CREATION, MODIFICATION AND DESTRUCTION OF ANDEAN LITHOSPHERE

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Summary
The Central Andes is a major site of creation, modification and destruction of continental lithosphere. The chemistry and distribution of the erupted magmas record dramatic changes linked to changes in Wadati-Benioff zone geometry since the Early Miocene. Major addition occurs by intrusion of mantle-generated arc magmas whereas loss occurs by removal of basal continental lithosphere above flat segments of the subducting slab, delamination of thickened eclogite-facies continental crust and forearc tectonic erosion. Shallowing of the slab under the modern "flatslab" since 18 Ma induced up to ~70% loss of the continental lithosphere in a 400 km E-W transect near 30°S. The process must be more mechanical than thermal as loss is associated with a cooling mantle and a thickening crust. Dramatic changes also occurred further north over an intermediately dipping slab where ~50 km of eastward arc front migration can be linked with backarc delamination of over-thickened eclogitic-facies crust and underlying mantle lithosphere. Chemical signatures of arc lavas reflect mixing of mantle-derived arc magmas with underlying garnet granulite/eclogitic crust or with tectonically removed basal arc and forearc crust that was subducted into the mantle. Other lithospheric modification and crustal differentiation processes are associated with steepening of the slab beneath the Andean high plateau as reflected by giant Neogene ignimbrite eruptions, crustal thickening and plateau uplift. These processes reflect more than a local story as substantial amounts of continental lithosphere have passed through Andean-like crucibles. The magnitude of continental lithospheric loss and gain has implications for crustal and mantle recycling.

Introduction
The Neogene Central Andes is a major locus of creation, modification and destruction of post-Archean continental crust and mantle lithosphere. The major process of new addition is arc magmatism whereas major processes of loss are foundering of thickened crust, forearc tectonic erosion, and loss of the base of the arc and backarc lithosphere. The three east-west transects across the Central Andes indicated in Figure 1 are discussed below as examples of along strike lithospheric creation, modification and loss as the dip of the slab varies in time and space. The transacts are across the modern Chilean flatslab near 30°S where the subducting oceanic Nazca plate has shallowed since the Early Miocene, across the central Puna-Altiplano plateau where the slab has steepened since the Early Miocene, and across the intervening southern Puna where the slab has remained at an intermediate dip. In each transect, evolving magmatic patterns carry robust keys to rapid changes in crustal and mantle lithospheric conditions. Total lithospheric modification is severest as magmatism ceases over a shallowing slab, as the arc front migrates, or as magmatism reinitiates over a steepening slab. The examples discussed are more than a local Miocene to Recent Andean story as substantial amounts of continental lithosphere worldwide has passed through similar scenarios of continental margin evolution.

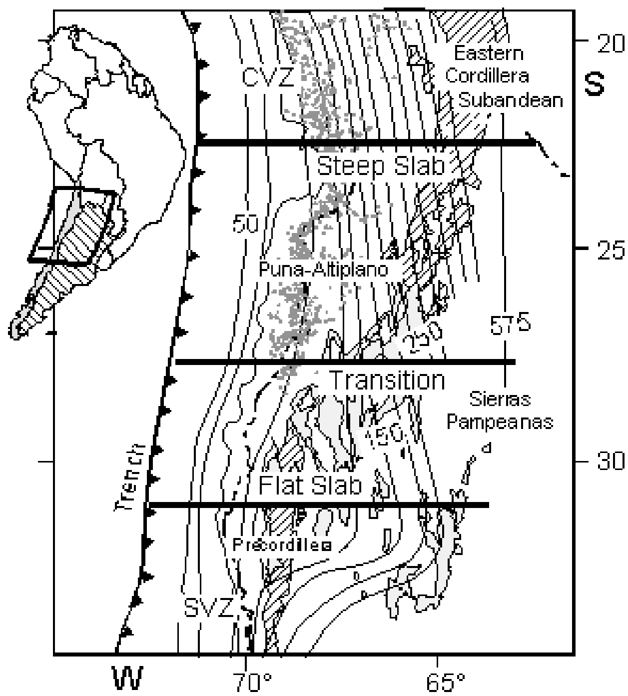

Figure 1. Map of central Andes showing transects discussed in text relative to contours to modern Benioff zone from Cahill and Isacks (1992), geologic provinces, Chile trench and Pliocene to Recent volcanic centers < 7 Ma (circles) largely after de Silva and Francis (1991).

Central Andean Lithospheric processes
The principal method of lithospheric addition has been from arc magmas generated by melting of the hydrated mantle wedge above the subducting Nazca plate. These magmas have interacted with and have been modified by interaction with the continental crust as they ascend. Addition processes are similar to those in arcs worldwide.

Processes of modification and destruction are influenced by the character of the pre-Miocene continental lithosphere and convergence parameters of the down-going Nazca and overriding South American plates. Convergence in the region discussed has been nearly perpendicular to the margin since about 27 Ma with relative overriding of the Nazca plate by the South American continent. Tectonic and magmatic processes have been dominated by compressional tectonics which has given rise to both the fold and thrust belts east of the high plateau and Cordillera regions and the uplift of the high plateau and Main Cordillera (see Fig.ure 1). The lithospheric destruction and modification processes are related to the dip of the underlying subducting plate which controls the thermal structure of the mantle wedge. Lithospheric modification and destruction processes in the three transects are examined below from this viewpoint.

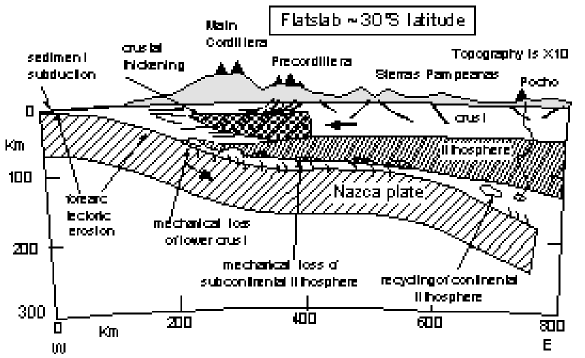

Figure 2. Lithospheric cross section of modern Chilean flatslab region showing lithospheric modification processes discussed in text. Section is modified from Kay and Abbruzzi (1996).

Chilean Flatslab

Miocene shallowing of the subducting slab initiated an important episode of loss of the base of the continental lithospheric beneath the modern volcanically inactive Chilean flatslab region (28°-33°S). The processes are illustrated in the lithospheric cross section in Figure 2. First order mass balance calculations comparing the lithospheric geometry proposed for 20 Ma with that today suggests that ≈ 60% of the basal continental lithosphere within 600 km of the trench at 20 Ma has been lost from an east-west transect near 30° to 31°S. Estimates are up to 69% for loss within 400 km of the trench (Kay and Abbruzzi, 1996). The mechanism must be more mechanical than thermal as loss occurred above a thinning lithosphere over a shallowing slab during a time of crustal thickening. Estimates of crustal thickening in the Main Cordillera under the arc region from 18 Ma to 6 Ma are ~ 25 Km. The principal driving force is inferred to be westward wedging of mid to lower crust from beneath the Precordillera thrust belt to the east into the hot magma-injected arc crust.

Lithospheric changes beneath the flatslab are recorded by temporal variations in Sr, Nd and Pb isotopic and trace element signatures in erupted magmas that reflect the cooling mantle, the changing crustal basement, and an increasingly higher pressure residual mineral assemblage in equilibrium with Main Cordilleran magmas. Contaminants in Early Miocene frontal arc lavas have less "enriched" isotopic and trace element signatures and flatter REE patterns than those in Late Miocene lavas. Progressive "enrichment" is attributed to: a) increasing amounts of sediment and tectonically eroded crust from the margin and beneath the forearc being incorporated into the mantle wedge, and b) contamination by a progressively 'enriched', thickening lower crust. Lower crustal "enrichment" occurred through addition of upper crust by an intracrustal mixing process driven by the propagating wedge tip associated with westward wedging, heating and deformation of crust from beneath the Precordillera thrust belt. Magmas erupted through backarc crust further east have more "depleted" signatures. Those in the evolving Precordilleran thrust belt were contaminated by an older, thinner Grenville (≈1100 Ma) basement which has a uniquely "depleted" signature among Central Andean terranes. Still further east, Late Miocene arc-related lavas erupted ~ 700 km east of the trench in the Pocho volcanic field in conjunction with uplift of the Sierras Pampeanas become more "enriched" through time. Their isotopic and trace elements signatures could arguably indicate a component that was mechanically removed from the base of the thinning continental lithosphere to the west, and progressively incorporated into the convecting asthenosphere (Kay and Abbruzzi 1996).

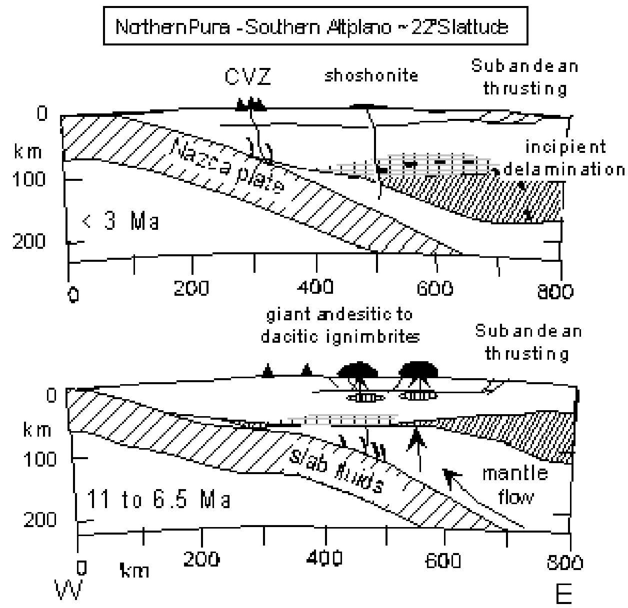

Figure 3. Lithospheric cross sections showing lithospheric modifications associated with Miocene steepening of subduction zone beneath the modern northern Puna-southern Altiplano region. Sections modified from Kay et al. (1999).

Northern Puna-Southern Altiplano Steep slab

Contemporaneous Miocene steepening of the subducting slab to the north at ~22°-25°S precipitated major lithospheric modifications that are reflected by the giant Miocene/Pliocene ignimbrites in the central part of the high Andean Puna-Altiplano plateau. As shown in the lithospheric cross sections in Figure 3, these silicic andesitic to dacitic ignimbrites reflect massive melting of thick crust and thin hydrated lithosphere developed over a formerly shallow subduction zone (see Kay et al. 1999). Their chemical and isotopic signatures reflect these sources as well as mid-crustal accumulation probably near the brittle-ductile transition. Eruption likely occurred in response to horizontal compressional collapse and thickening of the hot magma-injected crust. As in the foreland to the high Main Cordillera of the flatslab to the south, ductile deformation and thickening in the lower crust occurred in conjunction with brittle upper crustal shortening in a foreland fold and thrust belt, in this case in the Eastern Cordillera and Subandean belts (see Isacks 1988; Allmendinger et al. 1997; Kay et al. 1999).

Evidence for an Early Miocene shallow subduction zone comes from widespread compressional deformation across the modern plateau region and a gap in Early Miocene arc volcanism. As the subducting slab steepened, the volcanic zone narrowed to the west in response to lithospheric thickening, caused by underthrusting of the Brazilian shield and lithospheric cooling. Modern volcanism is largely restricted to the volcanic centers of the Central Volcanic Zone arc front. Seismic studies of the backarc lithosphere have led to the suggestion that the thickened lithosphere has become unstable and may be in the first stages of delamination (Myers et al. 1998). The eruption of shoshonitic and small acidic centers in the backarc supports reheating of the backarc region.

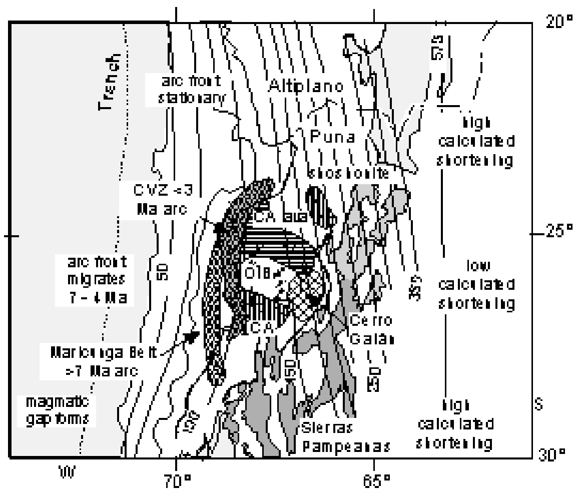

Figure 4. Map of southern Puna-flatslab transition zone of showing Miocene Maricunga and young CVZ arcs, distribution of OIB-like, backarc calc-alkaline and shoshonitic lavas, the Cerro Galan ignimbrite, and regions of high and low calculated shortening as determined in foreland thrust belts (in gray shades),

Southern Puna Transition Zone

Dramatic lithospheric modification and destruction also occurred in the intervening region north of the Chilean flatslab (25°-28°S) at the latitude of the southern Puna where the slab retained an intermediate dip and the arc front migrated ~50 km to the east from ~ 7 to 3 Ma (see Figures 4 and 5). The presence of Late Miocene arc lavas at only ~ 80 km above the modern seismic zone signals the magnitude of this change. Some of the highest La/Ta and La/Yb ratios known in post Archean magmatic rocks occur in the mafic andesitic to rhyolitic flows erupted in the zone of the migrating arc. High La/Ta ratios (to 100) suggest retention of Ti-group elements in oxide phases stabilized by especially Oxidizing and hydrous conditions above the adjusting slab. High La/Yb ratios which are up to 60 in mafic andesites suggest that mantle melts equilibrated with garnet peridotite above the shallowing and cooling slab. High La/Yb ratios (up to 100) in silicic flows reflect mixing of arc magmas with thickened garnet granulitic to eclogitic crust or with tectonically removed forearc crust subducted into the mantle. The REE patterns in some of the silicic volcanic rocks are among steepest found in post-Archean magmatic rocks on Earth (see Figure 6) and provide an alternative to melting of subducting oceanic crust for the origin of the Archean TTG (tonalite-tronjemite-granodiorite) suite (e.g. Martin 1996).

More "enriched" isotopic signatures in mantle-derived Pleistocene arc magmas ($^{87}Sr/^{86}Sr$ = 0.7058, Epsilon Nd = -2) than in Oligocene magmas erupted east of the sediment barren trench are consistent with mixing of tectonically removed lower crust into the mantle. Arc migration ended with eruption of widespread dacitic ignimbrites. Subsequently, typical modern CVZ Andean arc volcanic centers were established above the reestablished arc.

Other changes occurred in the backarc where delamination of over-thickened eclogitic crust and the underlying mantle lithosphere can explain the distribution of < ~ 6 Ma intraplate, calc-alkaline and shoshonitic lavas, and the voluminous dacitic Cerro Galan ignimbrite (Kay and Kay 1993; Kay et al. 1994). The intraplate lavas and crustal melting that produced the ignimbrite reflect asthenospheric mantle inflow into the gap left by the delaminated lithosphere. Evidence for melting of eclogitic crust comes from glassy dacitic flows with high La/Yb ratios (to 100) and radiogenic isotopes ($^{87}Sr/^{86}Sr$ = 0.7098, Epsilon Nd = -6.6) that erupted along faults generated by stress reorientation above the delaminated lithosphere. Other evidence supporting delamination includes the generally high topography of the region, the gap in intermediate depth slab seismicity (see Figure 5) and presence of a thin lithosphere (see Whitman et al. 1996).

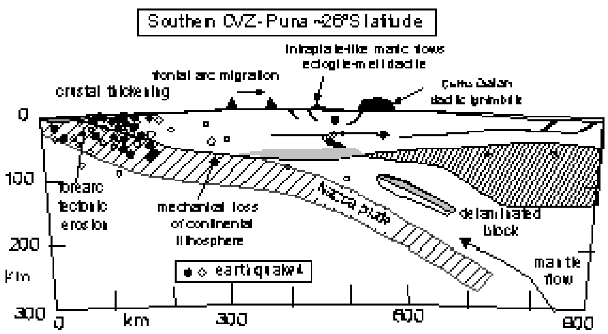

Figure 5. Lithospheric cross-section across southern Puna showing arc migration and lithospheric delamination. Section modified from Kay et al. (1994). Map view in Figure 4.

Conclusions

The chemistry of Central Andean erupted magmas records dramatic changes in the continental lithosphere in the past 10 Ma. Modification is severest as magmatism ceases over a shallowing slab, as the arc front migrates away from the trench, or as magmatism reinitiates over a steepening slab. Important lessons in understanding crustal evolution are that significant lithospheric changes that can occur on the order of 10 Ma and that along strike changes can be of an important magnitude over relatively short distances on a global scale.

Major destruction processes of Andean continental lithosphere are mechanical removal of basal lithosphere in the forearc and above a shallowly dipping subducting oceanic plate, and delamination of over-thickened crust along with the underlying mantle. The magnitude of continental lithospheric loss in the Central Andes has implications for crustal and mantle recycling and the overall evolution of the continental crust.

The Neogene Central Andes is a laboratory for understanding crustal evolution processes as substantial amounts of continental lithosphere has passed through Andean-like crucibles. An important modern analogue for the Archean tonalite-tronjemite-granodiorite (TGG) magmas could be melting of the thickened Central Andean lower crust especially in association with migration of the arc magmatic front. Tectonic forearc erosion could also be an important factor.

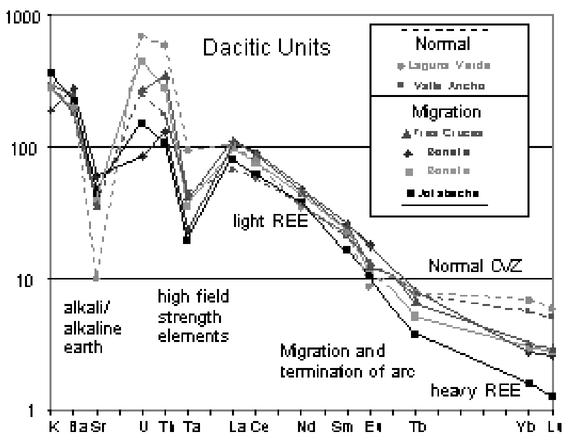

Figure 6. Extended trace element diagram for dacitic units erupted before and after (Normal – shown by dashed lines) and during arc migration and as arc magmatism terminates (Migration - shown as solid lines). Note extremely steep REE patterns of Bonete region lavas erupted at time of arc termination. These lavas are possible analogs for the Archean TGG suite. Normalization factors are K (116), Ba (3.77), Sr (14), Th (0.05), Ta (0.022), La (0.378), Ce (.976), Nd (0.716), Sm (0.23), Eu (0.0866), Tb (0.0589), Yb (0.249), Lu (0.0387).

Acknowledgments

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