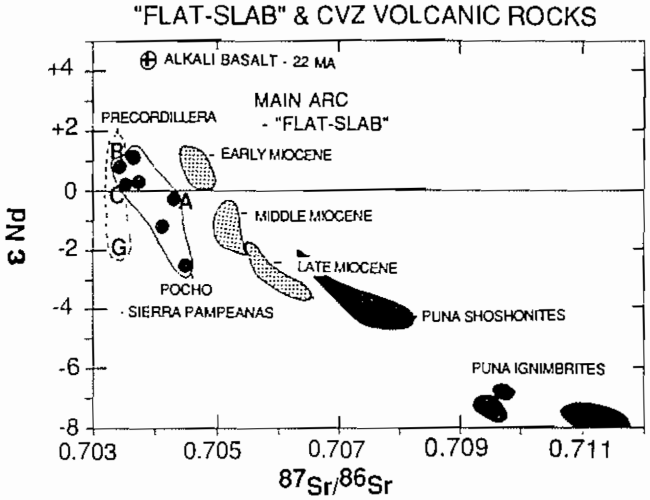

FIG. 2 εNd *versus* $^{87}Sr/^{86}Sr$ for 'flat-slab' and CVZ volcanic rocks. Locations of samples labeled R, C, and G shown in figure 1. 'A' is Miocene (≈10 Ma) andesite from Aconcagua. Alkali basalt is the Las Máquinas basalt from just east of Chilean border in Argentina at 30°S. Data are from Kay *et al.*[10], Kay and Gordillo[4], Francis *et al.*[2], and Kay and Coira (unpublished).

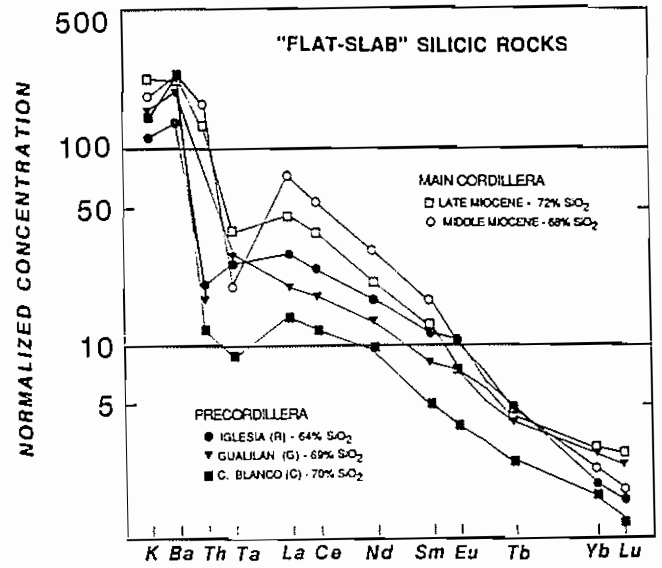

FIG. 3. Extended normalized trace element diagram for 'flat-slab' silicic rocks whose locations are shown in figure 1. Normalized factors are K (116), Ba (3.77), Th (0,05), Ta (0.022), La (0.378), Ce (0.976), Nd (0.716), Sm (0.23), Eu (0.0866), Tb (0.0589), Yb (0.249) and Lu (0.0387)

crustal' trace element signature and SiO_2 content seem to increase eastward from the tuffs and domes of the eastern Iglesia valley (R) to those at Gualilan (G) to those at Cerro Blanco (C) (Figs. 1, 3). Field relations suggest that these volcanic rocks are fissure eruptions associated with Precordillera thrust faults that young to the east. New K/Ar dates (F. Munizaga, personal communication) of 11.0 ± 0.5 for a dacite from the eastern Precordillera (R; Fig.1) and of 6.3 ± 0.7 Ma for a Cerro Blanco dacite are consistent with a temporal trend. Ages of the Pocho high -K and shoshonitic series volcanic rocks in the easternmost range of the Sierras Pampeanas (Sierra de Córdoba, patterned in figure 1) overlap those of the younger Precordillera rocks. The older (7.9-7.0 Ma) Pocho volcanic rocks have stronger 'lower crustal' signatures than the younger ones (5.5-4.7 Ma)[4].

To the north in the CVZ, pronounced 'upper crustal' signatures are seen in volcanic rocks from the frontal arc and across the Puna[2]. Higher $^{87}Sr/^{86}Sr$ ratios and lower εNd in Puna high-K andesites and dacites (ignimbrites) and shoshonites (Fig. 2) are consistent with the upper crustal contaminant being older than that in the 'flat-slab'.

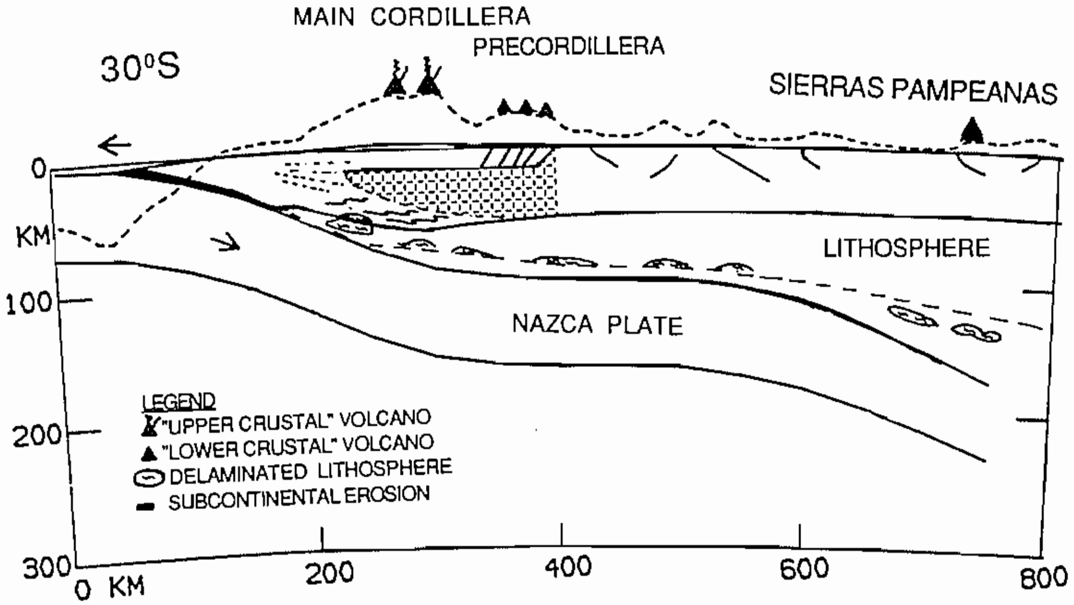

FIG. 4. Crustal and mantle cross-section of the Andes near 30-31°S (see Fig. 1). Dashed line is topographiy shown at ten times vertical exaggeration. Volcanoes are Miocene in age. Patterned wedge is crust that was originally under shortened Precordillera thrust belt. Dashed lines in crust east of wedge represent fractured brittle crust and curved lines represent ductile crust. Nazca plate configuration and topography from Isacks[3]. Crustal section modified fromn Allmendinger *et al.*[1].

Sources of 'Upper' and 'Lower Crustal' Geochemical signatures

Several sources appear unlikely to create the contrasting 'upper' and 'lower crustal' signatures in these volcanic rocks. Possible crustal sources such as the altered Nazca plate, subducting sediments, or parts of the forearc margin removed by subcrustal erosion can contribute to the 'upper crustal signature in the Main Cordillera rocks but do not explain the 'lower crustal' signature in the 'flat-slab' back-arc rocks. Adding regional differences by separating older terranes in the preexising crust[7] helps, but still fails to explain the 'flat-slab' east-west trends. The most significant crustal difference to consider is that the 'flat-slab' back-arc rocks erupted through the Precordillera and Pampean blocks of Godwana while the 'flat-slab' arc rocks erupted through the Chilenia terrane which was sutured to the continent in the middle Paleozoic (Fig. 1). However, Miocene volcanic rocks from Cerro Aconcagua (A on Fig. 2) on the Chilenia block have a 'lower crustal' signature while southern Puna rocks on the Gondwana block show an 'upper crustal' signature. Further east, these is no evidence that the pre-Tertiary history of the Sierra Pampeanas is fundamentally different to that of the southern Puna[7].

Advances in understanding the late Tertiary tectonic history of the foreland of the 'flat-slab' and the southern CVZ provide insight into the probable sources of the upper land lower crustal signatures in the volcanic rock[2]. Allmendinger *et al.*[1] have proposed that ≈150 to 170 km of Miocene to Recent crustal shortening across the flat-slab near 30°S has ocurred in three belts: The Main Cordillera, the Precordillera and the Sierras Pampeanas (Fig. 1 and 4). Importantly, most of the shortening (≈95 km) took place on thrust faults in the Precordillera above a decollement at ≈15 km. This decollement is projected beneath the Main Cordillera and is suggested to explain the plateau-like surface that characterizes the high cordillera at this latitude. In their preferred model, mid to lower crustal rocks complementary to the upper crustal rocks of the thrust belt are driven as a wedge to the west progressively splitting the upper crust from the mid crust beneath the arc. This model has important implications for the source of crustal components in 'flat-slab' magmatic rocks and a modified version is presented in figure 4.

In the modified model, the westward projecting rigid crust beneath the decollement (top of wedge patterned in figure 4) splits the crust and pushes midcrustal rocks along the wedge tip into the lower crust beneath the volcanic arc. Some of these descending rocks could have been upper crustal rocks incorporated into the mid-crust during pre-Miocene tectonic events. At depth, these rocks are metamorphosed at high temperature and pressure. Temperatures between the rigid mid to upper crust beneath the decollement and the lithospheric mantle should be such that the crust in this region behaves ductilely. As a result the newly added midcrust should be mixed with both the preexisting lower crust and the crust added from the east at the base of the wedge. Subduction-related mantle melts entering this modified lower crust are readily contaminated by components that were once in the mid, or even upper crust.

This mechanism for adding an upper crustal component does not rule out an additional contribution from material derived from sub-crustal erosion of the fore-arc to the west. In fact, subcrustal erosion could be enhanced by the wedge cutting across the arc (Fig. 4). However, given the necessity of balancing the shortening in the Precordillera, a very important crustal component must be added from the east to the crust beneath the arc. A similar situation could occur in the Puna to the north where volcanic rocks are also erupted through a ductilly thickened crust, east of the Santa Barbara (see figure 1) and Eastern Cordillera deformation belts[3].

The model also has implications for the origin of Precordillera 'flat-slab' volcanic rocks with lower crustal signatures. These volcanic rocks erupt through a lower crust that has not been modified in the Miocene by the addition of mid and upper crustal material. It is probably significant that the Precordillera volcanic rocks with the strongest 'lower crustal' signature occur at Cerro Blanco in the east, farthest from the thickened crust beneath the Main Cordillera. The proximity of the Precordillera volcanic rocks to thrust faults suggest a spatial and temporal relationship. Melting enhances the ductillity of the lower crust and the weakness combined with regional compressive stress may have localized the break-out zones of faults as thrusting advanced to the east across the Precordillera.

The situation beneath the crust is probably more complicated as crustal thickening implies that the lithosphere also must have been severely modified. Crustal thickening has been associated with shallowing of the subduction zone[5]. Both of these processes reduce the space between the crust and the slab which must contain the rigid mantle lithosphere and the convecting asthenosphere. Associated cooling and lithospheric shortening needed to accomodate crustal shortening should further increase lithospheric thickness creating a space problem (Fig. 4). Addition of material from subcontinental erosion only increases the problem.

The simplest solution to the space problem is to delaminate the lithosphere. Lithospheric cooling helps as the depth to the garnet-spinel transition decreases creating a denser mantle that can sink. Lower crust could also be lost as crustal thickening induces garnet formation which increases the density of the lower crust. Pieces of the lithosphere could have been carried out by the circulating asthenosphere above the plate or dragged along by the Nazca plate (see Fig. 4). As the early Miocene mantle in the eastern Main Cordillera has a depleted isotopic signature[6] (22 Ma alkali basalt in figure 2), a component from eastward transported delaminated lithosphere (and maybe lower crust) cannot be overlooked as a source of the 'lower crustal' signature in the Pocho, and possibly the Precordillera volcanic rocks.

Timing of 'Flat-Slab' Tectonic events and Eruption of Volcanic Rocks with 'Upper' and 'Lower Crustal' Signatures

The proposed mechanism for incorporating 'upper crustal' and 'lower crustal' components in 'flat-slab' magmatic rocks is supported by the timing of magmatic and deformation events related to the Miocene shallowing of the subduction zone in the 'flat -slab'[5, 6]. Extreme shallowing of the subduction zone in the 'flat-slab' segment relative to other parts of the Andes is due to the geometry of the Nazca and South American plates[3].

An important sequence of events near 30°S beginning at ≈18-16 Ma signals the initiation of flattening of the subduction zone in the 'flat-slab'. These events include thrusting in the Main Cordillera, the spread of volcanism into the back-arc, and initial thrusting and basin formation in the Precordillera (see Figs. 1, 4). The associated crustal thickening and transport of upper crustal material into the lower crust in the Main Cordillera provides the increased 'upper crustal' component and high pressure residual mineralogic signature in the mid Miocene volcanic rocks[5, 6]. This 'upper crustal' component increases in the Miocene Main Cordillera volcanic rocks as andesitic volcanism ends at ≈10 Ma and the final dacitic ignimbrite erupts at ≈6 Ma. Importantly, mid to late Miocene Main Cordillera magmatic activity was contemporaneous with thrusting in the Precordillera. Available dating shows that thrusting and magmatism in the western Precordillera were well underway by 11 Ma and that the leading thrust reached the eastern Precordillera by 6 Ma. The increasing 'upper crustal' component in the late Miocene volcanic rocks can thus be correlated with continued uplift and crustal thickening in the Main Cordillera due to shortening in the Precordillera[1].

The volcanic history of the 'flat-slab' near 30°S ends with the eruption of dacites in the Main Cordillera at ≈6 Ma and the eruption of the Pocho volcanic rocks in the eastern Sierras Pampeanas from 7.9 to 4.7 Ma During this period, major thrusting ended in the Precordillera and important uplift of the Sierras Pampeanas occurred. All of these events suggest a major step in the shallowing of the subduction zone that is probably associated with the almost complete loss of convecting asthenosphere beneath the flattened part of the slab 200 to 600 km from the trench (Fig. 4). The contemporaneity of the Pocho volcanism with these events could be consistent with a delaminated lithospheric component being partially responsible for the 'lower crustal' component in theses volcanic rocks.

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References

1. Allmendinger, R.W.; 5 others, 1990. Foreland shortening and crustal balancing in the Andes at 30°S latitude. *Tectonics*, Vol. 9, p. 789-809.
2. Francis, P.W.; 8 others, 1989. Petrology and geochemistry of volcanic rocks of the Cerro Galan caldera, northwest Argentina. *Geological Magazine*, Vol. 126, p. 515-147.
3. Isacks, B.L. 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. *Journal of Geophysical Research*, Vol. 93, p.3211-3231.
4. Kay, S. M.; Gordillo, C.E. 1990. Pocho volcanic rocks in the Sierra de Cordoba: Melting of depleted continental lithosphere above a shallow subduction zone. *In Congreso Geológico Argentino, No. 11, Actas*, Vol. 1, p. 36-38.
5. Kay, S.M.; Maksaev, V.; Mpodozis, C.; Moscoso, R.; Nasi C. 1988. Tertiary Andean Magmatism in Argentina and Chile between 28-33°S: Correlation of magmatic chemistry with a changing Benioff zone. *Journal of South American Earth Sciences*, Vol. 1. p. 21-38.
6. Kay, S. M.; Mpodozis, C.; Ramos; V.A.; Munizaga, F. (In press.). Magma source variations for mid-late Tertiary magmatic rocks associated with a shallowing subduction zone and a thickening crust in the Central Andes (28°-33°S). *In* Andean Magmatism and its Tectonic Setting (Harmon, R; Rapela, C.; editors). *Geological Society of America, Special Paper*, No. 265.
7. Ramos, V.A. 1988. Tectonics of the Late Proterozoic-Early Paleozoic: a collisional history of southern South America. *Episodes*, Vol. 11, p. 168-174.
8. Kay, S.M.; Maksaev, V.; Mpodozis, C.; Moscoso, R.; Nasi, C. 1987. Probing the Andean Lithosphere: Mid-Late Tertiary magmatism in Chile (29°-30,5°S) over the zone of subhorizontal subduction. *Journal of Geophysical Research*, Vol. 92, p. 6173-6189.
9. Kay, S.M.; Mpodozis, C.; Ramos, V.A.; Munizaga, G. (In press). Magma source variations for Mid-Tertiary magmatic rocks associated with a shallowing subduction zone and a thickening crust in the Central Andes (28-33°S). *In* Andean magmatism and its tectonic setting (Harmon R.S.; Rapela, C.; editors). *Geological Society of America, Special Paper.*