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# ORIGIN OF GIANT MIOCENE AND PLIOCENE Cu-Mo DEPOSITS IN CENTRAL CHILE: ROLE OF RIDGE SUBDUCTION, DECREASED SUBDUCTION ANGLE, SUBDUCTION EROSION, CRUSTAL THICKENING, AND LONG-LIVED, BATHOLITH-SIZE, OPEN-SYSTEM MAGMA CHAMBERS

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**Abstract** - Three of the world's largest Cu-Mo deposits, Los Pelambres, Río Blanco-Los Bronces and El Teniente, formed in close temporal association with southward migration of the locus of subduction of the Juan Fernández Ridge and the resultant decrease in subduction angle below central Chile during the Miocene and Pliocene. All three contain large Cu-mineralised magmatic-hydrothermal biotite ±tourmaline ±anhydrite breccia pipes generated by exsolution of saline, high-temperature fluids from crystallising magmas. Sr, Nd, Pb, S, Os, O and H isotopic data indicate that the metals these breccias contain, and aqueous fluids responsible for their emplacement, were derived from the same magmas that produced igneous rocks associated with each deposit. Isotopic data are consistent with derivation of these magmas from subduction-modified subarc mantle, and suggest that formation of these deposits did not involve either dehydration or melting of continental crust. Each deposit formed by multiple mineralising events occurring over a >2 m.y. period during which there is no evidence for coeval volcanic activity. Assuming an average Andean magma with 100 ppm Cu, the original $100x10^6$ tonnes of Cu in each deposit prior to erosion requires a parent body of magma with a batholith-size dimension of approximately >600 $km^3$. We suggest that the multiple Cu-mineralised breccia pipes in each deposit were generated by exsolution of magmatic fluids from the roofs of large, long-lived, open-system magma chambers, crystallising at depths of >4 km below the palaeosurface as indicated by geologic constraints. Input of mantle-derived mafic magmas into the base of these chambers provided heat for their progressive growth and persistence, as well as Cu, S, Fe, Ca and Cl-rich aqueous fluids which migrated to the tops of the chambers due to thermal gradients. As mafic magma supply from the mantle decreased, due to decreasing subduction angle caused by ridge subduction in the latest Miocene and Pliocene, the progressive growth stage of these magma chambers ended and they solidified. Crustal thickening, uplift and erosion speeded this crystallisation and de-fluidisation process, and caused telescoping of Cu-mineralised biotite followed by tourmaline breccias both as the roofs of these chambers became progressively closer to the surface and as multiple brecciation events caused confining pressures to change from lithostatic to hydrostatic conditions. Each deposit contains small, late, barren or weakly mineralised felsic porphyry intrusions with high "adakite-like" Sr/Y and La/Yb ratios. These felsic porphyries are both too small to have been the source of the enormous amount of Cu in these giant deposits, and they post-date the emplacement of the main mineralised breccias. Furthermore, they are not true adakites. Their isotopic compositions, which are similar to all the other igneous rocks associated with these deposits, indicate that they are not products of either slab-melting, nor melting of continental crust. Their unique chemical characteristics may result from crystal-liquid fractionation within, and extensive fluid transfer into and out of the tops of the crystallising batholith-size magma chambers that generated the mineralised breccias in each deposit.

## Introduction

Three of the largest and youngest Cu-Mo deposits in the world, Los Pelambres (Atkinson *et al.,* 1996; Reich *et al.,* 2003), Río Blanco-Los Bronces (Serrano *et al.,* 1996; Vargas *et al.,* 1999; Skewes *et al.,* 2003) and El Teniente (Skewes *et al.,* 2002, 2005), occur in the Andes of central Chile (Fig. 1). Not only are these deposits unusually large, El Teniente being the world's largest Cu-Mo deposit (Fig. 2), they are also distinctive relative to smaller more typical Cu porphyry deposits in that a significant proportion of their hypogene Cu is contained in multiple magmatic-hydrothermal breccia pipes (Skewes and Stern, 1994, 1995, 1996). This paper concerns the unique tectonic and magmatic factors that led to the formation of these three giant deposits.

These deposits occur just east of the locus of subduction of the Juan Fernández Ridge (Fig. 1). Their Miocene and Pliocene formation ages (Fig. 3) suggest that their origin is related to processes associated with subduction of this oceanic ridge (Stern, 1989; Skewes and Stern, 1994, 1995;

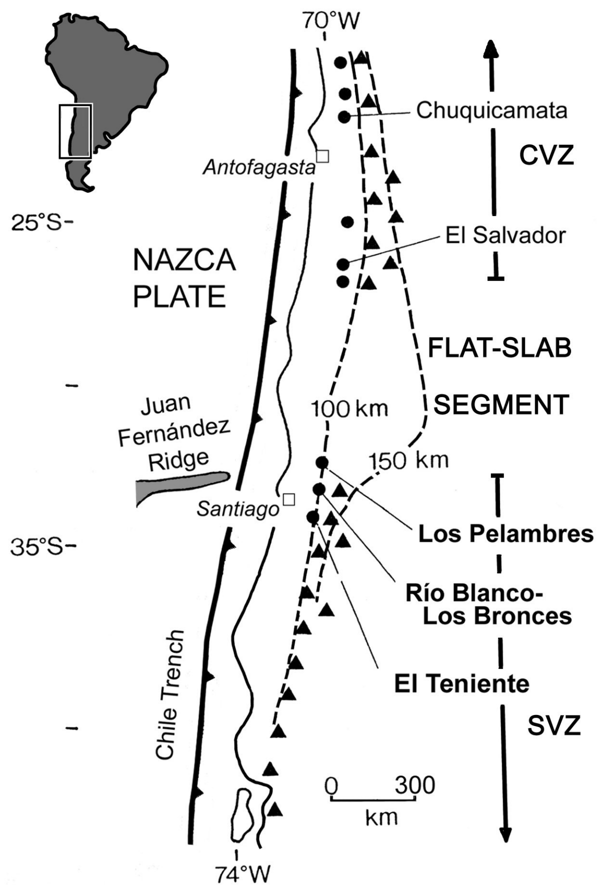


**Figure 1:** ***Location map of the three giant Late Miocene and Pliocene Cu deposits in the Andes of central Chile.*** These deposits occur just east of the locus of subduction of the Juan Fernández Ridge. This also marks the boundary between the Andean Flat-Slab segment, below which the subduction angle is very low, as indicated by the 100 and 150 km depths (dashed lines) to the upper boundary of the subducted slab, and the Southern Volcanic Zone (SVZ) of active volcanoes (triangles), below which the subduction angle is steeper. Figure also shows the location of the Central Volcanic Zone (CVZ) and some of the Late Eocene and Early Oligocene Cu deposits in northern Chile.

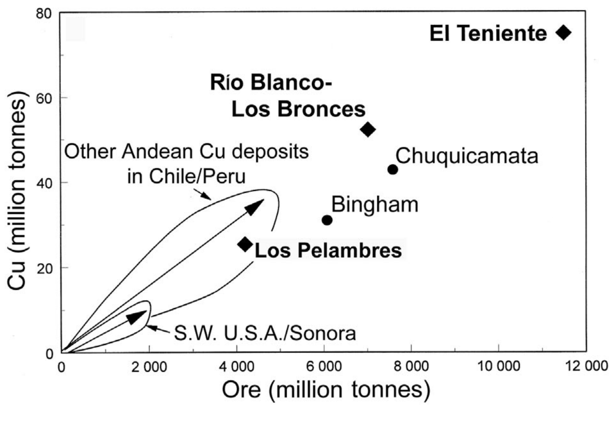


**Figure 2:** ***Current resources*** (equals original resources minus historic production as Cu versus ore in units of $10^6$ tonnes) of the three giant deposits in central Chile compared to other Cu deposits in the Andes and smaller deposits in western North America. *Modified after Clark, (1993)*

Stern and Skewes, 1995, 1997; Kay *et al.,* 2004; Kay and Mpodozis, 2002), the locus of which has migrated from north-to-south during the late Cenozoic (Yáñez *et al.,* 2001, 2002). Various geotectonic processes attributed to subduction of the Juan Fernández Ridge include: i). progressive decrease in the angle of subduction of Nazca oceanic lithosphere (Yáñez *et al.,* 2001, 2002), eastward migration of the location of the Andean arc (Stern, 1989; Kay *et al.,* 1999, 2004; Kay and Mpodozis, 2002) and possibly melting of subducted oceanic lithosphere as a result of its low angle of subduction (Gutscher *et al.,* 2000; Mungall, 2002); ii). crustal deformation resulting in increased crustal thickness and possibly dehydration and/or melting of thickened lower continental crust (Kay *et al.,* 1999, 2004; Kay and Mpodozis, 2002); and iii). increased subduction erosion of the continental margin and subduction of continental components into the subarc mantle source of Andean magmas (Stern, 1989, 1991, 2001; Stern and Skewes, 1995). Here we address which of these processes related to ridge subduction were most significant and how they worked together to generate the three giant Miocene and Pliocene Cu-Mo deposits in central Chile.

Small, late, barren or weakly mineralised felsic porphyry intrusions, with high "adakite-like" Sr/Y and La/Yb ratios, occur in each of the three giant deposits of central Chile (Stern and Skewes, 1995; Serrano *et al.,* 1996; Kay *et al.,* 1999, 2004; Rabbia *et al.,* 2000, 2001; Skewes *et al.,* 2002, 2005; Kay and Mpodozis, 2002; Reich *et al.,* 2003). Similar "adakite-like" felsic porphyries have also been described from Chuquicamata, another giant Cu deposit in northern Chile (Figs. 1 and 2; Oyarzún *et al.,* 2001, 2002). It has been suggested both that these felsic porphyries were the "productive" plutons providing the Cu in these giant Andean deposits, and that their unique "adakite-like" chemistry, and by implication their unique ability to generate a giant Cu deposit, resulted from either deep-crustal melting due to crustal thickening (Kay *et al.,* 1999, 2004; Rabbia *et al.,* 2002; Kay and Mpodozis, 2002) and/or subducted-slab melting due to a decreasing angle of slab subduction occurring in conjunction with ridge subduction (Gutscher *et al.,* 2000; Mungall, 2002; Reich *et al.,* 2003).

Here we discuss both the role of these felsic porphyries in formation of the giant Cu-Mo deposits in central Chile, and their origin. We make the points that these porphyry intrusions are both too small to have been the source of the enormous amount of Cu in these giant deposits, and also that they actually post-date the main stages of Cu-mineralisation (Fig. 3). They have merely truncated and redistributed Cu in these deposits, and created fractures that focused subsequent supergene enrichment (Skewes and Stern, 1995; Serrano *et al.,* 1996; Skewes *et al.,* 2002, 2003, 2005). Furthermore, these "adakite-like" felsic porphyries are not true adakites. They, as well as all the other igneous rocks in each deposit, have Sr, Nd, Pb, S, O and H isotopic ratios consistent with derivation from melting of the subarc mantle contaminated by small proportions of subducted pelagic and terrigenous sediments, sea-water and crustal components transported into the mantle by subduction. Isotopic data do not support the suggestion that formation of these deposits involved either melting of subducted slab

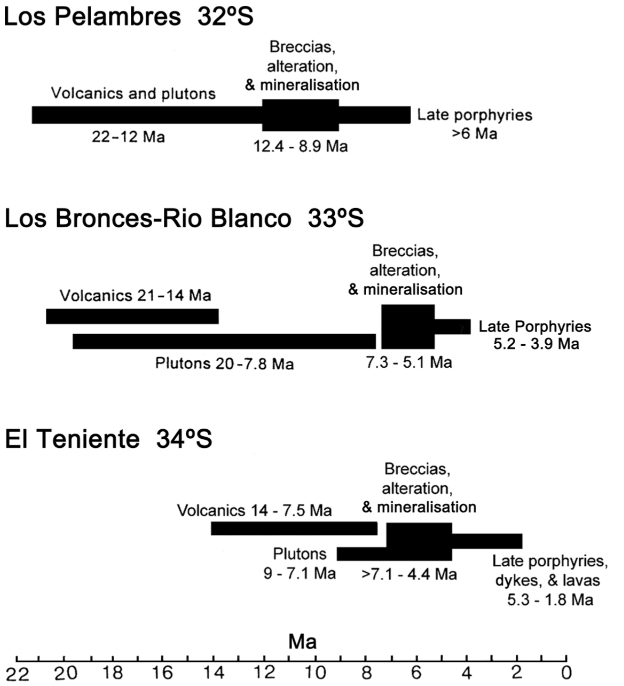


**Figure 3:** ***Schematic summary,*** modified after Skewes and Stern (1995), of the chronology of Los Pelambres (Atkinson *et al.,* 1996; Reich *et al.,* 2003), Río Blanco-Los Bronces (Serrano *et al.,* 1996) and El Teniente (Cuadra, 1986; Skewes *et al.,* 2002, 2004) deposits as determined by K-Ar dating techniques.

The figure demonstrates a southward decrease in ages of:
i). alteration and mineralisation associated with breccia emplacement,
ii). late porphyries and post-mineralisation dykes and lavas, and
iii). the last magmatic events associated with each deposit prior to eastward arc migration.

Their ages reflect the close temporal relation between the formation of these deposits and the southward migration of the locus of subduction of the Juan Fernández Ridge. More recent studies have refined the detailed chronological evolution of each deposit (for example El Teniente; Fig. 10) and have substantiated this conclusion.

or lithologically and isotopically heterogeneous roots of thickened continental crust.

Since these three giant deposits clearly were generated in association with Andean magmatic activity, we review first the geochemical evidence that Miocene and Pliocene igneous rocks associated with these deposits formed by melting of subarc mantle contaminated by subducted components, with the degree of contamination increasing as subduction angle decreased due to ridge subduction, and second that S, O, Pb and Os, and by implication Cu and Mo, in each deposit were derived from these igneous rocks. Next we address both the role and genesis of "adakite-like" felsic porphyries in these three deposits. Finally we summarise evidence that these giant deposits consist of multiple Cu-mineralised breccias generated by exsolution of metal-rich magmatic fluids from the roofs of large, long-lived, open-system magma chambers crystallising at >4 km below the palaeosurface. We propose a model in which the input of mantle-derived mafic magmas into the base of these chambers provided heat for their progressive growth and persistence, as well as Cu, S, Fe, Ca and Cl-rich water which migrated to the tops of these magma chambers due to thermal gradients. During the >2 m.y. period of their growth and crystallisation, a period marked by absence of coeval volcanic activity, aqueous fluids and volatile saturated magmas derived from their roofs formed the multiple mineralised breccia pipes found in these two giant deposits. As supply of mafic magma from the mantle decreased, due to decreasing subduction angle caused by ridge subduction in the latest Miocene and Pliocene, the progressive growth stage of these magma chambers ended and they crystallised and solidified. Crustal thickening, uplift and erosion increased the rate of this crystallisation and de-fluidisation process, and caused telescoping of Cu-mineralised breccias as the roofs of these chambers became progressively closer to the surface.

We argue that the unique chemical characteristics of the small, late "adakite-like" felsic porphyries in each of the three giant Miocene and Pliocene Cu deposits in central Chile resulted from fractionation of igneous phases, and from extensive fluid transfer into and out of the tops of these crystallising batholith-size magma chambers, and that these deposits are not giant because of any unusually magma composition or magma generation process. The magmas involved in the generation of these giant deposits were typical Andean basalts and their more felsic differentiation products. Although these magmas may have been highly oxidised (Garrido *et al.,* 2002; Funk *et al.,* 2004), there is no evidence that they were exceptionally enriched in Cu or S. However, compression prevented their extrusion, allowing development of long-lived, open-system magma chambers in which highly saline, $SO_2$ and metal-rich aqueous fluids were concentrated at the tops of the chambers due to thermal gradients. Magma extrusion, in contrast, allows volatiles such as $H_2O$ and $SO_2$ to exsolve directly into the atmosphere as magmas approach or erupt to the surface, and thus volcanic activity may decrease the potential for subsequent formation of a giant Cu deposit (Pasteris, 1996).

# Isotopic Constraints

### *Miocene and Pliocene Igneous Rocks*

The giant Cu deposits of central Chile were emplaced within Late Oligocene to Miocene and Pliocene extrusive and intrusive rocks (Figure 3). Igneous rocks in these and other Andean Cu deposits have been generated by processes associated with subduction of oceanic lithosphere below the South American continental margin. The Miocene and Pliocene in central Chile was marked by a decreasing angle of subduction of the down-going Nazca plate, which eventually lead to eastward migration of the volcanic arc, and crustal thickening and uplift, both ultimately associated with subduction of the Juan Fernández Ridge (Stern, 1989; Kay *et al.,* 1999, 2004; Skewes and Stern, 1994, 1995; Yáñez *et al.,* 2001, 2002; Kay and Mpodozis, 2002). These changes, as well as an increase in the rate of subduction erosion along the continental margin (Stern, 1991; Stern and Skewes, 1995), worked together to cause temporal changes in various factors that affect Andean magma-genesis. These changes are reflected in temporal variations in chemistry, in particular isotope and trace-element chemistry, of magmas erupted in central Chile during this time period.

The most significant temporal geochemical changes observed in Miocene and Pliocene igneous rocks associated with each deposit are an increase through time in initial $^{87}$Sr/$^{86}$Sr ratios and a decrease in $^{143}$Nd/$^{144}$Nd ratios (Figs. 4 and 5; Nystrom *et al.,* 1993, 2003; Stern and Skewes, 1995; Kay *et al.,* 1999, 2004). Fig. 4 illustrates these temporal changes in the vicinity of the El Teniente deposit at latitude 34°S, where they have been documented in most detail (Skewes *et al.,* 2002, 2005; Kay *et al.,* 2004). Fig. 5 shows that these changes were not synchronous for all of the deposits, but migrated progressively from north-to-south (Stern and Skewes, 1995), as did the age of eastwards migration of the magmatic arc at each latitude (Fig. 3), in association with southward migration of the locus of ridge subduction (Stern, 1989).

At the latitude of El Teniente, both Late Oligocene to Early Miocene Coya-Machalí (or Abanico) Group volcanics and the Mid to Late Miocene Teniente (or Farellones) Volcanic and Plutonic Complexes are isotopically similar to magmas currently being erupted from active volcanoes in the southern part of the Andean Southern Volcanic Zone (SSVZ; Figs. 4 and 5; Nystrom et al 1993, 2003; Stern and Skewes, 1995; Kay *et al.,* 1999, 2004). These older rocks, as well as magmas erupted from active volcanoes in the

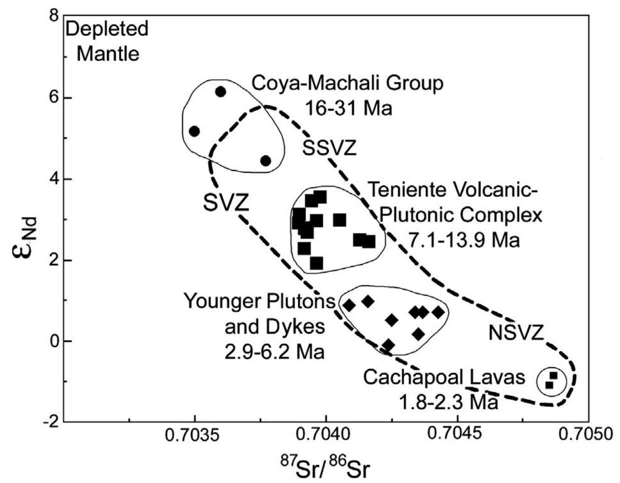


**Figure 4:** ***$^{87}$Sr/$^{86}$Sr versus $^{143}$Nd/$^{144}$Nd ratios for igneous rocks from the vicinity of the El Teniente copper deposit in central Chile*** (Nystrom *et al.,* 1993, 2003; Stern and Skewes, 1995; Kay *et al.,* 2004) compared to the field for samples from active volcanoes in the Andean SVZ (dashed line; Stern *et al.,* 1984a, Hickey *et al.,* 1986, 1989; Futa and Stern, 1988; Hildreth et al., 1988; Dungan *et al.,* 2001). The figure illustrates the temporal evolution, between the Miocene to Pliocene, from lower $^{87}$Sr/$^{86}$Sr and higher $^{143}$Nd/$^{144}$Nd ratios, similar to southern SSVZ volcanoes, towards higher $^{87}$Sr/$^{86}$SrSr and lower $^{143}$Nd/$^{144}$Nd similar to northern NSVZ volcanoes. These changes are independent of $SiO_2$ content and reflect increased mantle-source region contamination by subducted continental crust as both angle of subduction decreased and rate of tectonic erosion increased between the Miocene and Pliocene (Stern, 1989, 1991, 2001; Stern and Skewes, 1995, 1997; Kay *et al.,* 2004).

SSVZ, have isotopic and trace-element characteristics indicating that they formed by melting of peridotite in the subarc mantle wedge modified, or contaminated, by addition of crustal components derived from subducted pelagic and terrigenous sediments, and continental crust tectonically eroded of the continental margin, and released into the overlying mantle wedge during dehydration of down-going oceanic lithosphere (Stern *et al.,* 1984a, 1990; Hickey *et al.,* 1986, 1989; Futa and Stern, 1988; Hildreth and Moorbath, 1988; Stern, 1991, 2001; Dungan *et al.,* 2001). These rocks do not have isotopic or trace-element characteristics consistent with assimilation of significant amounts of material during transit through the continental crust, which consists in part of lithologically and isotopically heterogeneous Palaeozoic metamorphic and Mesozoic sedimentary rocks. Late Oligocene to early Miocene Coya-Machalí Group volcanics formed during a period of extension, when the continental crust was as thin as it currently is below the current Andean SSVZ (Nystrom *et al.,* 1993, 2003; Charrier *et al.,* 2002; Kay and Mpodozis, 2002; Kay *et al.,* 2004). In contrast, Middle to Late Miocene Teniente Volcanic and Plutonic Complex rocks formed during a period of mild compression, crustal thickening and uplift (Kurtz *et al.,* 1997; Godoy *et al.,* 1999; Kay *et al.,* 1999, 2004), and have higher initial $^{87}$Sr/$^{86}$Sr and lower $^{143}$Nd/$^{144}$Nd ratios than older Coya-Machalí Group volcanics (Fig. 4). However, their chemical characteristics are nevertheless consistent with derivation from subarc mantle modified by slab-dehydration, followed by only very limited assimilation of continental material during their transit through the crust.

Younger Pliocene stocks and dykes at El Teniente, including the Teniente Dacite Porphyry and post-mineralisation mafic dykes, and lavas in the valley of the Cachapoal river, have even higher initial $^{87}$Sr/$^{86}$Sr and lower $^{1143}$Nd/$^{144}$Nd ratios and resemble magmas erupted from active volcanoes in the northern part of the Andean SVZ (NSVZ; Figs. 4 and 5; Stern and Skewes, 1995; Kay *et al.,* 1999, 2004). They have incorporated greater amounts of continental crust, resulting from either increased intra-crustal assimilation due to the increased thickness of the crust in the latest Miocene and Pliocene, and/or an increase in the extent to which the subarc mantle magma source region was contaminated by subducted crustal components. Increased contamination of subarc mantle could have resulted from i). an increase in rate of subduction erosion associated with southerward migration of the locus of subduction of the Juan Fernández Ridge (Stern and Skewes, 1995; Yáñez *et al.,* 2001, 2002; Kay and Mpodozis, 2002; Kay *et al.,* 2004), and ii). a combination of decreasing subduction angle and increased crustal thickness, which together decreases the volume of subarc mantle wedge relative to the amount of crustal component released by dehydration of the subducted slab (Stern *et al.,* 1984a; Stern, 1989, 1991). Stern and Skewes (1995) demonstrated that higher initial $^{87}$Sr/$^{86}$Sr and lower $^{143}$Nd/$^{144}$Nd ratios in these younger lavas are independent of $SiO_2$ content and are observed for even the most mafic olivine-bearing basalts and lamprophyres. Also, timing of these isotopic changes is not correlated with timing of crustal thickening, and no isotopic change occurred between the Pliocene and Recent when the arc migrated 40 km eastwards to the continental divide above the thickest Andean crust (Fig. 5; Stern and Skewes, 1995). For all these reasons, we consider increased subduction erosion and source region contamination related to ridge subduction a better explanation for observed temporal changes in Sr and Nd isotopic compositions than

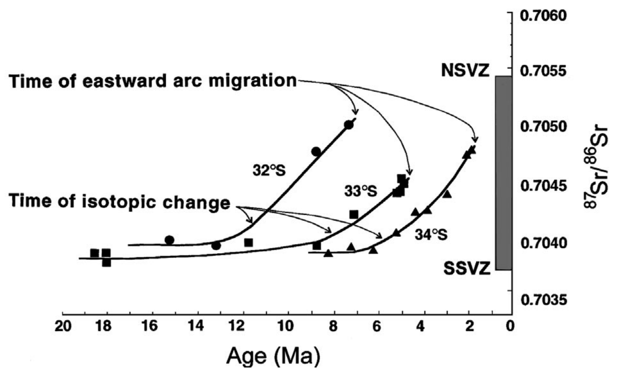


**Figure 5:** ***The $^{87}Sr/^{86}Sr$ ratios of igneous rocks (Stern and Skewes, 1995) and minerals from the matrices of magmatic-hydrothermal breccia pipes*** (Skewes and Stern, 1996), versus their age, for samples from the three giant deposits in central Chile at latitudes 32°S (Los Pelambres; circles), 33°S (Río Blanco-Los Bronces; squares) and 34°S (El Teniente; triangles), compared to samples from active Andean volcanoes between 33-34°S (NSVZ) and between 36-42°S (SSVZ).

The figure illustrates the diachronous southward change in time, at each latitude, of:
i) increasing $^{87}Sr/^{86}$ of igneous rocks, and
ii) eastward migration of the magmatic arc. These changes reflect southward migration of the locus of subduction of the Juan Fernández Ridge.

increased intra-crustal assimilation due to increased crustal thickness (Stern, 1991, 2001; Stern and Skewes, 1995).

Although the isotopic composition of Sr and Nd in igneous rocks associated with giant deposits in central Chile changed with time between the Late Oligocene and Pliocene, their Pb (Fig. 6; Rabbia *et al.,* 2001; Nystrom *et al.,* 2003; Kay *et al.,* 2004) isotopic compositions remained nearly constant, and equal to the isotopic composition of SSVZ basalts derived from the mantle plus small amounts of subducted components. This contrasting behaviour of Pb compared to Sr and Nd isotopic ratios is also observed in a comparison of SSVZ and NSVZ magmas. The Pb isotopic composition of Late Oligocene to Recent igneous rocks in the southern Andes, in both the SSVZ as well as the NSVZ, is controlled by the isotopic composition of Pb derived from the down-going slab, since the subarc mantle wedge has a very low Pb content, and the relatively large amount of Pb derived from subducted components overwhelms mantle Pb regardless of small variations in extent of source region contamination. In contrast, when crustal components are added to mantle-derived magmas by intra-crustal assimilation, Pb isotopes reflect much more strongly differences in extent of crustal assimilation, as in magmas erupted in the central Andes of northern Chile, where the crust is extremely thick (Fig. 6).

### *Copper Mineralisation*

Isotopes of Os, Pb and S provide indirect information concerning the ultimate source of metals such as Cu and Mo in mineralised deposits, as do isotopic data for Sr, Nd, O and H in phases co-precipitated with metal-bearing sulphides from high-temperature aqueous fluids. Os and Pb isotopic data for sulphides from El Teniente suggest that these metal, and by implication Cu and Mo, are derived

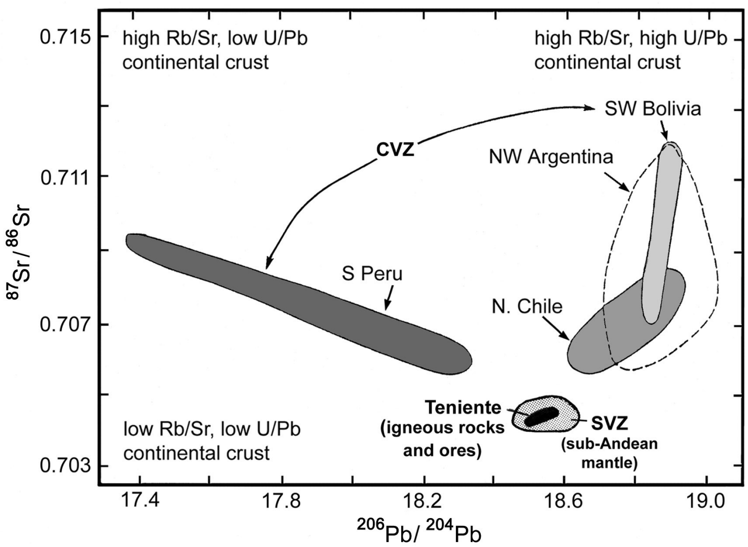


**Figure 6:** ***$^{206}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$ isotopic compositions of volcanic rocks in the Andean CVZ compared to SVZ*** (Zentilli *et al.,* 1988; Macfarlane, 1999). SVZ volcanic rocks have compositions consistent with derivation from Andean subarc mantle modified by addition of small amounts of subducted components, without any subsequent intra-crustal assimilation. In contrast, CVZ volcanics have more variable isotopic compositions reflecting intra-crustal assimilation during ascent through thick crust of variable geochemical character. Miocene and Pliocene igneous rocks from El Teniente have Pb and Sr isotopic values entirely within the range of SVZ volcanic rocks (Rabbia *et al.,* 2001; Nystrom *et al.,* 2003; Kay *et al.,* 2004), indicating that these rocks were also derived from the subarc mantle. Sulphide minerals in Río Blanco-Los Bronces and El Teniente also have Pb isotopic ratios similar to SVZ volcanic rocks (Zentilli *et al.,* 1988; Puig., 1988), indicating that Pb in these ores was derived from the associated igneous rocks which were themselves generated in the subarc mantle.

from the same magmas that formed the igneous rocks in the deposit. This is indicated by the similarity of $^{187}Os/^{188}Os$ ratios, which range from 0.171 to 0.223, measured in chalcopyrite, sphalerite and bornite precipitated during different alteration stages accompanying the formation of El Teniente (Fig. 7a; Freydier *et al.,* 1997). If these metals had been derived from surrounding country rocks, greater variability in $^{187}Os/^{188}Os$ ratios would be expected (Freydier *et al.,* 1997). Pb isotope ratios, measured in galena, also exhibit little variability, and Pb isotopes are the same as Pb isotopic compositions of recent Andean volcanic rocks erupted in central Chile (Fig. 6; Puig, 1988; Zentilli *et al.,* 1988; Macfarlane, 1999), implying that Pb in these galenas was also derived exclusively from magmas that formed the igneous rocks in this deposit. Furthermore, these Pb isotopic ratios, as well as Os isotopic ratios, which are more similar to mantle (0.13) than crustal (>>1.0) values (Fig. 7b; Mathur *et al.,* 2000; Schaefer *et al.,* 2000), indicate that these metals, and the magmas they were derived from, formed in sub-Andean mantle contaminated by subduction of a small amount of pelagic and terrigenous sediment, and continental crust tectonically eroded off the continental margin, but not within the lithologically and isotopically heterogeneous crust. This is true not only for the giant deposits in central Chile, but for Chuquicamata in northern Chile as well (Mathur *et al.,* 2000).

Sulphide (chalcopyrite and pyrite) $\delta^{34}S$ in El Teniente and Río Blanco-Los Bronces range from –5.6 to +1.6 per mil, and average approximately –2.2 per mil (Kusakabe *et al.,* 1984, 1990; Holmgren *et al.,* 1988). This small range is consistent with derivation of sulphur from igneous rocks associated with the deposit. A calculated total sulphur isotopic composition $\delta^{34}S$ of +4.5‰ for El Teniente and +7.5‰ for Río Blanco-Los Bronces (Kusakabe *et al.,* 1984, 1990) is also similar to $\delta^{34}S$ values of non-mineralised Andean granitoids, which range from +3.3 to +6.1‰ (Sasaki *et al.,* 1984), and these are in turn similar to Japanese granitoids generated from mantle contaminated by subducted marine sulphur. Sr, Nd, O and H isotopic ratios in minerals that have co-precipitated from high-temperature aqueous fluids with Cu-sulphides, in both veins and matrices of Cu-mineralised breccias at Río Blanco-Los Bronces and El Teniente, also imply derivation of these metal-bearing fluids from crystallising magmas (Figs. 5 and 8; Kusakabe *et al.,* 1984, 1990; Skewes and Stern, 1995; Skewes *et al.,* 2001, 2002, 2003), and not by derivation of dehydration of amphibole in the lower crust as suggested by Kay *et al.,* (1999).

***Summary***

In summary, all available isotopic data for igneous rocks, Cu and Mo sulphides, and minerals co-precipitated with these sulphides in the giant deposits of central Chile indicate derivation of igneous rocks in each deposit from the subarc mantle modified by addition of subducted components, and metals and sulphur, as well as aqueous fluids which transported and deposited them, from these magmas. There is no isotopic evidence to support any significant amounts of crustal assimilation in the generation of the igneous rocks, nor as the source of metals in these deposits.

## Felsic Porphyries

***Role in Copper Mineralisation***

Small, late, barren or weakly mineralised felsic porphyries occur in each of these giant deposits in central Chile. These include the late Miocene tonalite, quartz diorite (Porphyry A) and quartz monzodiorite (Porphyry B) at Los Pelambres (Atkinson *et al.,* 1996; Reich *et al.,* 2003), Pliocene Don Luis Porphyry and La Copa subvolcanic complex in Río Blanco-Los Bronces (Vergara and Latorre, 1984; Blondel *et al.,* 1988; Serrano *et al.,* 1996) and the Teniente Dacite Porphyry and latite dykes in El Teniente (Camus, 1975, Cuadra, 1986; Skewes *et al.,* 2002, 2005). These are among the youngest igneous rocks in each deposit, but even younger, more mafic post-mineralisation dykes and lavas also occur at El Teniente.

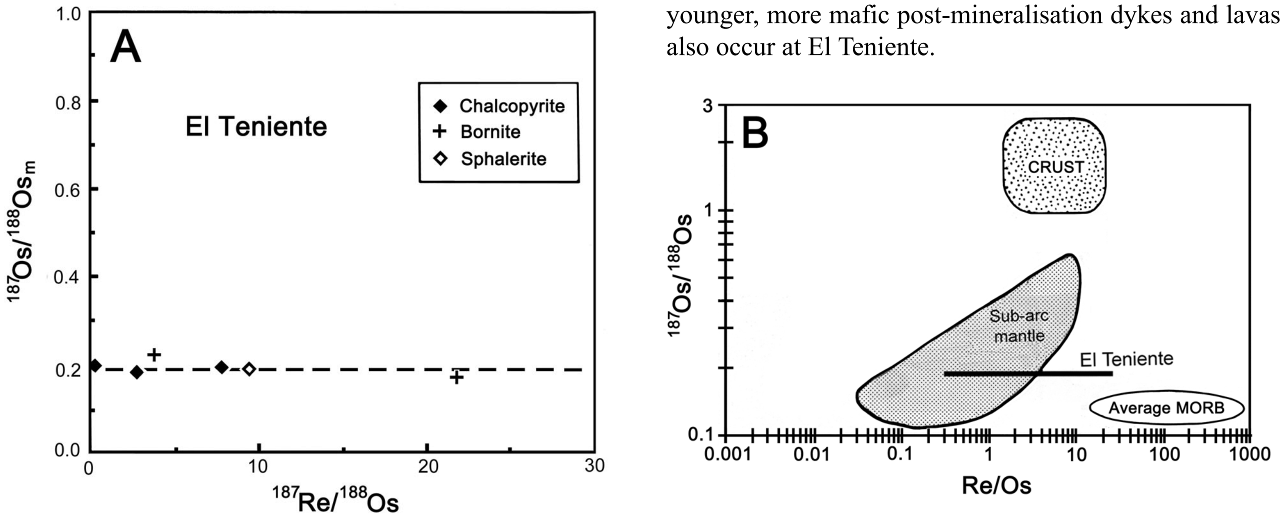


**Figure 7:** ***$^{187}Os/^{188}Os$ versus $^{187}Re/^{188}Os$ ratios for* A) *different sulphide minerals formed at different stages of mineralisation at El Teniente*** *(Freydier et al., 1997)*, ***and* B) *these values compared to oceanic basalts (MORB), subarc mantle modified by addition of subducted components*** *(Schaefer et al., 2000)* ***and continental crust.***

**A.** demonstrates the uniformity of Os isotopic composition in ore minerals formed at different stages of development of El Teniente, suggesting derivation of Os from magmas and not from country rock which would be expected to have more diverse Os isotopic compositions.

**B.** implies that Os in these source magmas was derived from Andean subarc mantle modified by addition of subducted components, and not from continental crust.

The small felsic porphyries intrusions in the giant deposits of central Chile have volumes <<10 km$^3$. When compared with the volume of other igneous rocks in these deposits it is clear that these porphyries comprise only a very small volume percent (Figure 9), and that mafic and intermediate rocks are volumetrically more significant than these small felsic intrusions. Although it has been suggested that late felsic porphyries are the so-called "productive" plutons in these deposits (Howell and Molloy, 1960; Ossandón, 1974; Camus, 1975; Cuadra, 1986; Maksaev *et al.,* 2002), it is clear that they are actually too small to have been the source of the enormous amount of Cu in these deposits. Assuming an average Andean andesite magma with 100 ppm Cu, and a mechanism for extraction of Cu that is somewhat less than 100% efficient, the original 100 million tonnes of Cu in each deposit prior to erosion (Skewes and Stern, 1995) requires a parent body of magma with a batholithic dimension of approximately >600 km$^3$. This would be consistent with the 60 km$^3$ of magma, with 62 ppm Cu, calculated to have produced the 6 million tonnes of Cu in the Yerington deposit in Nevada (Cline and Bodnar, 1991). Since felsic magmas have lower Cu contents than mafic and intermediate magmas, this estimated volume would be even greater if felsic porphyries were the source of Cu in these deposits, but they are not!

Furthermore, field relations demonstrate that the porphyries either cross-cut pre-existing mineralisation or were mineralised by younger breccias after they were fully crystallised and solidified (Serrano *et al.,* 1996; Skewes *et al.,* 2002, 2005). Chronological studies also indicate that intrusion of these porphyries did not coincide with the main stages of mineralisation in these deposits. In Río Blanco-Los Bronces, K-Ar ages indicate that the late porphyries intruded between 5.2 and 3.9 Ma, while Cu-mineralised breccias were emplaced and biotite and sericitic alteration occurred between 7.3 and 5.1 Ma (Fig. 3; Serrano *et al.,* 1996). At El Teniente, intrusion of the Teniente Dacite Porphyry at 5.28 Ma, as determined by a U-Pb in zircon crystallisation age (Fig. 10), was associated with an important alteration event in the deposit at 5.3 Ma, as indicated by $^{40}Ar/^{39}Ar$ ages of micas (Maksaev *et al.,* 2001). However, it was not associated with any significant mineralisation event, as demonstrated by the fact that not a single one among >20 Re-Os ages for molybdenite in association with chalcopyrite mineralisation in the deposit correspond, within ±300 000 years, to the intrusion age of this porphyry (Fig. 10; Maksaev *et al.,* 2002; Munizaga *et al.,* 2002). Also, where this dacite porphyry outcrops

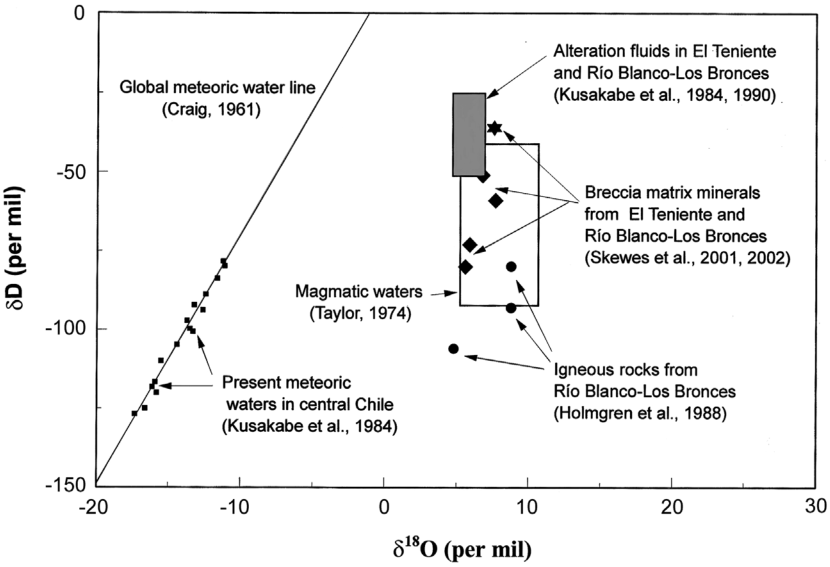


**Figure 8:** ***Plot of δ¹⁸O versus δD, in per-mil, for hydrothermal fluids from which the minerals in the matrices of breccias at both El Teniente (stars) and Río Blanco-Los Bronces (diamonds) precipitated*** (Skewes *et al.,* 2001, 2002, 2003). The figure also shows the field for fluids that formed minerals in veins related to different stages of alteration in both deposits (Kusakabe et al., 1984, 1990), values for fresh and weakly altered igneous rocks from Río Blanco-Los Bronces (circles; Holmgren *et al.,* 1988), the general field for magmatic water (Taylor, 1974), meteoric waters from central Chile (small squares; Kusakabe et al., 1984), and the global meteoric water line (Craig, 1961). The figure illustrates the magmatic affinities, and lack of any significant component of meteoric water, for the fluids that generated both breccias and alteration, including tourmaline breccias and associated sericitic alteration, in these two giant copper deposits.

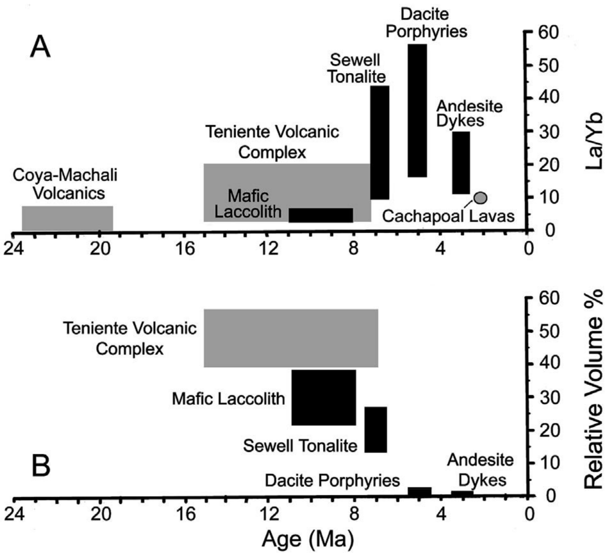


**Figure 9:** **A.** ***La/Yb ratios, versus age***, for samples of volcanic rocks (shaded fields) from in the area of El Teniente, including Coya-Machalí (Abanico) volcanic rocks (Charrier *et al.,* 2002), the rocks of the Teniente (Farellones) Volcanic Complex (Kay and Mpodozis, 2002), and also lavas from the Cachapoal River valley (Stern and Skewes, 1995). Plutonic igneous rocks from the mine, including the mafic laccolith that hosts most of the mineralisation at El Teniente, the Sewell Tonalite, Teniente Dacite Porphyry and post-mineralisation andesite dykes, are indicated in black (Stern and Skewes, 1995; Skewes et al., 2002).

**B.** ***Relative volume percent***, based on relative area of outcrop in the region of the deposit, versus age of the different igneous rocks in the vicinity of and within the mine (Skewes *et al.,* 2004).

north of the Teniente river, outside of the deposit, the extrusive rocks it intrudes are altered, but not mineralised (Floody and Huete, 1998; Skewes *et al.,* 2002, 2005). Detailed Re-Os dating at El Teniente indicates that only some episodes of Mo-mineralisation in the deposit occurred in association with intrusion of porphyries, and intrusion of the largest porphyry in the deposit, the Teniente Dacite Porphyry, produced alteration but not Cu-mineralisation.

***Origin of "Adakite-like" Chemistry***

Late felsic porphyries, which occur as stocks, plugs, dykes and diatremes, have variable chemistry and mineralogy. They are described as tonalites, quartz diorites, quartz monzonites, dacites, latites, trondhjemites, adakites, rhyodacites and rhyolites. Published $SiO_2$ values range from 63 to 72 wt %, while their MgO contents are always <3 wt %, and usually <1.5 wt %. Compared to older more mafic rocks in these deposits, they have relatively high Sr (350 to >900 ppm) and low Y (1.5 to 6.5 ppm) concentrations and therefore high Sr/Yb >>20, to as high as >100, and also high La/Yb ratios, typically >20 and in many cases >50 (Fig. 9). However, younger post-mineralisation intermediate and mafic dykes and lavas at El Teniente, the only deposit for which geochemical data on such post-mineralisation igneous rocks are available, indicate that these have lower La/Yb, more similar to older mafic and intermediate rocks associated with this deposit (Fig. 9). Small temporal changes between the Late Miocene and Pliocene in La/Yb of mafic and intermediate rocks in this deposit is consistent with a small decrease in the degree of mantle melting as the volume of subarc mantle wedge decreased with time due to decreasing subduction angle (Stern, 1989; Skewes and Stern, 1995).

With respect to their trace-element compositions, late felsic porphyries in each of the three giant deposits of central Chile have been described as "adakite-like". Adakites are a group of andesitic igneous rocks, first described by R. Kay (1978) from Adakite Island in the Aleutian chain and later from Cook Island (Futa and Stern, 1988; Stern and Kilian, 1996) and Cerro Pampa (Kay *et al.,* 1993) in the southern Andes, which have some unique trace-element characteristics, such as high Sr/Y and La/Yb, when compared to more typical andesites. It has been suggested that adakites form by partial melting of either subducted oceanic crust (R. Kay, 1978; Defant and Drummand, 1990), or the deep or delaminated roots of thickened continental crust (Atherton and Petford, 1993; Kay *et al.,* 1999, 2004; Kay and Mpodozis, 2002), at pressures that are high enough to stabilise garnet rather than plagioclase as a residual aluminous phase, since Y and Yb are compatible trace-elements in garnet, and Sr and La are not.

Even though it is clear, as discussed above, that these "adakite-like" felsic porphyries are not directly related to the enormous amount of Cu-mineralisation in these giant deposits, their presence is of interest because they may imply unique tectonic conditions, such as slab-melting due to decreasing subduction angle (Gutscher *et al.,* 2000; Mungall, 2002) or melting of the deep roots of thickened continental crust (Kay *et al.,* 1999, 2004; Kay and Mpodozis, 2002), during generation of these deposits. However, these "adakite-like" felsic porphyries are not true adakites. They have lower MgO than true adakites, which are actually high-Mg andesites, and most of these porphyries are dacites, rhyodacites and dacites, not andesites. Furthermore, they are certainly not derived by melting of subducted oceanic crust, since these felsic porphyries have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7043 to 0.7047, and $^{143}Nd/^{144}Nd$ ratios ranging from $\varepsilon_{Ndi} = +1.7$ to -0.3, within the range of isotopic compositions of all the other igneous rocks related to these deposits (Fig. 4), but significantly different from oceanic basalts. Richards (2002) and Rabbia *et al.* (2002) have presented similar arguments against the "adakite-like" porphyries found in the Late Eocene to Early Oligocene belt of large copper deposits in northern Chile, for example Chuquicamata, being derived by melting of subducted ocean crust. For the case of central Chile, the model of Gutscher *et al.* (2000) for slab-melting and adakite formation as a result of decreasing subduction angle predicts that a narrow calc-alkaline arc would evolve into a broad adakitic arc. However, the Andean arc south of 33°S has remained both narrow and calc-alkaline despite migrating over 40 km to the east as a result of decreasing subduction angle between the Pliocene and Present (Stern, 1989).

Isotopic data alone do not rule out partial melting or assimilation of mantle-derived mafic rocks in the roots of thickened continental crust in formation of the "adakite-like" felsic porphyries occurring in the two giant deposits of central Chile, but these rocks could not have formed as a result of partial melting or assimilation of lithologically and isotopically heterogeneous lower crust. In northern Chile, where the crust is significantly thicker (>50 km), isotopic signatures for crustal melting and/or assimilation are clear, as shown for Sr and Pb in Fig. 6. However, these crustal isotopic signatures are absent in the "adakite-like" felsic porphyries in the giant Cu deposits in central Chile.

Moreover, it is unsubstantiated that crust below El Teniente, which is located well west of the continental divide, reached a thickness of >35 km by 5.28 Ma when the Teniente Dacite Porphyry intruded. Furthermore, the presence in this deposit of syn- and post-mineralisation mafic and intermediate igneous rock (Fig. 10), with La/Yb similar to older mafic and intermediate rocks (Fig. 9), implies that such rocks continued to be generated in the subarc mantle and rise into the crust before, during and after formation of the "adakite-like" felsic porphyries. The similarity of isotopic composition of these mafic and intermediate rocks with the felsic porphyries (Fig. 4) suggest they all had a common source – subarc mantle contaminated by subducted crustal components – and that neither melting of lithologically and isotopically heterogeneous lower crustal, nor significant intra-crustal assimilation, was involved in genesis of the "adakite-like" porphyries.

Isotopic data for the felsic porphyries in the giant Cu deposits of central Chile are consistent with formation of these porphyries by igneous fractionation processes, without significant intra-crustal assimilation, from more mafic magmas derived from subarc mantle modified by the addition of subducted crustal components. Late-stage igneous fractionation processes that could combine to produce the very small volume of late felsic porphyries from isotopically similar mafic and intermediate magmas crystallising in crustal magma chambers include: i) extensive-crystal liquid fractionation of amphibole (López-Escobar, 1982; Richards *et al.,* 2001; Richards, 2002) and other minor igneous phases; ii) diffusive and/or vapour-phase transport creating chemical gradients within these magma chambers as a result of thermal gradients and roofward migration of volatiles (Hildreth, 1979, 1981; Cloos, 2001); and iii) extensive loss from the roofs of these chambers of the large volumes of aqueous fluids and dissolved solids which produced the biotite ± anhydrite ± tourmaline ± Cu-sulphide ± Fe-oxide hydrothermal breccia matrix and vein-fill minerals in the overlying deposits (Cloos, 2001). Hildreth (1979, 1981) has shown that diffusive and vapour-phase transport enriches magma near the roof of a magma chamber in Y and Yb, and depletes them in Sr and La. Repeated loss of magma from the roof of the magma chamber, due to either exsolution of high-salinity aqueous fluids that formed the large Cu-mineralised breccia pipes in each deposit, and/or direct tapping of volatile-saturated, anhydrite-bearing magmas that formed igneous breccias (Funk *et al.,* 2004), could generate late-stage felsic porphyries depleted in Y and Yb (and Cu) relative to Sr and La.

## Cu-Mineralised Breccia Pipes

Multiple large Cu-mineralised breccia pipes are prominent features in both of the giant Late Miocene and Pliocene deposits in central Chile (Warnaars *et al.,* 1985; Skewes and Stern, 1994, 1995, 1996; Serrano *et al.,* 1996; Vargas *et al.,* 1999; Skewes *et al.,* 2002, 2003, 2005). The Cu-mineralised breccia pipes in these deposits include different types, within which either biotite, anhydrite and/or tourmaline may dominate as the matrix phase. Fluid inclusion studies, and both stable (O and H; Fig. 8) and radiogenic isotopic data (Fig. 5), indicate that these breccia pipes formed by expansion of magmatic fluids exsolved from crystallising magmas, and that minerals in the matrices of these breccias were precipitated from these same magmatic fluids as they cooled (Skewes and Stern, 1996; Skewes *et al.,* 2001, 2003). Igneous or "magmatic" breccias, formed from volatile-saturated silicate melts, some with anhydrite as a primary igneous mineral (Funk *et al.,* 2004), also occur in these deposits. Individual breccia pipes, or complexes of superimposed breccias, have vertical extensions of over 2 km, and in many cases the depths to which their roots penetrate are unknown. Mineralised breccias contain high Cu grades, large amounts of Cu, and a large proportion of the hypogene Cu in these deposits (Skewes and Stern, 1994, 1995; Serrano *et al.,* 1996; Skewes *et al.,* 2002, 2003, 2005).

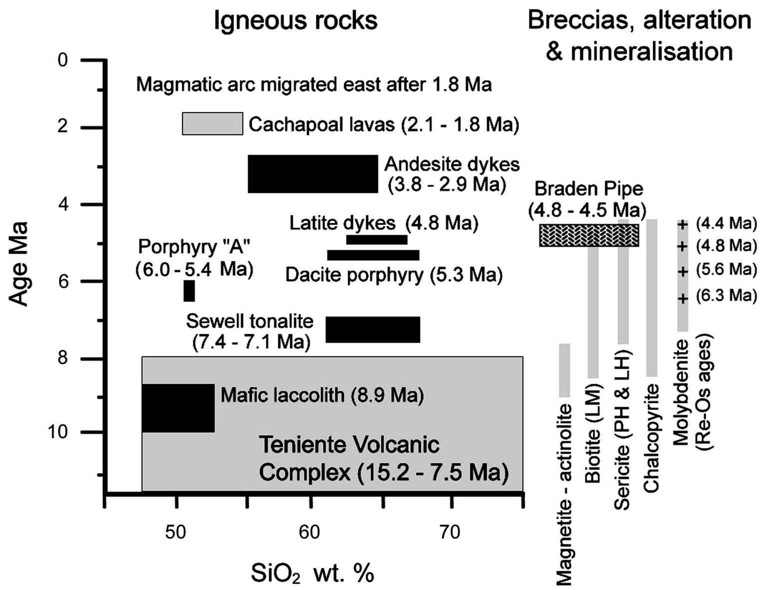


**Figure 10:** ***Age versus silica content for volcanic (shaded fields) and plutonic (black) igneous rocks, from both in the vicinity of and within the El Teniente mine, illustrating the repetitive episodes of formation of mafic igneous rocks associated with the deposit.*** Also shown are the age of the Braden Pipe and occurrences of both alteration assemblages (**LM** = Late Magmatic; **PH** = Principle Hydrothermal; **LH** = Late Hydrothermal) and copper and molybdenum sulphides (modified from Skewes *et al.,* 2004). Ages of igneous rocks determined by a combination of K–Ar (Charrier and Munizaga, 1979; Cuadra, 1986), U–Pb in zircons (Maksaev *et al.,* 2001, 2002), and a fission track in apatite date for a sample of the mafic laccolith outside the mine (K. Thiele, unpublished data). Age of the Braden Pipe determined by K–Ar (Cuadra, 1986) for a sericitised clast, and $^{40}Ar/^{39}Ar$ (Maksaev *et al.,* 2002) in sericite from a clast within the pipe. Estimated time periods for alteration assemblages include both cross-cutting relations as well as both K-Ar and $^{40}Ar/^{39}Ar$ ages for secondary biotites (6.0 to 4.7 Ma; Cuadra, 1986; Maksaev *et al.,* 2001) and sericite (6.4 to 4.4 Ma; Maksaev *et al.,* 2001). Episodes of molybdenite mineralisation (pluses) reflect multiple (>20) Re-Os ages in molybdenite (Maksaev et al., 2002; Munizaga *et al.,* 2002), but are only for molybdenite in felsic rocks and therefore do not date the entire period of Cu mineralisation within the mafic rocks which host 80% of the Cu ore in the deposit. None of these mineralisation episodes correspond to the 5.28 Ma age of the Teniente Dacite Porphyry.

The size, time period of emplacement, and mineralogy of different Cu-mineralised breccia pipes in the giant deposits of central Chile constrain processes of crystallisation and devolatilisation of the underlying magma chambers from which the magmatic fluids that formed these breccias were derived. The fact that their roots have yet to be encountered implies that they formed by exsolution of magmatic fluids from magma chambers that crystallised to form plutons still not exposed at the surface. Geologic field data suggest that these magma chambers were cooling and crystallising at least >4 km below the palaeosurface. This is indicated at El Teniente, for example, by the fact that the largest breccias are rooted >2 km under the current surface, below the deepest exploration drill holes that reach 800 meters lower than the lowest level of mine operations (Skewes *et al.,* 2002, 2005), and because, based on Pliocene to Recent erosion rates of 200 to 300 metres per million year (Skewes and Holmgren, 1993; Kurtz *et al.,* 1997), >1 km of erosion has likely occurred since the last episodes of breccia emplacement and mineralisation at 4.4 Ma (Fig. 10).

Emplacement of intrusive igneous rocks, magmatic-hydrothermal breccias and associated mineralisation at each deposit spanned a time period of >2 million years (Fig. 3). At El Teniente, for example, after emplacement at 8.9 Ma of the mafic laccolith which hosts all younger intrusions, breccias and mineralisation in the deposit, early Cu-mineralised biotite breccias were emplaced, followed by intrusion of the equigranular Sewell tonalite at 7.1 Ma (Fig. 10; Skewes *et al.,* 2002, 2005). Other porphyries and mineralised breccia complexes intruded both the mafic laccolith and Sewell tonalite between 6.5 to 6.0 Ma. The Teniente Dacite Porphyry formed at 5.28 Ma, followed by latite dykes and the Braden breccia pipe at 4.8 to 4.5 Ma. Re-Os age dates place a final mineralising event at 4.4 Ma. This implies a total time period for brecciation and associated mineralisation of >2.7 million years, with all breccias formed during this time period being generated from a magma chamber located at depths below the current deepest level of exposure, mining or explorations drill holes, and thus >4 km below the palaeosurface.

During the multistage development of the giant Cu deposits in central Chile, exsolution of magmatic-hydrothermal fluids from magma chambers created first early Cu- and S-poor actinolite + magnetite breccias, followed by biotite, igneous and anhydrite breccia complexes and associated pervasive biotite veining and alteration and Cu-mineralisation. Subsequently, tourmaline, anhydrite and rock-flour breccias, both mineralised and barren, were emplaced in association with sericitic veining and alteration as well as addition and redistribution of copper mineralisation. Breccia emplacement occurred in conjunction with intrusion of a sequence of igneous rocks that were initially equigranular and later porphyritic. This sequential evolution and telescoping of both plutonic rocks and breccias reflects the fact that these deposits formed during dynamic conditions of crustal uplift and erosion (Skewes and Holmgren, 1993; Stern and Skewes, 1994, 1995).

Significantly, no extrusive rocks formed in the area of the El Teniente deposit between 7.5 and 2.1 Ma, during the time period when Cu-mineralised breccias were being emplaced in this deposit. At Río Blanco-Los Bronces also, the La Copa subvolcanic complex, dated between 4.9 and 3.9 Ma, may reflect renewed volcanic activity above this deposit, but no extrusive rocks formed above this deposit during the main stages of breccia emplacement and mineralisation, which occurred between 7.3 and 5.1 Ma (Serrano *et al.,* 1996). It is clear that formation of these deposits involved a compressive tectonic regime that prevented coeval volcanism, and that they did not form below active volcanoes. The telescoping of different igneous rocks and breccias in these deposits were caused by crustal deformation, uplift and erosion over an extended >2 m.y. period of time (Skewes and Holmgren, 1993), not erosion and collapse of an overlying volcanic edifice (Sillitoe, 1994).

Oyarzún *et al.,* (2001) and Garrido *et al.,* (2002) have pointed out that a compressive tectonic regime is important for formation of the giant deposits in both northern and central Chile, as this prevents volatile loss, particularly loss of $SO_2$, from the magmatic system. However, it is also clear that the magma chambers that exsolved high-salinity aqueous fluids that formed Cu-mineralised breccias in the deposits in central Chile were by no means closed systems. These chambers did in fact lose large amounts of material through the process of devolatilisation and breccia formation, but not through magma extrusion. Magma extrusion allows volatiles such as $SO_2$ to exsolve directly into the atmosphere as magmas approach or erupt to the surface, and thus volcanic activity may decrease the potential for subsequent formation of a giant Cu deposit (Pasteris, 1996; Oyarzún *et al.,* 2001).

# Discussion and Conclusions

The giant Miocene and Pliocene Cu deposits of Los Pelambres, Río Blanco-Los Bronces and El Teniente of central Chile are clearly not typical "porphyry" deposits in a number of ways, including their giant size, which is an order of magnitude larger than such deposits (Fig. 2; Clark, 1993), and the large amount of hypogene Cu ore occurring in and around multiple magmatic-hydrothermal breccia pipes in each deposit (Skewes and Stern, 1995; Serrano *et al.,* 1996; Skewes *et al.,* 2002, 2003, 2005). These deposits are giants because they were formed by multiple events associated with emplacement of large mineralised breccias over an extended period of time (Skewes and Stern, 1995). They are not simply larger versions of smaller, more typical Cu-porphyry deposits, which is why we prefer to refer to them as "breccia" or "megabreccia deposits" (Skewes *et al.,* 2002, 2003, 2005).

Other notable differences with typical "porphyry" deposits include the lack of isotopic evidence for participation of significant quantities of meteoric water in the generation of alteration phases in these deposits (Fig. 8; Skewes *et al.,* 2002, 2003). Instead, stockwork vein minerals at all stages of alteration have isotopic signatures indicating precipitation from magmatic fluids. Specific types of stockwork vein and disseminated alteration (biotitic, sericitic, etc.) are spatially associated with specific types of magmatic-hydrothermal breccias and do not occur in a concentrically zoned system resulting from hydrothermal circulation of meteoric water driven by cooling of a central igneous stock (Hedenquist and Lowenstern, 1994). The multiple breccia pipes formed by exsolution of magmatic fluids from magma chambers crystallising at >4 km below the palaeo-surface. These breccias did not form in subvolcanic systems as has been suggested for smaller, more typical porphyry deposits (Sillitoe, 1994), which may be one reason why meteoric water played a less significant role in their genesis. The lack of coeval volcanic activity during formation of these deposits maintained $SO_2$ and other volatiles in the crystallising magma chambers, but these chambers were not closed systems, since exsolution of volatiles produced the multiple large mineralised breccia pipes which contain the bulk of the Cu in each deposit.

These are among the major first-order features of the giant deposits in central Chile which must be addressed in a model for their origin and in order to evaluate what role subduction of the Juan Fernández Ridge played in their generation. Another feature that must also be accounted for are temporal changes in isotopic and trace-element characteristics of the igneous rocks during the time period when these deposits formed (Figs. 4 and 9).

***Genesis of these Giant Cu-breccia Deposits***

We propose that the giant Miocene and Pliocene Cu deposits in central Chile formed above large, long-lived, open-system magma chambers (Fig. 11), fed from below by mantle-derived mafic magmas, that persisted for the >2 m.y. time period of the multiple episodes of breccia emplacement and mineralisation that formed these deposits. Both the very small volume of late felsic porphyries in each deposit, <<10 km$^3$, and the fact that most Cu-mineralisation occurs in multiple breccias that were emplaced prior to these felsic porphyries, precludes these late, weakly mineralised felsic bodies from being the "productive" plutons in the deposits. In fact, mafic and intermediate igneous rocks are volumetrically more significant than felsic rocks in these deposits (Fig. 9). At El Teniente for example, Late Miocene (8.9 Ma) mafic igneous intrusive rocks host the deposit, and after an episode of intrusion of felsic plutons between 7.1 and 4.8 Ma, mafic and intermediate dykes and lavas were again emplaced in and surrounding the deposit (Fig. 10). This is consistent with the dominantly mafic nature of Andean magmatic activity, which is generated by melting in the mantle wedge above a subducting, dehydrating slab (Hickey *et al.,* 1986, 1989; Futa and Stern, 1988; Hildreth and Moorbath, 1988; Stern *et al.,* 1990; Stern, 1991; Dungan *et al.,* 2001; Kay *et al.,* 2004). Even during the period when felsic plutons intruded the mafic intrusive rocks that host the deposit at El Teniente, volatile-rich mafic magmas continued to be generated in the subarc mantle and rise into the crust, as indicated by intrusion of mafic Porphyry A between 6.6 and 6.0 Ma (Figs. 10 and 11; Skewes *et al.,* 2002, 2005). Other mafic magmas may have mixed with or underplated magmas in deeper parts of the evolving magma chamber below the deposit, rather than reaching the surface. This process of open-system behaviour has been well demonstrated for magma chambers below many active and ancient volcanoes (Sparks *et al.,* 1977; Hildreth, 1981; Pallister *et al.,* 1996).

In general, mafic magmas contain more Cu than felsic magmas, as well as much more S, Fe and Ca, all of which occur in anomalous concentrations in the giant Cu deposits of central Chile. Mafic magmas emplaced into the base of an evolving, open-system magma chamber provide heat to allow this chamber to grow and intrude to higher levels in the crust, and they also supply water and S (Hattori, 1996; Pallister *et al.,* 1996, Kress, 1997; Candela, 1997; Hattori and Keith, 2001), as well as Cu, Fe, Os, Pb and other elements derived from the subarc mantle, to felsic magmas forming near the top of the chamber that otherwise might be poor in S (Nagashima and Katsura, 1973) and chalcophile elements. Evidence for open-system behaviour involving mixing of mafic and felsic magmas during evolution of Andean copper deposits has been presented by Cornejo *et al.,* (1997) and Rowland and Wilkinson (1998).

As volatile-rich mafic mantle-derived magmas replenished the base of these open-system magma chambers, exsolution of metal-rich aqueous brines and vapour from the crystallising upper part of the chambers produced brecciation, veining, alteration and mineralisation of overlying roof rocks (Burnham, 1985; Cloos, 2001). During the sequential, multi-stage development of the giant deposits in central Chile, exsolution of magmatic fluids created first early magnetite ±actinolite breccias and alteration, followed by biotite, igneous and anhydrite breccia complexes and associated pervasive biotite veining and alteration and Cu-mineralisation. Subsequently, tourmaline and anhydrite breccias, both mineralised and barren, formed in association with sericitic alteration. Isotopic data indicate that this change in the nature of alteration effects, from early and/or deep biotite alteration, to later and/or shallower sericitic alteration, apparently did not involve input of significant amounts of meteoric water into the deposit (Fig. 5; Kusakabe *et al.,* 1984, 1990; Skewes *et al.,* 2001, 2003). Although influx of meteoric water has been invoked to explain sericitic alteration in many porphyry deposits (Hedenquist and Lowenstern, 1994), it was not the fundamental cause of this type of alteration in these giant breccia deposits, which formed above magma chambers located at >4 km depth rather than in a subvolcanic environment.

The temporal change from biotitic to sericitic alteration in these two deposits is associated with the appearance of tourmaline rather than biotite breccias (Skewes *et al.,* 2002, 2003, 2005). This shift may have been caused by changes in the depth and nature of the fluids exsolved from the underlying magma chambers during the >2 m.y. period, marked by crustal deformation, uplift and erosion, when breccias formed above these chambers. Early biotite breccias and biotite alteration formed from fluids exsolved from deeper, possibly more mafic magma chambers, during early stages of development of these systems, when saline brines exsolved from magmas under lithostatic conditions, at sufficiently high pressures to prevent either extensive boiling or simultaneous exsolution of an immiscible vapour phase (Cline and Bodnar, 1994). Later tourmaline breccias and sericitic alteration resulted from fluids derived from possibly more felsic magmas formed within the same chambers at a later stage of their development, when they had intruded to shallower levels in the crust. As high pressure lithostatic conditions gave way to later lower pressure hydrostatic conditions, due to a combination of uplift and erosion (Skewes and Holmgren, 1993), and also progressive fracturing in the later stages of development of the deposit, simultaneous exsolution of brine and immiscible vapour phase may have occurred from the same magma chambers that previously had exsolved only brines. This would increase the amount of vapour formed, and the extent of mixing between saline brines and condensed vapours, thereby increasing the potential for sericitic alteration (Skewes *et al.,* 2003).

Input of mantle-derived mafic magma into the base of the long-lived, open-system magma chambers below each deposits diminished, from the Late Miocene to the Pliocene, due to the progressive decrease in subduction angle that ultimately led to the eastward migration of Andean magmatic activity (Stern, 1989; Skewes and Stern, 1994, 1995; Stern and Skewes, 1995, 1997). This caused crystallisation and solidification of these magma chambers. Crustal thickening, uplift and erosion speeded this crystallisation and de-fluidisation process (Skewes and Holmgren, 1993; Skewes and Stern, 1994, 1995). Crystal-liquid fractionation combined with loss of both volatile enriched magmas and aqueous fluids from the roofs of these chambers created small volumes of "adakite-like" felsic porphyry magma that intruded into already biotite-altered and mineralised rocks in each deposit. These felsic magmas were Cu-poor both because they contained less input of Cu from mantle-derived mafic magmas, and because they formed in conjunction with extensive loss of volatile-saturated and metal-rich anhydrite-bearing magmas and aqueous fluids from the roofs of the chambers. These late felsic porphyry dykes and stocks cut and redistributed previously emplaced Cu mineralisation, and generated fractures that focused subsequent supergene enrichment, but were not the main source of Cu in these deposit.

The most significant temporal chemical trends observed among igneous rocks related to these deposits are towards higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios (Figures 3 and 4). These trends are independent of the $SiO_2$ content of the rocks, and are most likely the result of progressively greater contamination of their mantle source by subducted sediments and continental crust. This was due to both increased subduction erosion caused by subduction of the Juan Fernández Ridge and decreasing volume of the subarc mantle wedge as the angle of subduction decreased (Stern, 1989, 1991a, 2001; Stern and Skewes, 1995; Kay *et al.,* 2004). Southwards temporal migration of these changes (Fig. 3) reflects southward migration of the locus of subduction of the ridge (Yáñez *et al.,* 2001, 2002). The La/Yb ratios of the more mafic rocks associated with the El Teniente deposit also increase,

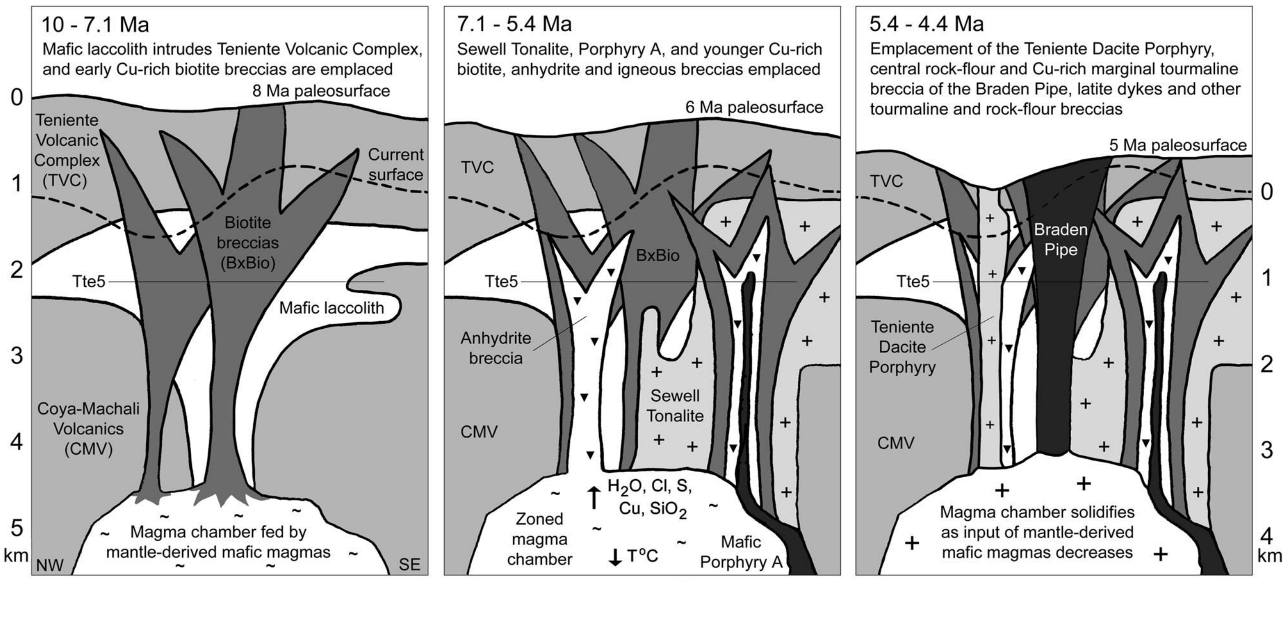


**Figure 11:** ***Model for the multistage development of the El Teniente deposit*** (modified from Skewes *et al.,* 2002, 2005) ***as well as the other giant Miocene and Pliocene Cu megabreccia deposits in central Chile.***

The main features of the model include:

i). a large, long-lived (>2 m.y.), open system magma chamber, which crystallised at approximately >4 km depth, fed from below by mantle-derived mafic magmas and exsolving aqueous fluids through its roof to produce the large breccia pipes that are prominent features in each deposit;

ii). decreasing magma supply in the Late Miocene and Pliocene as the subduction angle decreased, leading to crystallisation and solidification of this chamber;

iii). progressive uplift and erosion that enhanced this crystallisation and solidification process and resulted in telescoping of different types of breccia and igneous rocks; and

iv). progressive igneous differentiation of the magma chamber associated with crystallisation and volatile loss, ultimately generated "adakitic-like" felsic porphyries that intruded previously mineralised rocks above the chamber. No coeval volcanism occurred during mineralisation, but once the chamber solidified, post-mineralisation dyke and lavas were emplaced. The depth of the magmatic system precluded significant interaction with meteoric waters, and the deposits are not zoned around the magma chamber, but consist of numerous individual mineralised breccia pipes and veins and alteration zones that each breccia created.

but only approximately two-fold, from ≤5 in the Early Miocene Coya-Machalí volcanic rocks, to ≤7 in the Late Miocene mafic rocks that host the deposit, to ≈10 for the Pliocene post-mineralisation olivine-basalt mafic dykes and basaltic andesite lava flows in the Cachapoal River valley (Fig. 9). This change may reflect a decrease in degree of mantle partial melting as subduction angle decreased prior to eastward arc migration (Stern, 1989; Stern and Skewes, 1995). It is clearly independent of crustal thickness since these mafic rocks form in the mantle, not the crust.

### *Role of Ridge Subduction*

Subduction of the Juan Fernández Ridge played an important role in the formation of the giant Miocene and Pliocene deposits in central Chile. Ridge subduction resulted in decreasing subduction angle, which in turn caused crustal deformation, uplift and erosion. Ridge subduction and decreasing subduction angle together increased the rate of subduction erosion of the continental margin and the tectonic transport of continental components and Cl-rich seawater into the subarc mantle (Stern, 1989, 1991). Both decreasing subduction angle and increasing crustal thickness decreased the volume of the subarc mantle wedge and thereby also increased the significance of contamination of the mantle by subducted components. Together these effects caused the isotopic changes in igneous rocks at the latitude of each deposit. Decreasing the volume of the subarc mantle wedge also caused a decrease in degree of mantle melting and input of mantle-derived mafic magmas into the bottoms of the large, long-lived open-system magma chambers above which the giant deposits formed. This ultimately led to their solidification. Crustal thickening, uplift and erosion speeded this crystallisation and devolatilisation process, and has continued to erode the deposits to their current level of exposure. However, neither slab-melting as a result of decreasing subduction angle, nor the melting or dehydration of the lithologically and isotopically heterogeneous deep roots of thickened continental crust, played any significant role in the formation of these deposits.

### *Why the Deposits are Giant*

Clark (1993) suggested special litho-tectonic conditions might influence the formation of unusually large Cu deposits, proposing that such deposits in the Andes might "owe their origin to an unusually protracted (+200 m.y.)" subduction-related magmatic history, producing a Cu-rich zone "in the lowermost crust or lithospheric upper mantle" that could periodically produce the magmas associated with giant deposits. We suggest instead that the special litho-tectonic conditions that generated these deposits involved protracted magmatism, but only on the order of at least +2.5 m.y., not +200 m.y. as suggested by Clark (1993). Magmas involved in the generation of these deposits were typical Andean basalts and their more felsic differentiation products. They may have been highly oxidised (Garrido *et al.,* 2002; Funk *et al.,* 2004), but there is no evidence that they were exceptionally enriched in Cu or S. However, compression prevented their extrusion, allowing development of long-lived, open-system magma chambers in which highly saline, $SO_2$ and metal-rich aqueous fluids were concentrated at the tops of the chambers due to thermal gradients. Magma extrusion, in contrast, allows volatiles such as $H_2O$ and $SO_2$ to exsolve directly into the atmosphere as magmas approach or erupt to the surface, and thus volcanic activity may decrease the potential for subsequent formation of a giant Cu deposit (Pasteris, 1996). Exsolution of these $SO_2$ and metal-rich fluids only through the process of devolatilisation which generated multiple mineralised breccia pipes over a >2.5 m.y. period, but not in association with magma extrusion, is what produced these anomalously large deposits, not an unusually oxidised, S or Cu-rich magma produced by melting of either the subducted slab (Gutscher *et al.,* 2000; Mungall, 2002) nor the thickened roots of lower crust (Kay *et al.,* 1999; Kay and Mpodozis, 2002).

What focused magmatism and mineralisation in such specific areas over a > 2.5 m.y. period of time remains a fundamental question in understanding why giant deposits develop in some locations in the Andes, but most plutons in the extensive Andean batholiths are barren. We suggest three inter-related possibilities for genesis of these world-class Cu systems. First, important N-S, NE-SW and NW-SE crustal structures intersect at these deposits. In the active southern Andean arc, the largest long-lived (>1 million years) magmatic systems, producing giant, >10 km in diameter calderas, such as Maipo caldera at 34°S (Stern *et al.,* 1984b), Calabozos caldera at 36°S (Hildreth *et al.,* 1984), Copahue caldera at 38°S (Muñoz and Stern, 1988), and Puyehue caldera at 40°S (Gerlach *et al.,* 1988), also occur where the generally N-S trending Andean arc is intersected by NW-SE arc segments (see Figs. 1 and 2 in Muñoz and Stern, 1988). Alternatively, focusing of magmatic activity and mineralisation may reflect segmentation of the subducted slab. The Los Pelambres and El Teniente deposits, for example, occur on the northern and southern boundary respectively of the segment of the Nazca plate that has ruptured to produce large earthquakes in central Chile every 83 ± 9 years for the last 500 years (Comte *et al.,* 1986), and the Río Blanco-Los Bronces deposit occurs on the boundary between the Flat-Slab and Southern Volcanic Zones segments of the Andes (Fig. 1). A third possibility is long-term focusing of magmatic activity may result from rheological contrasts between areas below each deposit and intervening areas, due to diapiric rise of magmas, either within the crust (Damon, 1986; Yáñez and Maksaev, 1994), or as deep as the subducted slab (Marsh, 1979).

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