SETTING OF CENTRAL ANDEAN NEOGENE ORE DEPOSITS

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Summary
The formation of central Andean (22°S to 34°S latitude) Late Oligocene to Recent giant ore deposits is related to the magmatic and tectonic evolution of the magmatic belts that host them. Common factors are a shallow subduction zone, a thickened continental crust, and formation at the time of initiation, expiration or migration of the magmatic arc. A key ingredient is hydration of the mantle and crust above a shallowing cooling slab over a period of some million years . Chemical analyses of > 500 El Teniente, El Indio, Maricunga, and Cerro Rico region samples provide evidence for temporal changes in hydrous to anhydrous mafic mineral residual assemblages in equilibrium with magmas erupted before and during mineralization. The data indicate that pyroxene-based residual assemblages evolve to hydrous amphibole -based ones as shallowing of the subducting plate proceeds. At the same time, compression related to South America-Nazca plate convergence leads to shortening and thickening of the crust and progressive entrapment of ascending magmas in the crust. Eventually, the hot, magma -charged crust fails catastrophically under compression leading to dramatic crustal thickening. Fluids related to mineralization are liberated from over-pressured plutons and as hydrous amphibole-based residual assemblages break down to anhydrous garnet -based ones. Mineralization is followed by magmatic quiescence or eruption of magmas that equilibrated with garnet -based residual assemblages in the thickened lower crust. Unless continental lithospheric thinning or arc migration allows re- hydration of the mantle wedge, mineralization ceases.

Introduction
Some of the world's richest Tertiary copper and gold deposits occur in the Central Andes. This presentation provides an overview of how deposits between 22°S and 33°S latitude can be related to Miocene to Recent Andean magmatic and tectonic evolution. Districts considered (see Fig. 1) are the Maricunga and El Indio gold belts, the Farallon Negro copper/gold district, the El Teniente copper belt, and the Cerro Rico silver/gold district. Their formation is tied to changes in the geometry of the Neogene subduction zone and continental crustal and lithospheric thickn ess. Trace element data are presented from the erupted magmas that provide evidence that fluids for mineralization are derived from a shallowing subducting slab, but are not available for mineralization until amphibole-bearing assemblages break down in tectonically thickened crust.

The subducting slab and Giant Miocene Central Andean Ore Deposits
Figure 1 shows the major Central Andean Miocene mineral districts discussed relative to contours to the Wadati-Benioff zone seismic zone, modern geologic provinces, and Late Miocene to Recent volcanism. The seismic zone can be divided into steeper segments with active volcanism and an intervening "flat" non-volcanic segment resulting from a seismic bench between ~ 90 and 135 km. (e.g., Cahill and Isacks 1992). The most prominent geologic province is the Puna-Altiplano plateau (average 3700 meters) with its extensive array of Neogene volcanic centers that occur along the western margin and in chains across the plateau. Uplift of the plateau is principally attributed to Miocene crustal shortening with magmatic addition as a secondary factor (see Isacks, 1988). The Subandean and Eastern Cordillera and Santa Barbara belts east of the plateau along with the Precordillera fold/thrust belt and the block-faulted Pampean ranges over the flat-slab, and the Aconcagua fold -thrust belt in the Main Cordillera (~32°-36°S) provide a temporal record of crustal shortening.. Models of Miocene evolution of subduction zone geometry show the slab beneath the modern flat-slab segment has flattened as that below the central Puna Altiplano plateau has steepened (see Isacks 1988; Kay et al. 1999).

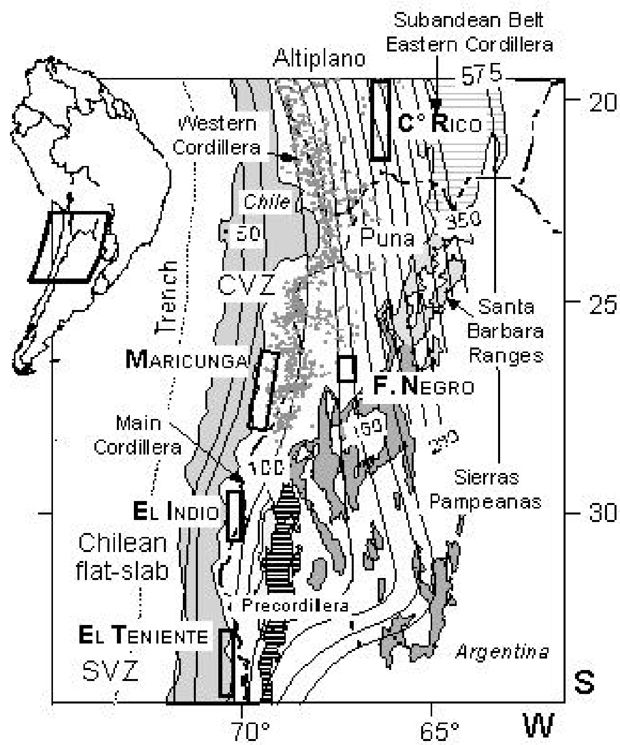

Figure 1: Central Andean map showing major mineralized areas relative to Southern (SVZ) and Central (CVZ) volcanic zone centers <7 Ma (circles), contours in km to Wadati-Benioff seismic zone (Cahill and Isacks 1992), foreland thrust belts (dark gray), Sierras Pampeanas uplifts (gray), and area over 3000 m - Puna Altiplano plateau and boundaries, flatslab Main Cordillera.

In this framework, the El Indio mineral belt is in the center of the flat slab, the Maricunga belt and Farallon Negro district on its northern transition, the El Teniente belt at its southern transition, and the Cerro Rico district above a steep slab. All of these districts occur in extinct Miocene volcanic areas formed over relatively shallow segments of the subducting slab and are underlain by thickened continental crust on the arc side of the thrust belts. Their setting and magmatic sequences have been summarized by Kay et al. (1999) and are reviewed below before presenting a generalized model for their formation..

Flatslab region

Important mineralization in this region took place in the El Indio belt (29° to 31°S) at ~ 12-9 Ma and 7-5 Ma (Clavero et al., 1997), in the Maricunga belt (26°-28°S) at ~ 25-22 Ma and at ~ 12-10 Ma (see Mpodozis et al., 1995), in the Farallon Negro district at 8-7 Ma (Sasso and Clark, 1996), and from north to south in the Teniente belt (32°-34°S) from 10 to 5 Ma (see Skewes and Stern 1994). Post early-Miocene shallowing of the subduction zone contemporaneous with continental lithospheric thinning and near loss of the asthenospheric wedge is well accepted to account for the magmatic, structural, and sedimentological history of this region. The mechanism of lithospheric thinning is unclear but has to be largely mechanical as thinning was contemporaneous with reduction of the asthenospheric wedge and mantle cooling. Smearing out and thinning of the wedge caused eastward broadening of the magmatic arc, and cessation of andesitic volcanism in the Main Cordillera by ~ 9 - 10 Ma. Mantle cooling led to a reduction in magmatism but augmented hydration of the mantle wedge by dewatering of the underlying slab. This hydration is a critical ingredient in creating giant Miocene ore deposits. Volcanism ceased across the region at ~5 Ma as the flat slab segment became too dehydrated to flux melting in the thicker asthenospheric wedge further east.

Compressional crustal thickening accompanied shallowing of the subduction zone. Thickening was most dramatic beneath the Main Cordillera where it occurred in response to shortening in the Precordillera (~ 20-18 Ma to ~ 7-5 Ma, peak at ~ 11 Ma) and the Sierras Pampeanas (~5-7 to 0 Ma), and to displacement of crust from beneath the forearc as South America overrode the Nazca plate. The major thickening pulse is attributed to Precordilleran mid to lower crust being driven westward into the hot, magma-injected Main Cordillera crust at times of peak compression.

A critical ingredient in forming these ore deposits is arc volcanism. El Indio transect volcanism occurred in three major episodes bounded by arc and backarc deformational peaks. Each succeeding episode has a distinct distribution, petrology, and geochemistry, and is marked by a decrease in volume of erupted magma. Mineralization occurred in association with the last two. The Late Oligocene to Early Miocene Doña Ana episode consists of voluminous 27 to 23 Ma biotite-bearing dacitic Tilito tuffs followed by 21 to 18 Ma pyroxene-bearing mafic andesitic to andesitic Escabroso flows in the arc, and minor ~ 23 Ma backarc Las Máquinas alkali basalt flows. The unconformity marks a mild deformation at ~22 Ma (Clavero et al., 1997). This episode ends with high angle normal faulting in the Main Cordillera, the inception of thrust faulting in the Precordillera, and the beginning of backarc andesitic to dacitic volcanism. No important mineralization is associated with these units whose large erupted volumes and low pressure phenocryst and inferred residual assemblages indicate ascent through a normal thickness crust over a relatively steep subduction zone. The second magmatic episode comprises the Cerro de Las Tórtolas group I (~17 to 14 Ma) and II (~13 to 9 Ma) hornblende-bearing andesitic to dacitic stratovolcanoes in the Main Cordillera and small backarc andesitic/dacitic centers as far east as the central Precordillera. The first El Indio belt mineralization is associated with the Cerro de Las Tórtolas II group as Precordillera thrusting peaked near ~ 11-10 Ma. These magmas evolved under more hydrous, higher pressure conditions in a thicker crust than the Doña Ana group. The last volcanic episode at ~ 7 to 5 Ma accompanied increased shallowing of the slab. Volcanism extended from the small silicic centers of the Main Cordillera Vallecito Group and Precordillera to the mafic andesitic to dacitic Pocho volcanic field in the easternmost of the rising Pampean ranges. The second El Indio mineralization is associated with the Vallecito Group which marked the end of Main Cordillera volcanism.

Temporally similar deformational and magmatic peaks are recognized in the Maricunga/Farallon Negro transect at the northern border of the flatslab region. Differences in style of events to the El Indio belt are consistent with a shallower Early Miocene subduction zone and a thicker crust. Early Miocene La Coipa-Refugio stratovolcano/dome complexes are similar to mid-Miocene Cerro de las Tórtolas units and like them are associated with mineralization. A virtual volcanic lull from ~ 20 to 17 Ma is contemporaneous with faulting and a volcanic low in the El Indio region. Volcanism resumed with the Maricunga/Cadillal group andesitic/dacitic stratovolcanoes. The youngest centers of this group host the fault-controlled 12 to 10 Ma "gold porphyries" of the second mineralization event. Subsequent volcanism is largely restricted to the dacitic Copiapó center erupting at ~ 11-10 and ~ 8-7 Ma, rhyodacitic units at the 7-5 Ma Jotabeche center, and the 7-5 Ma Pircas Negras mafic andesite flows. These magmas erupted through thick crust as the arc front began to migrate eastward. The last mineralization event occurred further east (Sasso and Clark, 1996) and is associated with the 8-7 Ma Farallon Negro andesitic/dacitic units that erupted as volcanism ceased in the thickening crust on the northern margin of the flatslab west of the rising Pampean ranges.

To the south, volcanic units in the El Teniente Belt fall into three recognizable episodes separated by deformational peaks (Kurtz et al., 1997; Skewes and Stern, 1994; Kay et al., 1999). The Late Oligocene to Early Miocene Coya Machalí mafic and silicic magmas evolved at shallower depths in a thinner crust over a steeper subduction zone than the contemporaneous Doña Ana magmas. Their eruption was followed by a ~ 19 to 16 Ma lull associated with compressional deformation leading to initial uplift and crustal thickening. Magmatism resumed with the voluminous ~ 15 to 7 Ma Teniente Volcanic/Plutonic Complex (Farellones Fm) units to the east. These units, like the chemically equivalent El Indio Doña Ana flows, are not mineralized. Magmatism ended with dramatic regional uplift as the arc front migrated eastward and mineralization occurred with the emplacement of porphyries and breccias in the zone of the former arc. Mineralization ages decrease to the south with the Pelambres-El Pachon deposit at 32°S at 10 to 9 Ma, the Rio Blanco-Los Bronces deposit at 33°S at 7 to 4.9 Ma, and the El Teniente deposit near 34°S at ~ 4.9 Ma

Puna-Altiplano region

Important mineralization in the northern Puna-southern Altiplano region occurred at ~ 14-12 Ma with the emplacement of the stocks and domes including the Cerro Rico de Potosí stock. A previous Early to mid Miocene shallow subduction zone is consistent with widespread deformation and volcanic quiescence. As in the Chilean flatslab region, a thin asthenospheric wedge inhibited arc magmatism, but enhanced mantle hydration above the cooling shallow slab. Subsequent

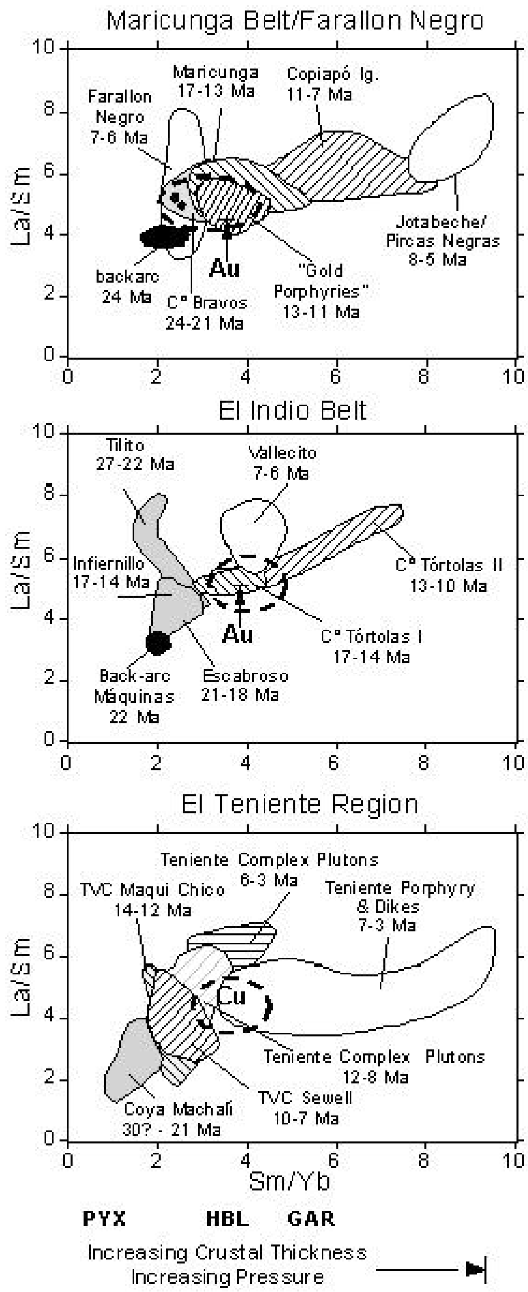

Figure 2: Plots of light (La/Sm) versus heavy (Sm/Yb) REE ratios for > 500 samples from Central Andean Miocene mineralized belts. Dashed region includes magmas erupted near time of mineralization. Figure modified from Kay et al. (1999) with data from Farallon Negro addded (Sasso and Clark 1996).

steepening accommodated a thicker asthenospheric wedge leading to melting of the overlying hydrated mantle and lower crust. Evidence for initial steepening and melting comes from the 14 to 12 Ma stocks and domes contemporaneous with the Cerro Rico mineralization event. Heating of the crust by mantle magmas led to enhanced ductile deformation producing crustal thickening in response to regional compression. As in the flatslab, mineralization was associated with a shallowly dipping slab under a thickening crust. The crust reached even greater thickness as huge ignimbrite sheets erupted from Late Miocene calderas and brittle deformation terminated on the plateau. Crustal thickening associated with plateau uplift occurred at ~ 11 to 7 Ma in conjunction with Subandean belt thrusting as both the motion on Subandean thrusts and large ignimbrite eruptions are associated with horizontal collapse of the melt-weakened crust. Subsequent volcanism was progressively concentrated to the west as underthrusting of the Brazilian shield and associated lithospheric cooling produced a thickened lithosphere. No major post ~ 10 Ma mineralization is recognized in the transect.

A persistent intermediate dip to the slab in the southern Puna region between that to the north and that to the south is supported by a generally continuous magmatic record. In accord with lack of a shallow subduction zone, no giant Neogene mineral deposits are known.

Chemical Signatures

Geochemical fingerprints of magmas erupted over the evolving subduction zone reveal clues to otherwise unseen magma source characteristics at depth). Trace element patterns are characterized by high K, Ba and Th and low Ta concentrations that signal an arc-like character, generally similar light REE patterns, and more variable heavy REE patterns. To a first order, increasing heavy REE (Sm/Yb) ratios in magmas of similar SiO_2 content can be explained by changes from clinopyroxene to amphibole to garnet in the mafic mineral residue as pressures increase in the source region. Comparing ranges of Sm/Yb ratios (see Fig. 2) with those appropriate for clinopyroxene and amphibole stability in basaltic composition rocks shows that mineralization occurred as the dominant residual mafic mineral changed from hornblende to garnet. Hornblende and garnet are not seen as phenocrysts in the erupted lavas as they remain in the source region. An implication for mineralization is that pressure induced breakdown of amphibole releases low-salinity aqueous fluids.

Discussion and Conclusions

Common features of giant Miocene Andean ore deposits include formation over a relatively shallow subduction zone in a thickened crust near the end or at the beginning of an volcanic episode and equilibration of magmas with a residual mineralogy changing from amphibole to garnet-bearing. The general model presented in Figure 3 builds on long standing ideas of association of these deposit types with hydrous magmas over subduction zones (e.g. Barnes 1997). The association with a shallowing slab which provides a fluid source is a critical element of the model.

Fluids for mineralization come from several sources. The first is from breakdown of hydrous minerals in the mantle and lower crust. One way to form hydrous minerals is from magmas that are largely produced in the hydrated mantle above the shallowing slab and crystallize amphibole as they are underplated beneath or intruded into the lower crust. Hydrous minerals also occur in the upper mantle and in metamorphosed older units in the lower crust. These hydrous minerals can be present for some time before mineralization as shown by the mineralogy and trace element patterns of El Indio and Teniente magmas erupted up to 8 million years before mineralization. Trace element evidence for breakdown of amphibole during deformational peaks associated with crustal shortening highlights a role for a thickening crust in release of fluids from these hydrous minerals. In basaltic composition units, amphibole should begin to breakdown to garnet at depths of ~ 40 to 50 km which is equivalent to pressures near 12 to 15 kb. The best indicators for lower crustal mineral assemblages are silicic magmas containing large proportions of lower crustal partial melts. Post-mineralization silicic magmas in the Maricunga, El Teniente, and El Indio belts provide such evidence for residual lower crust in transition from the amphibolite/garnet amphibolite to the granulite/eclogite facies. Such magmas are not seen at Farallon Negro (Sasso and Clark, 1996) and in the El Indio belt where no post-mineralization volcanism occurs.

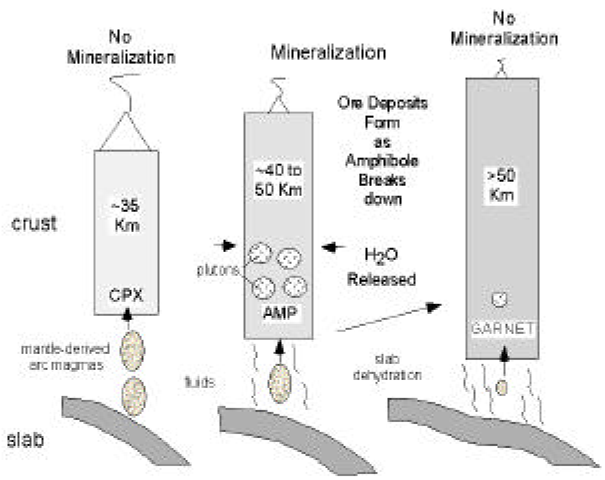

Figure 3: Formation of Andean giant ore deposits. Critical ingredients are arc setting, hydrated mantle above shallow slab, and release of fluid from plutons and break-down of hornblende to garnet-bearing assemblages during horizontal collapse and thickening of ductile, magma-injected crust.

Another fluid source is from magmas trapped at depth in thickening crust that is under compression. These trapped magmas promote crustal melting producing a ductile crust that is increasingly susceptible to horizontal compressional failure. Eventual failure lead to dramatic crustal shortening and thickening raising basal crustal pressures and promoting amphibole breakdown. Rapid crustal thickening leads to over-pressured fluids being expelled from plutons at high rates as suggested for the Teniente belt by Skewes and Stern (1994). Temporal correlations of crustal thickening in the arc and crustal shortening in the back-arc are evident in the flat-slab, the El Teniente (Kurtz et al., 1997) and Maricunga (Kay et al., 1994b) belts. Such correlations link mineralization, plutonism, and deformational peaks.

Crustal thickening due to shortening must also be compensated in the lithospheric mantle. Thickening of the lithosphere reduces space for the asthenospheric wedge above the shallowing slab and forces foreland retreat of the melt zone. As such, a thicker crust and a shallower slab under the El Indio and southern Maricunga belts than under the northern Maricunga and El Teniente belts can account for volcanic quiescence in the former, and eastward arc migration in the later. Extreme crustal shortening can also be compensated by mechanically removing continental lithosphere and even continental crust above the shallowing slab – a form of tectonic erosion. The occurrence of such lithospheric thinning can explain the second mineralization in the El Indio belt after the eruption of Cerro de Los Tórtolas II andesites whose REE patterns reflect eclogite residuals.

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