THE EL TENIENTE MEGABRECCIA DEPOSIT, THE WORLD'S LARGEST COPPER DEPOSIT

[1]M. Alexandra Skewes, [2]Alejandra Arévalo, [2]Ricardo Floody, [2]Patricio H. Zuñiga and [1]Charles R. Stern

[1]*Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0399 U.S.A.*
[2]*Superintendencia Geología, El Teniente, CODELCO-CHILE, Rancagua, Chile*

Abstract - El Teniente, located in the Andes of central Chile, is the world's largest known Cu-Mo deposit with estimated resources of >75x10^6 metric tonnes of fine Cu in ore with grades greater than 0.67%. Most of the high-grade hypogene Cu at El Teniente occurs in and surrounding multiple magmatic-hydrothermal breccia pipes. Mineralized breccia complexes, with Cu contents >1%, have vertical extents of >1.5 km, and their roots are as yet unknown. These breccias are hosted in a pervasively biotite-altered and mineralized mafic intrusive complex composed of gabbros, diabases, and porhyritic basalts and basaltic andesites. The multiple breccias in El Teniente include Cu and sulfide-rich biotite, igneous, tourmaline and anhydrite breccias, and also magnetite and rock-flour breccias. Biotite breccias are surrounded by a dense stockwork of biotite-dominated veins which have produced pervasive biotite alteration, and Cu mineralization characterized by chalcopyrite >> bornite + pyrite. Later veins, with various proportions of quartz, anhydrite, sericite, chlorite, tourmaline, feldspars and Cu and Mo sulfide minerals, formed in association with emplacement of younger breccias and felsic porphyry intrusions. These generated sericitic alteration in the upper levels of the deposit, and in some cases contributed more Cu, but in other cases eliminated or redistributed pre-existing mineralization. Both the Teniente Dacite Porphyry and the central rock-flour Braden Pipe breccia, the dominant litho-structural unit in the deposit, are Cu-poor. Their emplacement at a late stage in the development of the deposit created a relatively barren core, surrounded by a thin (~150 m) zone of bornite > chalcopyrite, in the larger main area of chalcopyrite-rich, biotite-altered mafic rocks and mineralized breccias. The small Teniente Dacite Porphyry is not the "productive" pluton responsible for the enormous amount of Cu in the deposit. Instead, the deposition of the large amount of high grade Cu, and other key features of the deposit such as the barren core, are the result of the emplacement of multiple breccias generated by exsolution of magmatic fluids from a large, long-lived, open-system magma chamber cooling and crystallizing at >4 km depth below the paloesurface. It is for this reason that genetically El Teniente, like other giant Miocene and Pliocene Cu deposits in central Chile, is best considered a megabreccia deposit. The multistage emplacement of breccias, alteration and Cu mineralization at El Teniente spanned a time period of >2 million years, between >7.1 and 4.4 Ma. This occurred at the end of a >10 million year episode of Miocene and Pliocene magmatic activity, just prior to the eastward migration of the Andean magmatic arc as a consequence of decreasing subduction angle due to the subduction of the Juan Fernández Ridge below central Chile. Ridge subduction and decreasing subduction angle also caused crustal thickening, uplift and erosion, resulting in telescoping of the various breccias and felsic intrusions in the deposit. El Teniente is located at the intersection of major Andean structures, which focused magmatic activity and mineralization at this one locality for an extended period of time.

Introduction

El Teniente, located in the Andes of central Chile, 70 km southeast of Santiago (Figure 1), is the world's largest known copper-molybdenum deposits. It originally contained an estimated total copper content of >93x10^6 metric tonnes, of which 18x10^6 tonnes have already been extracted, leaving current resources of >75x10^6 tonnes of copper (Figure 2) in ore with grades greater than 0.67%, and >1.4x10^6 tonnes of fine molybdenum in ore with grades greater than 0.019%. El Teniente, known between 1904 and 1967 as the Braden deposit, is exploited by the world's biggest underground mine, which encompasses an area of approximately 4 km^2 and has a vertical extent of >1,000 m, between 1,983 m (level Teniente 8) and 3,137 m (level Teniente J) above sea level. Copper ore in the deposit occurs over an area of at least 2.7 km by 2 km, and has a known vertical extent of >2,000 m, from between the surface at 3,200 m down to the deepest point intersected by drill holes at 1,200 m above sea level, 800 m below the current lowest level of mine operations. The actual depth to which copper mineralization extends is unknown!

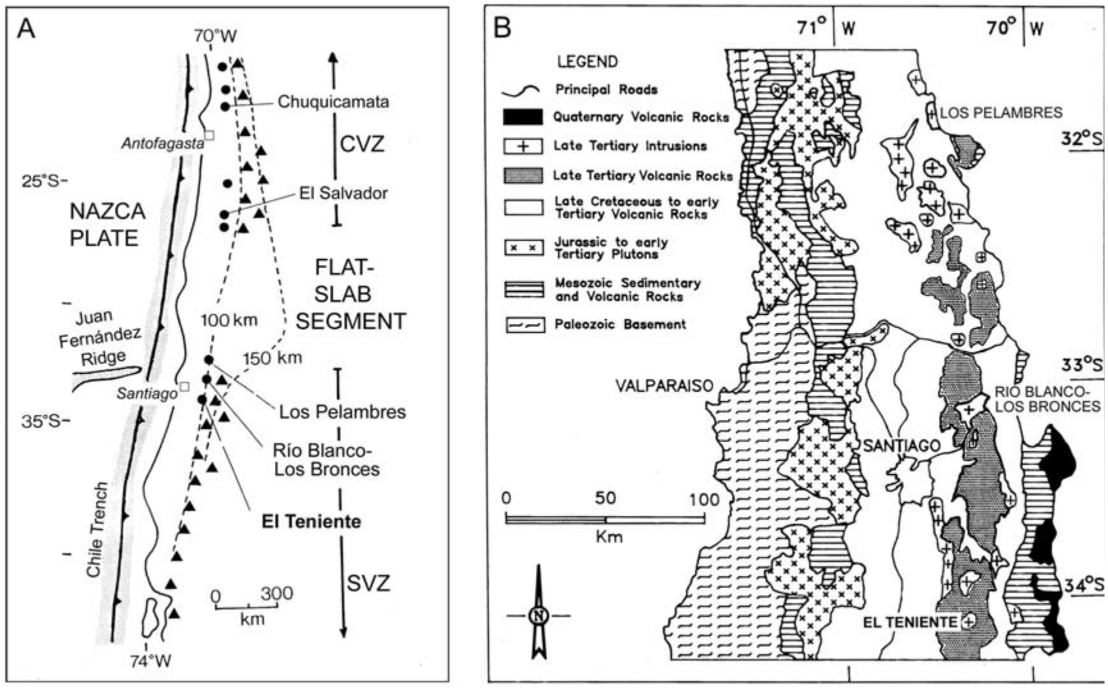


Figure 1. Location maps of the three giant late Miocene and Pliocene copper deposits – Los Pelambres, Río Blanco-Los Bronces and El Teniente – in the Andes of central Chile, east of Santiago. A) Tectonic features such as the position of the Chile trench, which is the boundary between the Nazca and South American plates, and the depth in kilometers (100 and 150 km) to the Benioff zone of seismic activity below South America. A significant change in subduction angle, from very shallow below the Flat-Slab segment, to a steeper dip below the Andean Southern Volcanic Zone (SVZ) of active volcanoes (triangles), takes place at the latitude of Santiago (33°S), where the Juan Fernández Ridge is presently being subducted (Yáñez et al., 2001, 2002). B) Simplified regional geology of central Chile (Serrano et al., 1996). In this schematic map, both the Coya-Machalí and Farallones Formation are included in the belt of Tertiary volcanic rocks.

Lindgren and Bastin (1922) recognized that this deposit formed by multiple hydrothermal events associated with a sequence of igneous intrusions. Howell and Molloy (1960), Camus (1975) and Cuadra (1986) described El Teniente as a porphyry copper deposit formed around the Pliocene El Teniente Dacite Porphyry dike, with 80% of its copper mineralization hosted in Miocene andesitic extrusive rocks. During the last decade, however, regional mapping (Figure 3; Morel and Spröhnle, 1992; Floody and Huete, 1998), and mapping in extensive new underground mine workings in the deeper hypogene zone (Figure 4), along with petrological studies, have together provided new information about the host rocks (Skewes and Arévalo, 2000), hypogene ore distribution (Figure 5; Arévalo et al., 1998), and history of ore emplacement at El Teniente. These new results indicate that El Teniente is best described as a megabreccia deposit (Skewes et al., 2002), within which most high-grade hypogene copper occurs in and surrounding multiple magmatic-hydrothermal breccia pipes emplaced in a mafic intrusive complex composed of gabbros, diabases, and porphyritic basalts, and not andesite extrusives.

The copper-poor rock-flour breccia of the Braden Pipe, the central litho-structural unit in the deposit (Figures 3-5; Floody, 2000), and the Teniente Dacite Porphyry, both cut pre-existing copper mineralization originally deposited in and surrounding multiple breccia pipes in the mafic complex. These two copper-poor bodies, both emplaced at a late stage, have obscured the role of the earlier copper-rich breccias in the generation of the deposit. Although intrusion of the Teniente Dacite Porphyry, and subsequent supergene enrichment effects, concentrated previously emplaced mineralization along the margins of this small, late, copper-poor stock, this porphyry was not the source of the enormous amount of copper in the deposit. The intrusion of the dacite porphyry at 5.28 Ma, as determined by a U-Pb in zircon crystallization age, 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 a significant mineralization event, as indicated by the fact that not a single one among >20 Re-Os ages for molybdenite mineralization in the

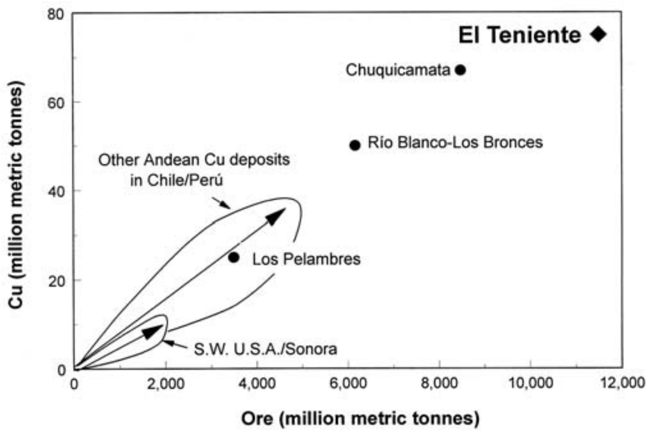


Figure 2. Size, measured in millions of metric tonnes of fine copper, versus millions of metric tonnes of ore, for estimated reserves in the three giant late Miocene to Pliocene copper deposits of central Chile, compared to another giant Chilean copper deposit, Chuquicamata, and the ranges of smaller deposits in both the Andes and the western U.S.A. The values for Los Pelambres include the Pachón deposit, which is part of the same deposit in Argentina (Atkinson et al., 1996). Figure modified after Clark (1993).

deposit correspond, within ±300,000 years, to the age of the intrusion of this porphyry (Maksaev et al., 2002; Munizaga et al., 2002). Also, where this dacite porphyry outcrops north of the Teniente River (Figure 3), the extrusive rocks it intrudes are altered, but not mineralized (Floody and Huete, 1998).

General background

Baros (1996) has compiled a detailed history of the development of the El Teniente mine. In 1904, William Braden bought the property and formed the Braden Copper Company, which in 1915 was acquired by Kennecott Corporation. The Braden Copper Company installed a 250-ton per day concentrator in 1906, and by 1960 the Kennecott Company was producing 34,000 tons of ore per day. Since 1967, El Teniente has been owned by the people of Chile and run by the Corporación Nacional del Cobre de Chile (CODELCO-CHILE). The mine currently produces 98,000 metric tonnes of ore a day, with an average grade of 1.2% copper and 0.026% molybdenum, and planned expansion of the mine over the next decade will further increase production. Information concerning many aspects of the operation of the mine can be found on the CODELCO-CHILE website **www.codelco.com**.

Lindgren and Bastin (1922) presented the first comprehensive geologic description of the deposit. They described El Teniente as a copper deposit hosted in a sill, formed by andesite porphyry and quartz diorite, which intruded into a thick pile of volcanic rocks. They identified "a record of alternating igneous activity and ore deposition, which affords convincing evidence of the intimate genetic connection between igneous rocks and ore deposits." Lindgren and Bastin (1922) considered El Teniente, along with Río Blanco-Los Bronces in central Chile (Figure 1), to belong to a distinct type of Andean copper deposit dominated by tourmaline and chalcopyrite, along with pyrite and quartz. Lindgren (1933) noted that this type of tourmaline-copper deposit was associated with mafic rocks, including gabbros, diabases and diorites. Lindgren and Bastin (1922) distinguished these deposits from a second type, which includes Chuquicamata in northern Chile (Figure 1A), dominated by enargite, also along with pyrite and quartz.

Howell and Molloy (1960) described El Teniente as "a model porphyry copper deposit" with "a circular configuration of alteration" and mineralization "arrayed concentrically around a common center." They suggested that mineralization in El Teniente was emplaced around the barren core of the Teniente Dacite Porphyry intrusion within the extrusive rocks of the Farellones Formation, and not in a sill as described by Lindgren and Bastin (1922). Camus (1975) summarized wall rock alteration and sulfide mineral distribution in the deposit, and also concluded that the Teniente Dacite Porphyry intrusion is directly associated with the main period of mineralization and alteration. Ojeda et al. (1980) identified four stages of alteration and hypogene ore emplacement, which they termed Tardimagmática (Late Magmatic), Hidrotermal Principal (Principal Hydrothermal), Hidrotermal Tardía (Late Hydrothermal), and Póstuma. Zuñiga (1982) detailed different vein types associated with these stages of alteration.

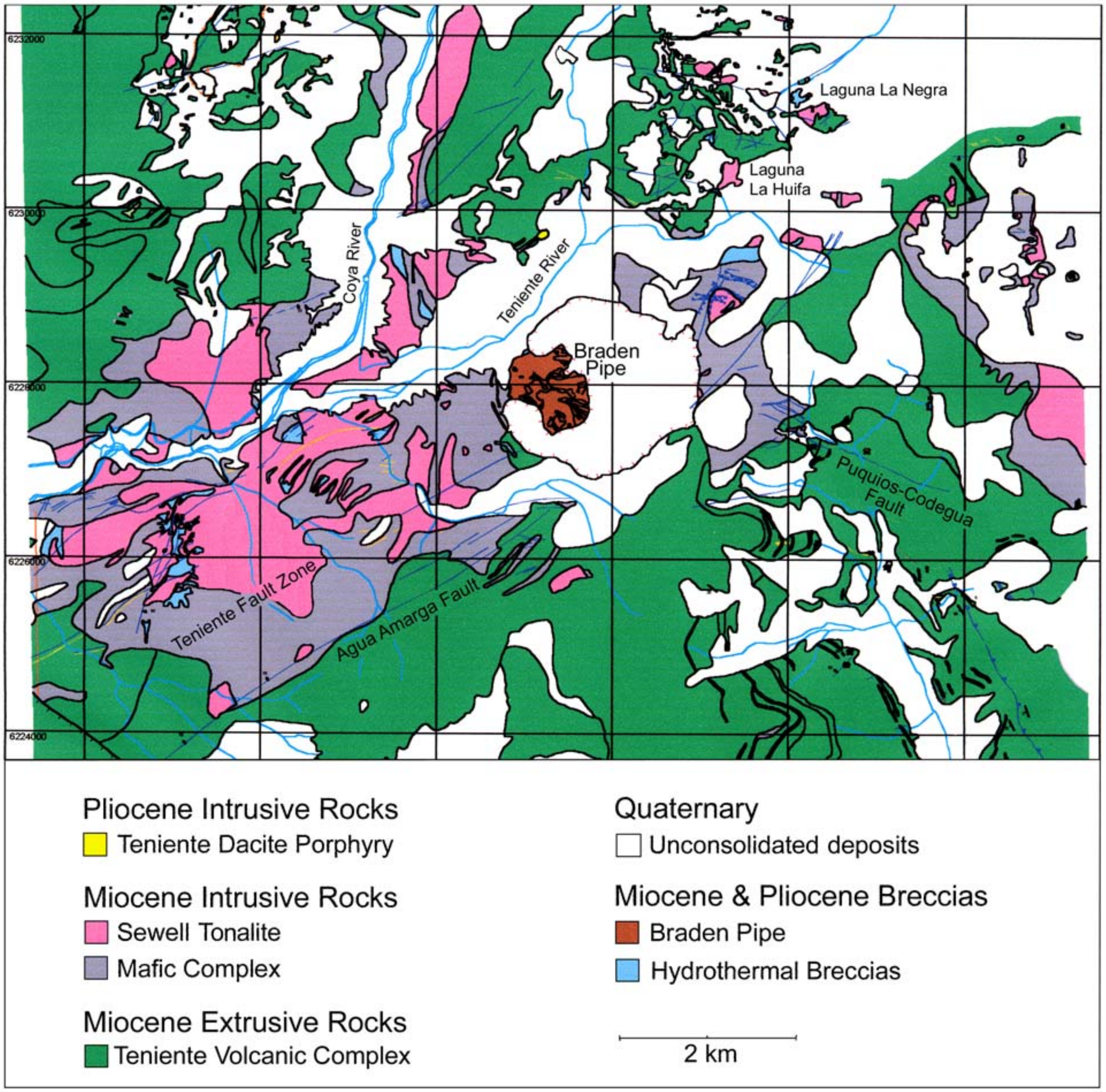


Figure 3. Geologic map of the area surrounding El Teniente copper deposit (Morel and Spröhnle, 1992). The Braden Pipe occurs close to the intersection of the NE-SW-trending Teniente fault zone, which is located between the Teniente River and Agua Amarga fault, and the NW-SE-trending Puquios/Codegua fault.

Cuadra (1986) presented a basic chronology of the development of the deposit based on K-Ar dates of extrusive and intrusive igneous rocks, breccias and alteration events in and surrounding the El Teniente mine. He concluded that Miocene extrusive rocks in the vicinity of El Teniente range in age from 14 to 8 Ma, and felsic intrusive rocks within the deposit from 7.4 to 4.6 Ma. He dated latite ring-dikes surrounding the Braden Pipe between 5.3 to 4.8 Ma, and the Teniente Dacite Porphyry between 4.7 to 4.6 Ma. Both of these units predate the emplacement of the Braden Pipe, which he dated as between 4.7 to 4.5 Ma. He dated two post-mineralization hornblende andesite dikes, the youngest igneous rocks within the deposit, as 3.8 to 2.9 Ma. Charrier and Munizaga (1979) dated basaltic andesite lava flows in the Cachapoal River valley, just outside the area of the mine, as 2.3 to 1.8 Ma.

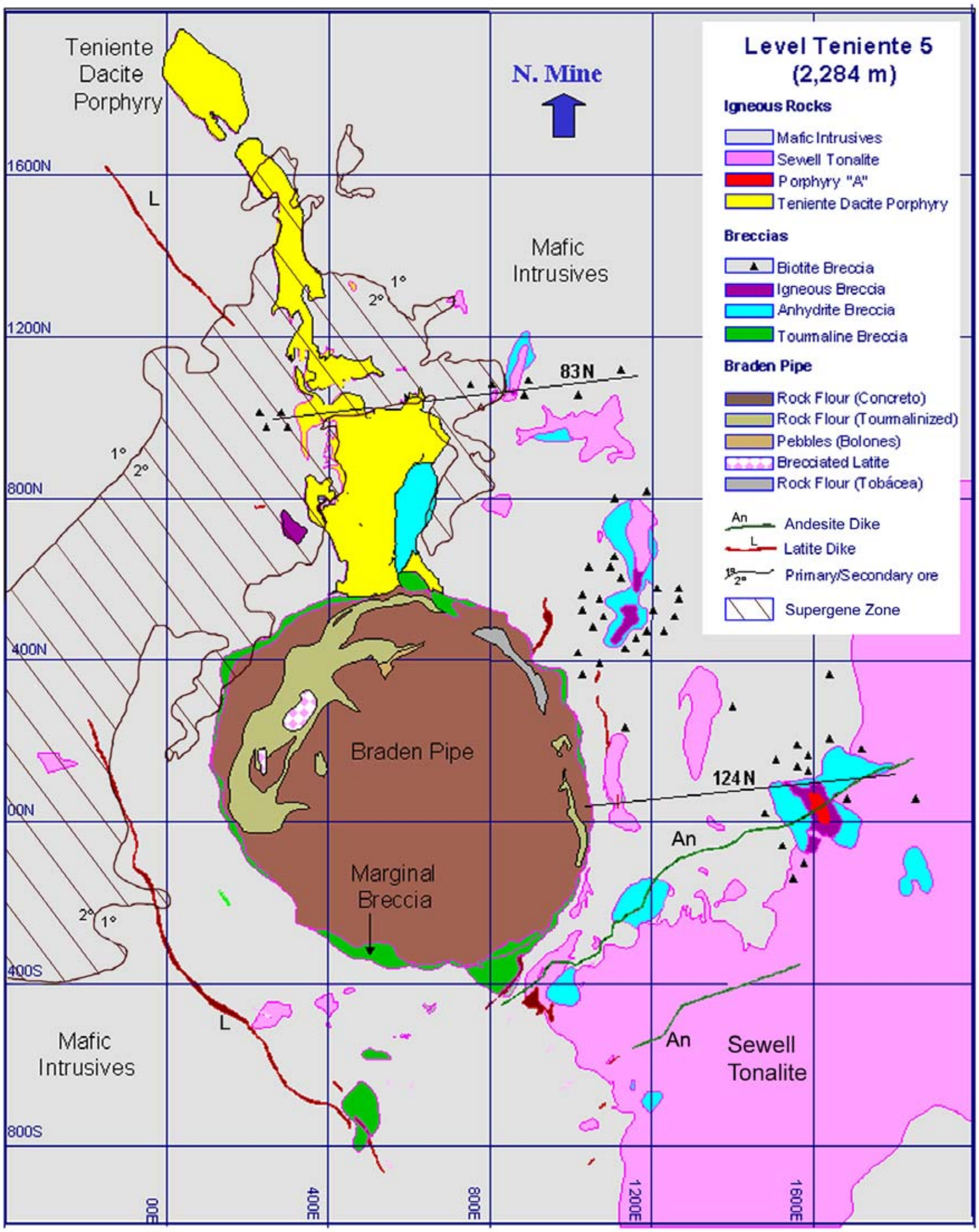


Figure 4. Geologic map of level Teniente 5 (2,284 m above sea level) in the mine. Apophyses of porphyritic tonalite north of the Sewell Tonalite are mapped as distal parts of this pluton, although they are younger and have an independent origin (Guzmán, 1991; Maksaev et al., 2002). Spatial extent of biotite breccias are projected onto this level from where they have been recognized between levels Teniente 4 and 8 in sections 124N and 83N, and also section 111N northeast of the Braden Pipe. Their full extent elsewhere in the deposit is as yet undetermined, and is likely to be much more extensive than shown as indicated by the spatial extent of pervasive biotite alteration. Area of secondary supergene alteration and mineralization runs below the Teniente River valley (Figure 3).

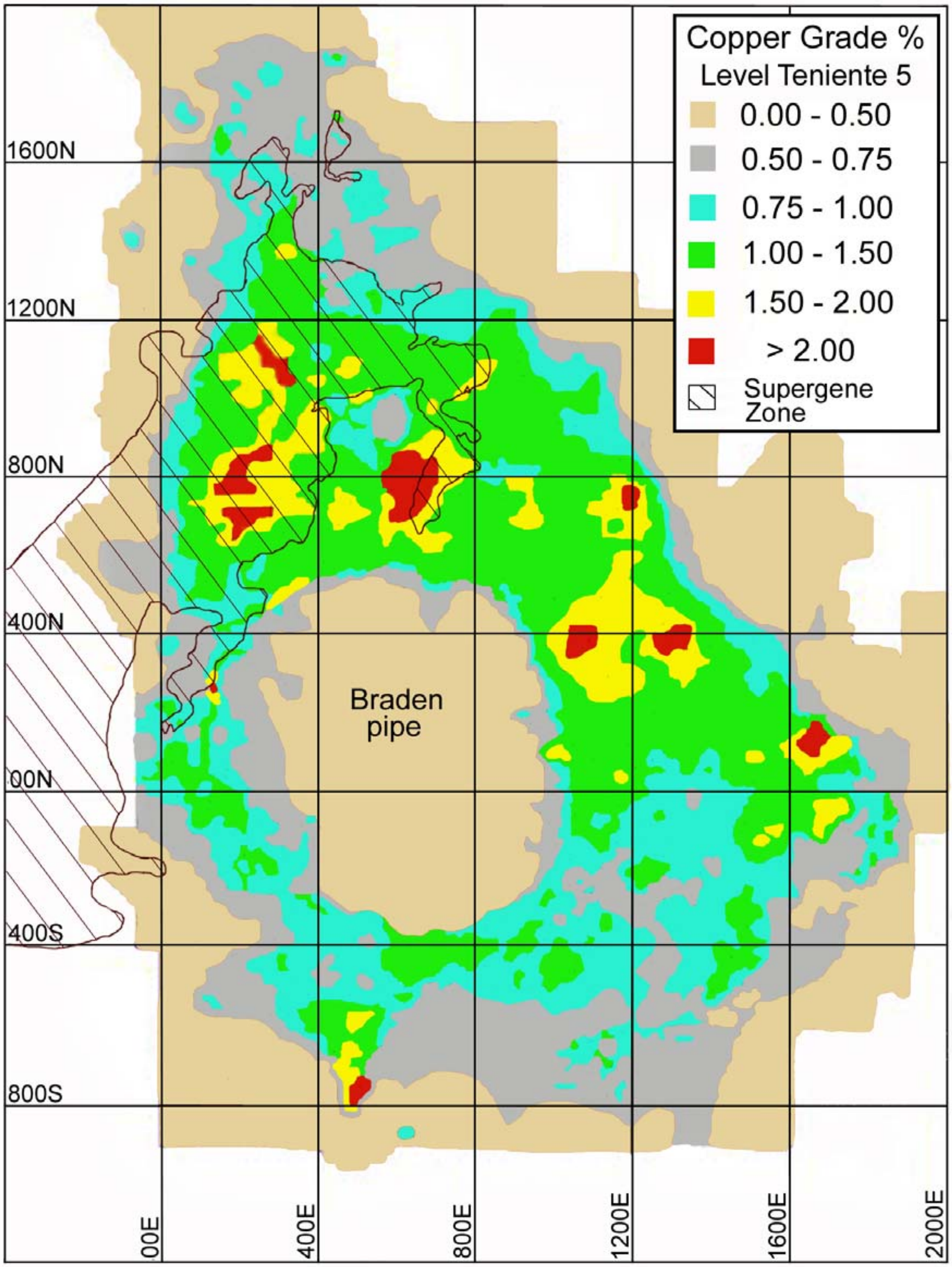


Figure 5. Copper grades between levels Teniente 4 and 5 in the El Teniente mine (Arévalo et al., 1998). Copper grades surrounding the Teniente Dacite Porphyry, north of the Braden Pipe, are enhanced by supergene enrichment effects that penetrate below level Teniente 5 in this area of the mine. Grades in the central rock-flour breccia of the Braden Pipe are generally <0.5%, but 0.75 to >1.5% in the tourmaline-rich Marginal Breccia of this pipe. Areas of high grade copper east and northeast of the pipe are totally within the hypogene zone and correspond to the location of multiple breccias (Figure 4).

Skewes et al. (2002) presented an updated description and interpretation of the genesis of the deposit based on results from numerous new studies conducted during the last fifteen years. They argue that El Teniente is a megabreccia deposit, and discuss the similarities between this deposit and the other giant Miocene and Pliocene deposits in the Andes of central Chile (Figure 1) -- Los Pelambres (32°S; >25x10^6 metric tonnes of copper; Atkinson et al., 1996) and Río Blanco-Los Bronces (33°S; >50x10^6 metric tonnes of copper; Warnaars et al., 1985; Serrano et al., 1996) -- which are among the youngest and largest (Figure 2) copper deposits in the Andes. These are all copper-, sulfur-, iron-, calcium-, molybdenum- and boron-rich, but gold-poor deposits that share important features such as their large tonnage and high hypogene copper grade, and the fact that most of their copper mineralization occurs as primary ore. Supergene processes have enhanced copper concentrations in these three deposits, but not to the same extent as in Chuquicamata and other deposits in northern Chile.

A distinctive feature of each of these three deposits is the presence of large magmatic-hydrothermal breccias, both mineralized and unmineralized (Skewes and Stern, 1994, 1995). As noted by Howell and Molloy (1960), "On the west coast of South America, the study of porphyry copper deposits seems to be almost synonymous with the study of breccia pipes." In El Teniente, the enormous Braden Pipe has a known vertical extent of >2,100 m, with a diameter at the current surface of approximately 1,200 m (Figures 3 and 4; Floody, 2000), and possibly as much as 1,000 m has been eroded off the upper part of the pipe since it was emplaced (Skewes and Holmgren, 1993; Kurtz et al., 1997). It is >650 m in diameter at its deepest documented level, 800 m below the current mine. Although this is the largest and most prominent, it is only one among a number of magmatic-hydothermal breccias at El Teniente (Figure 4; Skewes et al., 2002). The multiple breccias in each of the three giant deposits in central Chile include copper- and sulfide-poor magnetite-actinolite breccias, copper- and sufide-rich biotite, igneous, tourmaline and anhydrite breccias, and rock-flour breccias. The genesis of these magmatic-hydrothermal breccias has been attributed to the exsolution of aqueous magmatic fluids from cooling plutons (Warnaars et al., 1985; Skewes and Stern, 1994, 1995, 1996; Vargas et al., 1999; Skewes et al., 2001, 2002, 2003). In each of the three deposits, the multiple breccias are emplaced within extrusive and intrusive rocks of the Miocene Farellones Formation. The youngest late Miocene and Pliocene felsic intrusions in each deposit are weakly mineralized dacite porphyries, the emplacement of which has redistributed, both cutting and concentrating, pre-existing copper mineralization.

The igneous rocks in these and other Andean copper deposits, and by implication the deposits themselves, have been generated by processes associated with the subduction of oceanic lithosphere below the South American continental margin (Sillitoe, 1988). The three deposits in central Chile occur across the boundary between two major Andean tectonic segments (Figure 1A): the Flat-Slab segment to the north, below which the angle of subduction has decreased significantly since the Miocene and where volcanism is now absent, and the Southern Volcanic Zone (SVZ), below which the subduction angle is steeper and volcanism is active. The formation of these three deposits is closely associated in time with the changing geometry of subduction that has produced this segmentation of the Andes (Stern, 1989; Skewes and Stern, 1994, 1995; Stern and Skewes, 1995, 1997; Garrido et al., 2002). As with the older copper deposits in northern Chile, such as Chuquicamata and El Salvador (Figure 1A), copper mineralization was emplaced during a relatively restricted time interval (2 to 3 million years), at the end of a more extended period of magmatic activity (>10 million years), just prior to the eastward migration of the locus of the Andean volcanic arc (Maksaev and Zentilli, 1988; Skewes and Stern, 1994, 1995; Cornejo et al., 1997).

Eastward migration of the magmatic arc occurred in central Chile during the late Miocene and Pliocene, as the angle of subduction decreased due to the subduction of the Juan Fernández Ridge below the South American continent (Stern, 1989; Stern and Skewes, 1995, 1997; Kay et al., 1999; Kay and Mpodozis, 2002). The age of the youngest igneous activity in the vicinity of each deposit, which was approximately 6 Ma for Los Pelambres, 3.9 Ma for Río Blanco-Los Bronces, and 1.8 Ma for El Teniente, decreases southwards (Figure 6), reflecting the southward sweep of the locus of subduction of the Juan Fernández Ridge (Yáñez et al., 2001, 2002). As the locus of subduction of the Juan Fernández Ridge migrated south and the angle of subduction decreased below central Chile, both the rate of subduction erosion of the continental margin, and consequently the extent of contamination with crustal components of the mantle source region of Andean arc magmas, increased, as indicated by the progressive temporal increase in $^{87}Sr/^{86}Sr$ ratios of these magmas (Figure 6; Stern and Skewes, 1995). Subduction, into the mantle source region of Andean magmas, of oceanic crust, pelagic and terrigenous sediments, and continental crust tectonically eroded off the edge of the continent, may provide the large amounts of water, sulfur, copper, chlorine and boron involved in the generation of the giant copper deposits of central Chile (Stern, 1989, 1991; Macfarlane, 1999; Garrido et al., 2002).

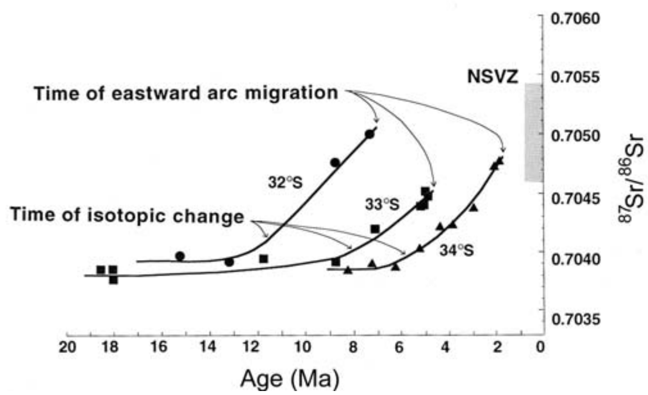


Figure 6. Figure, modified from Stern and Skewes (1995, 1997), showing the $^{87}Sr/^{86}Sr$ ratios of igneous rocks, versus their age, at the latitudes of the three giant deposits in central Chile (32°S – Los Pelambres (circles); 33°S - Río Blanco-Los Bronce (squares); 34°S - El Teniente (triangles); NSVZ for active volcanoes between 33-34°S). The figure illustrates the diachronous southward decrease in the time, at each latitude, of 1) increases in $^{87}Sr/^{86}Sr$ of igneous rocks, and 2) eastward migration of the magmatic arc. Both these changes reflect the southward migration of the locus of subduction of the Juan Fernández Ridge.

As subduction angle below central Chile decreased, beginning in the middle Miocene, the crust was deformed and thickened (Jordan et al., 1983; Godoy et al., 1999), and uplifted and eroded (Skewes and Holmgren, 1993; Kurtz et al., 1997). Recent estimates of the regional rates of erosion from down-cutting of rivers (Charrier and Munizaga, 1979; Stern et al., 1984), fluid inclusion analyses (Skewes and Holmgren, 1993), and $^{40}Ar/^{39}Ar$ mineral dating of exhumed plutons (Kurtz et al., 1997), range from 150 to 300 m per million years over the last approximately 15 million years. These erosion rates are an order of magnitude higher that the 30 m per million years estimated by Camus (1975). Uplift and erosion has exposed different levels of each deposit. Los Pelambres, the more northern and oldest of the three deposits, which is located on the drainage divide of the High Andes (Figure 1B), is most deeply eroded. El Teniente, the more southern and youngest of the three deposits, located well west of the Andean drainage divide, is the least eroded. The differences in the sizes of these three deposits (Figure 2) have been attributed in part to differences in the extent of erosion (Skewes and Stern, 1995).

Kinematic analysis of Neogene faults in central and southern Chile (Lavenu and Cembrano, 1999), and specifically in the area of El Teniente (Garrido et al., 1994, 2002), indicates maximum shortening oriented N94°±9E, consistent with the direction of convergence of the Nazca plate with the South American plate at approximately N82°±4E (Pardo-Casas and Molnar, 1987). Godoy et al. (1999) have suggested that rocks of the Farellones Formation that host the El Teniente deposit were uplifted and transported eastward along a low-angle thrust fault between 9 and 3.5 Ma. According to Garrido et al. (1994, 2002), the deposit is emplaced within the El Teniente fault zone, which consists of anastomosing strike-slip faults, trending N65°E, within a 14-km-long and 3-km-wide block located between the Coya and Teniente River valleys on the north and the Agua Amarga fault on the south (Figure 3). In the mine, a group of tourmaline and anhydrite breccia complexes south and east of the Braden Pipe are aligned along this trend, and intruded by post-mineralization andesite dikes with the same NE-SW strike (Figure 4). They also recognized regional N48°±11W magnetic lineaments, possibly related to older Paleozoic and Mesozoic basement structures, and strike-slip fault structures, such as the Puquios (Morel and Spröhnle, 1992) and/or Codegua fault (Rivera and Falcón, 1998), which intersect the El Teniente fault zone in the vicinity of the central Braden Pipe (Figure 3; Garrido et al., 1994). In the mine a group of breccia complexes located east and northeast of the Braden Pipe (Figure 4), each intruded by small felsic porphyry apophyses, lie along or close to the NW-SE-trending Puquios/Codegua fault. Finally, regionally significant N-S structures may also have played a role in controlling the emplacement of the N-S-striking part of the Teniente Dacite Porphyry and a N-S zone of tourmalization within the Braden Pipe (Floody, 2000). Generally subvertical faults in all three of these directions (NE-SW, NW-SE, and N-S) were active before, during and after the formation of the deposit (Garrido et al., 1994). Inside the area of the mine, the emplacement of the Braden Pipe also exerted an important local structural control, resulting in both radial and concentric stockworks of hydrothermal veins, latite ring-dikes and pebble-dikes.

Igneous host rocks

El Teniente is located in middle to late Miocene extrusive and intrusive igneous rocks, which are part of the Farellones Formation (Figure 3). Extrusive rocks of the Farellones Formation overlie older continental igneous rocks of the Oligocene to early Miocene Coya-Machalí (Abanico) Formation (Charrier et al., 2002), which were initially uplifted and deformed beginning in the early Miocene (19-16 Ma; Kurtz et al., 1997), and again more strongly in the late Miocene and Pliocene (9-3.5 Ma; Godoy et al., 1999). Older Mesozoic igneous and sedimentary rocks and Paleozoic metamorphic rocks occur both well to the west of El Teniente, along the Pacific coast, and also to the east, in the High Cordillera along the drainage divide between Chile and Argentina (Figure 1B). These older rocks may occur in the deep crust below El Teniente, but they do not outcrop either within the mine or in the immediate vicinity surrounding the deposit (Figures 3 and 4).

Farellones Formation extrusive rocks

Extrusive rocks of the Miocene Farellones Formation, locally referred to as the Teniente Volcanic Complex, are the oldest rocks exposed in the immediate area surrounding the deposit (Figures 3 and 7). The Farellones Formation is a sequence of >2,500 m of lavas, volcanoclastics rocks, dikes, sills and stocks of basaltic to rhyolitic composition (Vergara et al., 1988; Rivano et al., 1990). The Teniente Volcanic Complex near the deposit has been correlated with the upper part of this formation and dated between 15.2 and 7.5 Ma. Extrusive rocks of the Teniente Volcanic Complex were intruded by gabbro, diabase, diorite, tonalite, latite, and dacite porphyry plutons between 12.4 to 4.8 Ma (Cuadra, 1986; Kurtz et al., 1997; Rivera and Falcón, 1998; Maksaev et al., 2001, 2002).

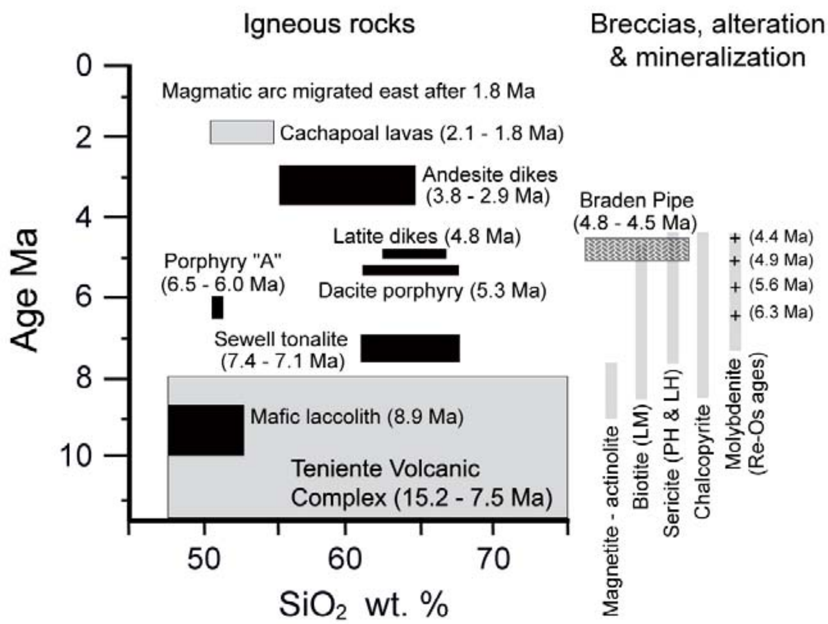
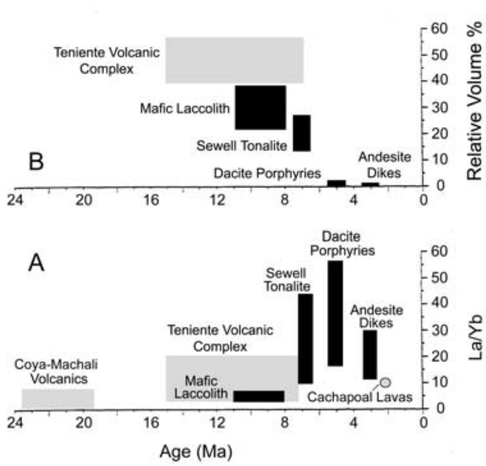


Figure 7. Age versus silica content for volcanic (shaded fields) and plutonic (black) igneous rocks from both in the vicinity of and within the El Teniente mine, and the age of the Braden Pipe and occurrences of both alteration assemblages (LM = Late Magmatic; PH = Principle Hydrothermal; LH = Late Hydrothermal) and copper and molybdenum sulfides. Ages of igneous rocks determined by a combination of K-Ar (Charrier and Munizaga, 1979; Cuadra, 1986, 1992), 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 date). Age of the Braden Pipe determined by K-Ar (Cuadra, 1986) for a sericitized 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 mineralization (pluses) reflect multiple (>20) Re-Os ages in molybdenite (Maksaev et al., 2002; Munizaga et al., 2002), but are only for molybdenites in felsic rocks and therefore do not date the entire period of mineralization within the mafic rocks which host 80% of the copper mineralization in the deposit. None of these mineralization episodes correspond to the 5.28 Ma age of the Tenienete Dacite Porphyry.

The Teniente Volcanic Complex consists of tholeiitic to calc-alkaline extrusive rocks, which plot in the medium to high-K group of convergent plate boundary arc magmas (Kay and Mpodozis, 2002), in contrast to the rocks of the older Coya-Machalí Formation, which are low and medium-K tholeiitic arc igneous rocks (Charrier et al., 2002; Yáñez et al., 2002). Rocks of the Teniente Volcanic Complex also generally have higher ratios of light-rare-earth (La) to heavy-rare-earth (Yb) elements compared to rocks of the older Coya Machalí Formation (Figure 8A), and also higher initial $^{87}Sr/^{86}Sr$ and lower initial $^{143}Nd/^{144}Nd$ ratios (Figure 9). These differences are interpreted to represent a change from magma genesis in an extensional environment within relatively thin continental crust during the mid-Tertiary, when the Coya Machalí Formation formed (Charrier et al., 2002), to conditions of thickened continental crust when the Teniente Volcanic Complex formed in the Miocene.



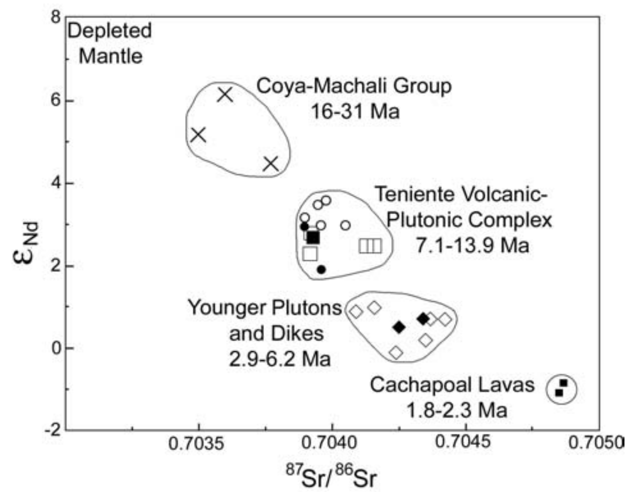


Figure 8. A) La/Yb ratios, versus age, for samples of volcanic rocks from in the area of El Teniente, including Coya-Machalí (Abanico) volcanic rocks (Charrier et al., 2002), the rocks of the Teniente Volcanic Complex (Kay and Mpodozis, 2002), and also lavas from the Cachapoal River valley (Stern and Skewes, 1995). Plutonic igneous rocks from the mine, including the mafic laccolith that hosts most of the mineralization, the Sewell Tonalite, Teniente Dacite Porphyry and post-mineralization andesite dikes, 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 (Figure 3), versus age of the different igneous rocks in the vicinity of and within the mine.

Figure 9. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ ratios for igneous rocks from the vicinity of the El Teniente copper deposit in central Chile, with data from Kay and Mpodozis (2002; open sysmbols) and Stern and Skewes (1995; solid symbols). The figure illustrates the temporal evolution, through the Miocene, towards higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$, which may reflect a combination of crustal thickening (Nystrom et al., 1993; Kay et al., 1999), and/or increased mantle-source region contamination by subducted continental crust as the angle of subduction decreased and the rate of tectonic erosion increased during the Miocene and Pliocene (Stern, 1989, 1991, 2001; Stern and Skewes, 1995, 1997).

El Teniente mafic intrusive complex

The oldest rocks within the mine are dark colored, with aphanitic to porphyritic appearance (Figures 10A and 10B), and locally have been called the "Andesites of the Mine." These rocks, which host 80% of the copper mineralization in El Teniente (Camus, 1975; Arévalo et al., 1998), are strongly altered, brecciated and mineralized, and aspects of their original petrology have been obscured. The name "Andesites of the Mine" suggests intermediate extrusive rocks, and they have been correlated in the past with the andesitic extrusives of the Farellones Formation (Howell

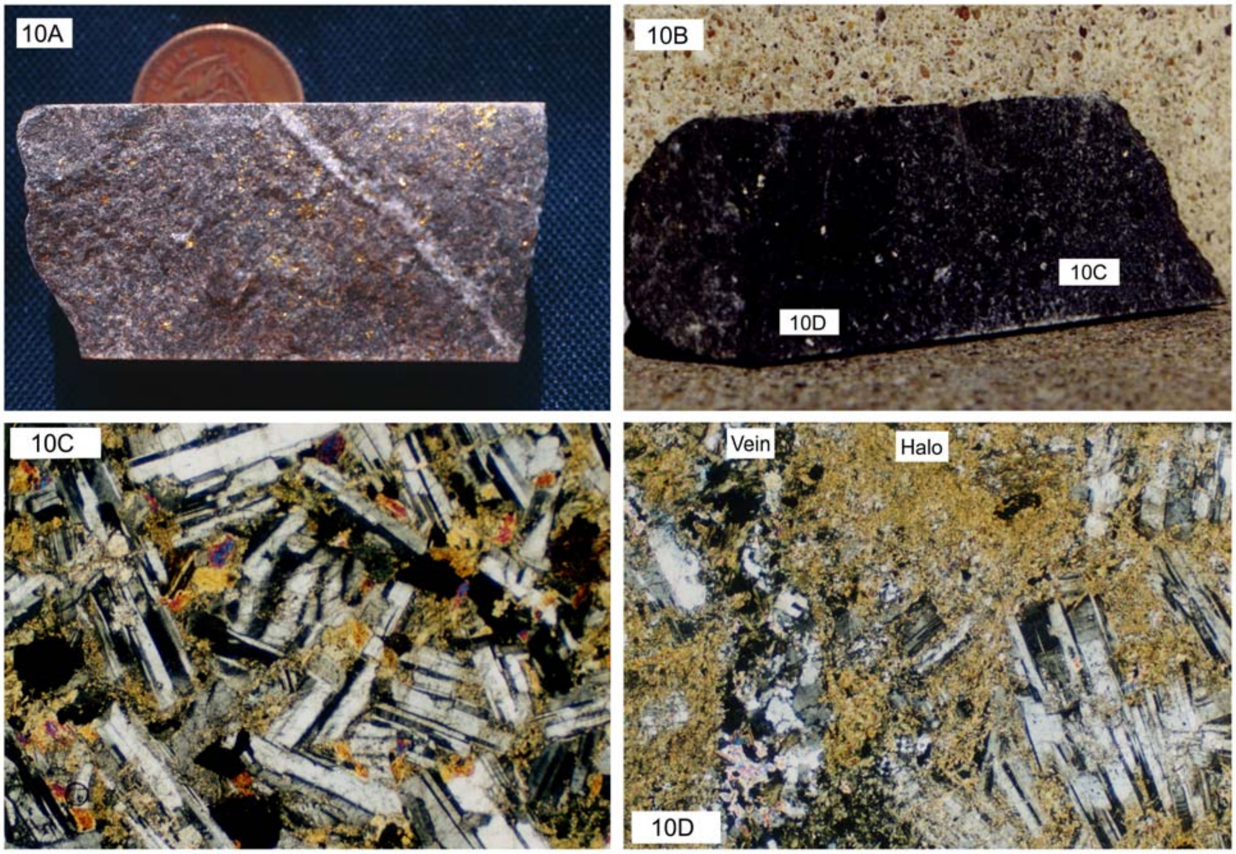
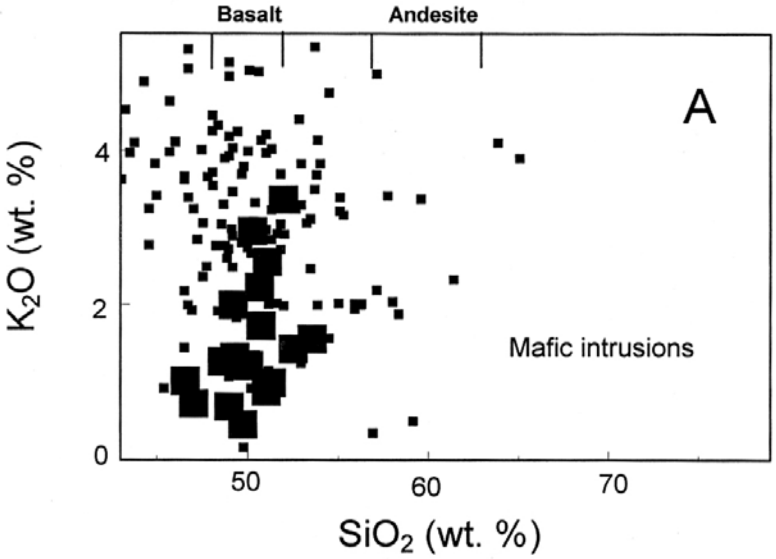


Figure 10. A) A typical dark, mafic, altered and mineralized (1.82% Cu) “Andesite of the Mine” cut by a biotite + quartz + chalcopyrite vein (sample DDH1034-712 from a drill hole inititated on level Teniente-5, northeast of the braden Pipe; 619N, 1323E, 2,284 m above sea level). B) Another typical dark “Andesite of the Mine” that is actually a biotite-altered gabbro (Figure 10C) cut by a thin biotite vein (<2 mm across) with a wide biotite-rich halo (4 cm across; Figure 10D), that appears darker than the rest of the rock, and within which the texture of the original gabbro is essentially obliterated (sample DDH1411-1680; from a drill hole initiated at level Teniente 4-Production, south of the Braden Pipe; 363S, 300E, 2,057 m above sea level). C) Photomicrograph (crossed polarizers; 5.8 x 3.7 mm) of this biotite-altered gabbro (Figure 10B), 3 cm from the center of a biotite vein (Figure 10D), and just outside the intense biotite-altered halo of this vein. Outside this vein halo the gabbro preserves weak magnetite-actinolite alteration that has pseudmorphically replaced original mafic minerals, but left calcic plagioclase unaltered. A very thin biotite vein (<1 mm), barely visible in the macrophoto (Figure 10B), cuts the upper part of the gabbro angling upwards to the right. D) Photomicrograph (crossed polarizers, 5.8 x 3.7 mm) of the center of the thin biotite vein, which contains chlorite partially replacing biotite, anhydrite, quartz, chalcopyrite and pyrite, and a part of the surrounding and much wider vein halo within which this same gabbro (Figures 10B and 10C) has been intensely biotite-altered. Within the halo, only relic calcic plagioclase grains remain, whereas just outside the halo, the original texture of the gabbro is preserved, as are earlier magnetite-actinolite alteration effects (Fig. 10B). When the density of such veins is high, and their halos coalesce, the original texture of such gabbros is nearly completely obliterated by the intense biotite alteration, and the rock appears porphyritic although it was originally both holocrystalline and equigranular.

and Molloy, 1960; Camus, 1975; Ojeda et al., 1980; Cuadra 1986), despite the fact that evidence for individual lava flows has not been found in the mine, and chemical analyses (Villalobos, 1975; Camus, 1975; Skewes and Arévalo, 2000; Skewes et al., 2002) show SiO_2 contents that range from 47 to 57 wt % (Figure 11A), indicating these rocks are more basic than andesites. Recent geologic mapping (Figure 3; Morel and Spröhnle, 1992), and petrological studies (Skewes and Arévalo, 2000; Skewes et al., 2002), indicate that the “Andesites of the Mine” are mafic intrusive rocks, including gabbros (Figure 10C), diabases, and basaltic and basaltic andesite porphyries. They constitute part of a mafic complex, with the form of a laccolith, that intruded rocks of the Teniente Volcanic Complex, as was originally suggested by Lindgren and Bastin (1922). Concordant intrusive contacts at the margins of this laccolith can be observed southwest of the El Teniente mine along the Coya River valley below the Copado tunnel, in the Teniente River valley both southwest and northeast of the mine (Figure 3), and in the Diablo Canyon along the Puquios River to the southeast of the mine (Lindgren and Bastin, 1922). The central part of this mafic complex, within which the mine is located, has a vertical extent or more than 2,000 m.



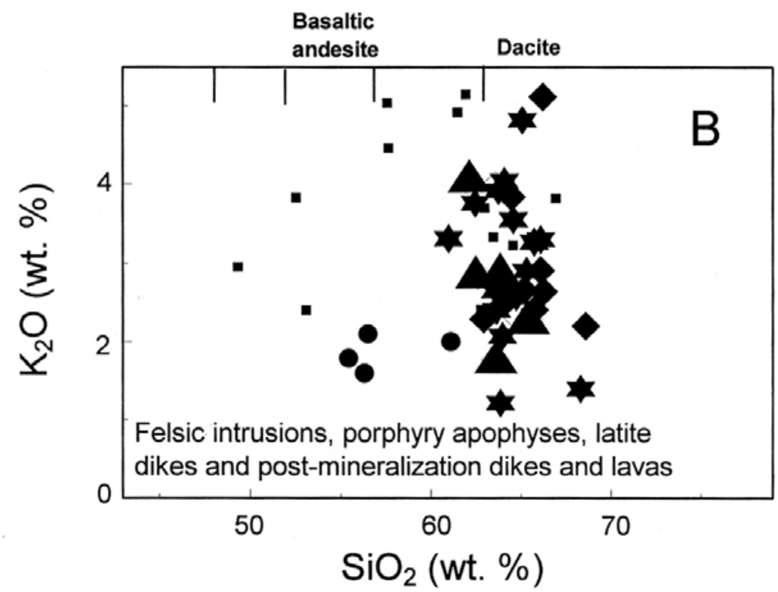


Figure 11. SiO_2 versus K_2O for A) gabbros, diabases and porphyritic basalts and basaltic andesites from the mafic igneous complex that hosts most of the mineralization within the El Teniente mine. Small squares are data from Villalobos (1975) and include both weakly and strongly altered samples, the latter which have high K_2O, and larger squares are from Skewes et al. (2002); and B) felsic intrusions (Guzmán, 1991; Stern and Skewes, 1995; Rojas, 2002; Skewes et al., 2002), including the Sewell Tonalite (triangles), porphyritic tonalite apophyses (small squares), latite dikes (stars) and the Teniente Dacite Porphyry (diamonds), and post-mineralization andesite dikes and basaltic andesite lavas (circles; Stern and Skewes, 1995).

Although mafic rocks of this complex have important textural variations, it is very difficult to recognize contacts or gradations between the different textural types, either in the mine or in drill core, because they are all dark colored, and strongly altered to biotite, copper mineralized and brecciated. These mafic rocks consist of medium to large crystals (1-6 mm) of calcic plagioclase (An_{92-41}), and occasionally clinopyroxene, surrounded by a fine-grained (0.1-

0.5 mm) crystalline mass generally dominated by biotite and/or actinolite, with varying amounts of plagioclase, chalcopyrite, magnetite, anhydrite, tourmaline, chlorite, rutile, pyrite, and quartz. The bimodal population of crystal sizes in the "Andesites of the Mine" has been interpreted in the past as a porphyritic texture, typical of extrusives, with the plagioclase phenocrysts preserved and surrounded by a groundmass that was more susceptible to biotite alteration (Howell and Molloy, 1960; Villalobos, 1975; Camus, 1975). This texture is in fact the result of intense alteration, which has replaced not only the groundmass in originally porphyritic rocks, but also original mafic igneous minerals, even in coarse-grained holocrystalline gabbros, with fine-grained secondary biotite and other phases, without significantly affecting the original igneous plagioclase (Figures 10C and 10D). Plagioclase may be partly altered to biotite, sericite and/or tourmaline along crystal borders and fractures, but original crystals of plagioclase are still recognizable. Clinopyroxene, in contrast, is typically preserved in only the more coarse-grained gabbros. In some samples, clinopyroxene has been pseudomorphically replaced by actinolite and magnetite, but in most by secondary biotite, along with anhydrite, chalcopyrite, bornite, and Fe-Ti-oxides. Primary igneous hornblende or biotite, or pseudomorphs of these minerals, do not occur in these rocks. Fresh olivine and orthopyroxene have also never been found, but possible pseudomorphs of both these minerals have been observed.

The least altered gabbros, diabases and basaltic porphyries have SiO_2 contents that generally range between 47 to 54 wt. %, and chemically they correspond to basalts and basaltic andesites (Figure 11A; Skewes et al., 2002). They have between 6 and 11 wt. % CaO, and 16 to 22 wt. % Al_2O_3, which are consistent with their high calcic plagioclase content. The FeO (6 to 11.7 wt. %) is high with respect to MgO (<6.2 wt. %), and TiO_2 and P_2O_5 contents are relatively low, consistent with tholeiitic affinities for these mafic rocks. There is no chemical distinction between gabbros, diabases, and basaltic porphyries. These mafic rocks have low rare-earth-elements (REE) concentrations, with light-REE not very strongly enriched relative to heavy-REE (La/Yb <8; Figure 8A). The alkali components and volatile content vary according to the type and degree of alteration. The freshest rocks, with only minor actinolite and/or chlorite, have the lowest K_2O (0.5 to 1.5 wt %) and H_2O (typically <1.5 wt %) contents. The samples with more intense biotite alteration have higher K_2O content, as much as 4 wt % (Figure 11A).

An apatite fission track age of 8.9 Ma was obtained for a sample of the mafic laccolith from west of the mine (K. Thiele, unpublished data), but the age of the mafic intrusive rocks inside the mine have not been determined. They are intruded by all the different felsic intrusions and breccias in the mine (Figure 4), including the Sewell Tonalite in the southern part of the mine, the Teniente Dacite Porphyry in the northern part of the mine, the Braden Pipe in the central part of the mine, and numerous other magmatic-hydrothermal breccias and minor felsic porphyries.

Felsic Intrusions

Two felsic plutons which intrude the mafic rocks in the area of the mine include the larger Sewell Tonalite southeast of the Braden Pipe and the smaller Teniente Dacite Porphyry north of the pipe (Figures 3 and 4). Their spatial distribution, published ages, and general petrologic characteristics confirm that they are two independent bodies intruded at different times. The Sewell Tonalite is dated, by K-Ar, between 7.4 and 7.1 Ma, and the younger Teniente Dacite Porphyry between 4.7 and 4.6 Ma (Cuadra, 1986), and more recently the latter at 5.28 Ma by U-Pb in zircons (Figure 7; Maksaev et al., 2002). Other smaller felsic bodies, which include apophyses of porphyritic diorite, tonalite and/or dacite, occur east of the Braden Pipe (Figure 4; Guzmán, 1991). A K-Ar age of 6.0 Ma (SERNAGEOMIN, 1986) has been obtained for relatively mafic Porphyry A among this group, and others have been dated as 6.46 to 6.11 Ma by U-Pb in zircons (Figure 7; Maksaev et al., 2002). Also latites, dated between 5.3 and 4.8 Ma by K-Ar (Riveros, 1991; Cuadra, 1992), between 4.8 and 4.4 by $^{40}Ar/^{39}Ar$ (Maksaev et al., 2001), and more recently at 4.82 Ma by U-Pb in zircon (Figure 7; Maksaev et al., 2002), occur both as ring-dikes concentric to the Braden Pipe (Figure 4) and as blocks within this breccia.

The Sewell Tonalite is one among a number of plutons of the Teniente Plutonic Complex that intruded Teniente Volcanic Complex extrusive rocks between 12.4 and 7.0 Ma (Cuadra, 1986, 1992; Kurtz et al., 1997; Rivera and Falcón, 1998). The Sewell Tonalite consists of oligoclase plagioclase, altered amphiboles, biotite, quartz, and minor potassium feldspar, with textures that vary from medium-grained (1-5 mm) equigranular to porphyritic. Although mineralogically similar, is not clear if the equigranular and porphyritic portions of the Sewell Tonalite represent one or more intrusive bodies. Camus (1975) suggested that porphyritic tonalite represents the more rapidly chilled margin of this pluton, whereas Guzmán (1991) suggested that the porphyritic tonalite was a separate, younger intrusive phase more closely related to the porphyritic apophyses to the north.

The Teniente Dacite Porphyry is a dike-like body, extending 1.5 km to the north of the Braden Pipe, with a maximum width of 300 m (Figure 4). The Teniente Dacite Porphyry has been truncated on the south by the emplacement of the Braden Pipe. It is composed of several texturally different porphyritic units, with variable proportions of phenocrysts of oligoclase-albite plagioclase, biotite, small amounts of replaced amphiboles, and "quartz eyes", surrounded by a groundmass with quartz, albite, potassium feldspar and biotite (Rojas, 2002). It has been considered by many authors to be the "productive" igneous intrusion responsible for mineralization at El Teniente (Howell and Molloy, 1960; Camus, 1975; Ojeda et al., 1980; Cuadra, 1986). However, relative to other igneous rocks associated with this giant deposit, this pluton has a very small volume (Figures 3 and 8B), much less than the >600 km^3 of magma calculated to be required to yield the approximately $100x10^6$ metric tonnes of copper originally in the deposit (see discussion). Also, its core is practically barren and it clearly cuts copper mineralized mafic rocks, veins and breccias in the deposit (Figure 12). Furthermore, its northernmost extension, north of the Teniente River valley (Figure 3), is unmineralized (Floody and Huete, 1998), and none of the Re-Os ages for mineralization in the mine correspond to the 5.28 Ma crystallization age of this pluton (Figure 7).

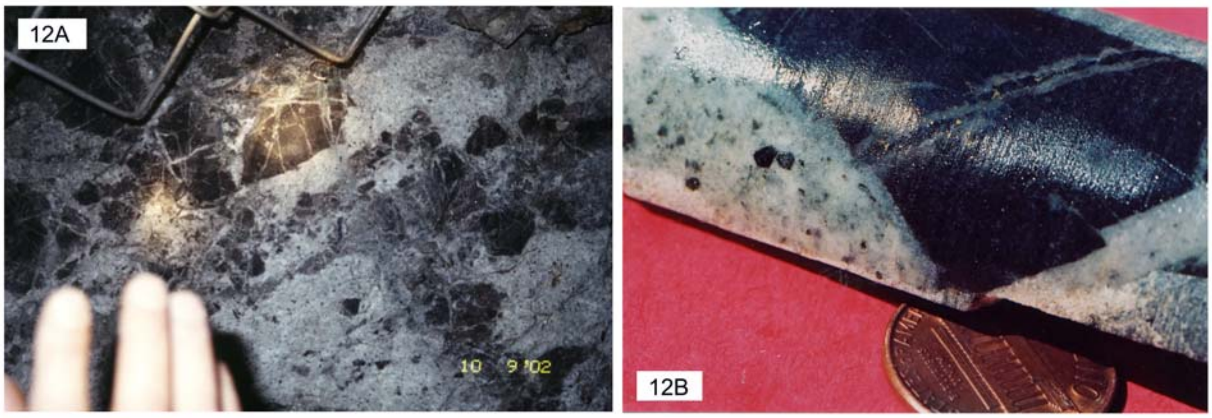


Fig. 12. A) Mechanically brecciated contact zone where the Teniente Dacite Porphyry has intruded previously biotite altered, veined and mineralized mafic rocks (outcrop in a mine tunnel on level Teniente sub-6H at 620N, 620E, 2,121 m above sea level). B) Porphyritic dacite, with fresh biotite phenocrysts, quartz and feldspars, and amphiboles pseudomorphically replaced by chlorite and sericite, cutting a previously veined and biotite-altered mafic rock (sample DDH1659-713'; from a vertical drill hole initiated at level Teniente sub-6, northeast of the Braden Pipe; 593N, 835E, 1,908 m above sea level).

Major element chemical analyses do not distinguish the Sewell Tonalite and Teniente Dacite Porphyry (Figure 11B). The available analyses of these two stocks range between 61.5 and 67.3 wt % SiO_2, with K_2O content between 1.8 to 6.3 wt % (Skewes et al., 2002). Rare-earth-elements in the Teniente Dacite Porphyry are strongly fractionated (La/Yb = 19.3 to 61.6), whereas for the equigranular Sewell Tonalite, this ratio ranges between both lower, less fractionated values, to highly fractionated values (La/Yb = 9.9 to 44; Figure 8A). Rabbia et al. (2000) also report high La/Yb ratios (27 to 44) for the 7.0 Ma Laguna La Huifa quartz-diorite porphyry located a few kilometers northeast of the mine. As with the major elements, it appears that these trace element ratios do not distinguish the Sewell Tonalite from the Teniente Dacite Porphyry. The porphyry apophyses to the northeast of the Braden Pipe (Figure 4) are, however, chemically more variable than either the Teniente Dacite Porphyry or Sewell Tonalite, with SiO_2 ranging between 51 to 72 wt % (Figure 11B; Guzmán, 1991). This is also consistent with their ages, summarized above, which indicate that the porphyry apophyses are independent small bodies intruded between the times that the larger Sewell Tonalite and Teniente Dacite Prophyry were emplaced, and that they are not all simply marginal portions of either the Sewell Tonalite or Teniente Dacite Porphyry. The Sewell Tonalite, and other plutons of the Teniente Plutonic Complex, have Sr and Nd isotopic compositions similar to extrusive rocks from the Teniente Volcanic Complex (Figure 9). Their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are higher and lower, respectively, than extrusive rocks of the older Coya-Machalí Formation.

Latite porphyry ring-dikes occur concentrically surrounding the Braden Pipe (Figure 4). Both their K-Ar age (5.3 to 4.8 Ma; Cuadra, 1992), and the occurrence of blocks of this rock type in the pipe, suggest that that at least some latite porphyry intruded prior to the formation of the Braden Pipe and may have played a role in the formation of the pipe (Floody, 2000). This is consistent with a zircon U-Pb age of 4.82 Ma for one latite dike, and a sericite $^{40}Ar/^{39}Ar$ age of 4.75 Ma for altered clasts within the Braden Pipe, which suggest that the latite dikes and pipe formed together

(Maksaev et al., 2002). The latite is a porphyritic rock, with a higher proportion of plagioclase phenocrysts than the Teniente Dacite Porphyry. It also contains phenocrysts of biotite, altered amphibole, and quartz eyes, in a groundmass of quartz and feldspar. Available chemical analyses indicate that the latite is chemically similar to both the Teniente Dacite Porphyry and the Sewell Tonalite, with between 62.5 and 66.7 wt % SiO_2 and 1.2 to 4.8 wt % K_2O (Figure 11B), and a high La/Yb ratio of about 30 (Kay and Mpodozis, 2002).

Post-mineralization dikes and lava flows

The youngest igneous rocks in the deposit are post-mineralization hornblende andesite dikes, dated as 3.8 to 2.9 Ma (Figure 7; Cuadra, 1986). They contain phenocrysts of amphiboles and andesine plagioclase in a fine-grained groundmass of plagioclase, amphibole, iron oxides and glass. They have SiO_2 between 55.8 and 64.7 wt % (Figure 11B), La/Yb values of 14.1 to 25.7 (Figure 8A), and their $^{87}Sr/^{86}Sr$ ratios are slightly higher and $^{143}Nd/^{144}Nd$ ratios slightly lower than rocks of the older Teniente Volcanic and Plutonic Complexes (Figure 9).

The youngest igneous rocks in the vicinity of the deposit are 2.3 to 1.8 Ma lava flows in the valley of the Cachapaol River (Figure 7; Charrier and Munizaga, 1979). These are two-pyroxene basaltic andesites with 55.4 to 56.5 wt % SiO_2 (Figure 11B). They have lower La/Yb ratios (9.7) than the older andesite dikes in the mine (Figure 8A), but higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios (Figure 9).

Breccias

El Teniente deposit contains many different magmatic-hydrothermal breccias, both mineralized and unmineralized. The Braden Pipe, the largest breccia pipe and the central litho-structural unit in the deposit (Figures 13A and 13B), biotite-rich breccias cutting the Sewell Tonalite, and anhydrite breccias (Figure 13C) are easily recognized and mapped because the color, texture, and/or mineralogy of their matrices contrast clearly with their contained clasts and the surrounding host rocks. However, many breccia bodies at El Teniente, including some associated with high-grade copper mineralization, such as biotite breccias cutting the biotite-altered mafic host rocks of the deposit (Figure 13D), are difficult to recognize both in the mine and in drill core. This is because 1) the matrix of these breccias lack color, mineralogic and/or textural contrast with clasts; 2) they are located in areas where subsequent emplacement of other breccias, felsic igneous intrusions and associated alteration have occurred; and 3) supergene events have obscured them even further. For these reasons, some important breccias have only recently begun to be identified and mapped. As mine operations have developed deeper into the zone of hypogene mineralization, the presence of biotite and igneous breccias, and the recognition of the important role they played in the emplacement of copper mineralization, has become evident (Skewes et al., 2002).

Breccias at El Teniente are both monolithic (Figures 13B and 13D) and/or heterolithic (Figures 13A and 14A). The nature of their clasts depends in part on the location of the breccias in the deposit, and in part on at what stage they were emplaced. For this reason, most breccias at El Teniente are classified according to the most abundant minerals or components in their matrices. They include tourmaline (Figure 13B), anhydrite (Figure 13C), biotite (Figure 13D), gypsum, magnetite, igneous (Figure 14) and rock-flour (Figure 13A) breccias (Arredondo, 1994; Morales, 1997; Floody, 2000). In rock-flour breccias, small crystals and rock fragments form a significant part of the matrix, and this rock-flour may itself be cemented by biotite, tourmaline, quartz, sericite, and/or pyrite. Individual breccias or breccia complexes may form in multiple events, with different matrix minerals precipitating during each event. The Braden Pipe, for example, consists of a marginal ring of copper-rich tourmaline breccia (Figure 13B) and a central core of copper-poor rock-flour breccia (Figure 13A), which may have formed at several different stages during the development of this single large breccia pipe (Figure 4; Floody, 2000).

Contacts between the margins of the breccias and the host rocks can be sharp, or gradational with a stockwork of veins developing from the border of the breccia into the adjacent host rocks. Veins in stockwork that surround breccias typically have a central fracture filled with the same minerals as in the breccia matrix, and halos of the same alteration minerals that occur in clasts within the breccia. Specific types and/or events of stockwork veining, alteration and mineralization in El Teniente are often clearly spatially and genetically associated with the emplacement of specific breccias.

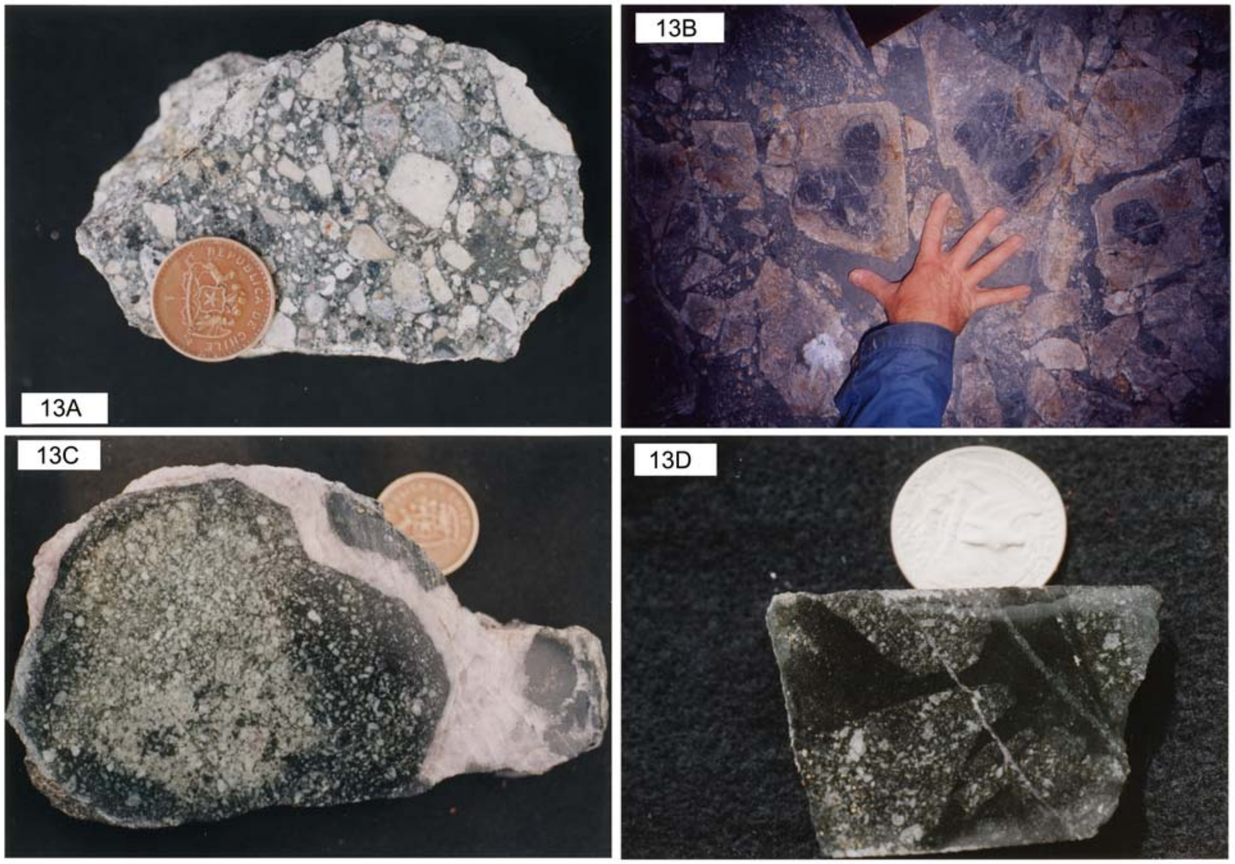


Figure 13. A) Heterolithic rock-flour breccia from the central “bolones” portion of the Braden Pipe (Figure 4; Floody, 2000). Rock-flour is cemented by sericite and quartz, along with fine tourmaline, which gives it a dark appearance relative to the almost completely sericitized and silicified clasts (sample from level Teniente 4, 2,346 m above sea level). B) Tourmaline-rich Marginal Breccia of the Braden Pipe, with clasts of biotite-altered mafic rocks that have developed strongly bleached borders consisting almost completely of sericite and quartz, along with minor carbonates and clay. Photo taken on the northeast margin of the Braden Pipe in a tunnel on level Teniente sub-5 (323N, 910E, 2,190 m above sea level), in an area where the emplacement of Marginal Breccia clearly involved some significant pulverization and displacement of clasts. C) A heterolithic anhydrite breccia, containing a large clast of dacite porphyry, altered to biotite around its edges, a small clast on the right of biotitized mafic rock, and a clast just in front of the coin of dark colored anhydrite containing numerous inclusions of co-precipitated biotite and chalcopyrite (sample from a tunnel on level Teniente 6, within the Esmeralda project (Morales, 1994), just northeast of the Braden Pipe; 500N, 1090E, 2,210 m above sea level). D) Biotite breccia containing clasts of biotite-altered and mineralized porphyritic basalt (sample DDH1951-711’; from a horizontal drill hole initiated at level Teniente 8, northeast of the Braden Pipe; 816N, 1400E, 1,983 m above sea level). Similar biotite breccias have been mapped in the past as part of the “Andesite of the Mine”. Both the breccias and clasts are cut by quartz-anhydrite Late Magmatic veins, with some chlorite after biotite, chalcopyrite and pyrite.

Different magmatic-hydrothermal breccias observed at El Teniente reflect a complex sequence of multiple events that resulted in the emplacement of the large quantity of high-grade hypogene copper ore in the deposit. General characteristics of the major types of breccias, and their associated stockwork veins and alteration effects, are described below, in an approximate chronological sequence, from those emplaced early to those emplaced later in the evolution of the deposit. However, some types of breccias formed repeatedly during the development of the deposit and there is in fact no simple chronological sequence of different breccia types.

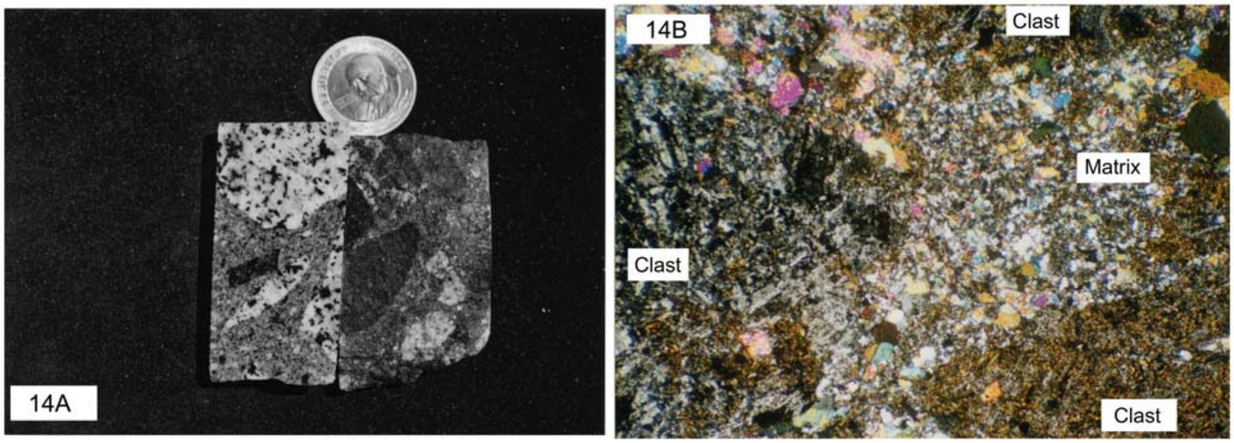


Figure 14. A) Two heterolithic igneous breccias with different proportions of felsic and biotite-altered mafic clasts (samples: on the right – DDH1034-100'; from a drill hole initiated at level Teniente 5, northeast of the Braden Pipe; 619N, 1313E, 2,256 m above sea level; and on the left - DDH1337-349; from drill hole initiated at level Teniente 4-Production, east of the Braden Pipe; 109N, 1600E, 2,200 m above sea level; section 124N). The lack of secondary biotite in the felsic clasts suggests that the mafic clasts were altered prior to their incorporation in these breccias. B) Photomicrograph (crossed polarizers, 5.8 x 3.7 mm) of fine-grained igneous breccia, with biotite-rich matrix containing anhydrite, quartz, feldspar and chalcopyrite, and biotite-altered gabbro clasts (sample DDHH1698-174'; from a nearly horizontal drill hole initiated at level Teniente 8, northeast of the Braden Pipe; 1076N, 1024E, 1,960 m above sea level; section 83N).

Magnetite breccias

Magnetite breccias have been described from a few kilometers north of the El Teniente deposit in the area of Laguna La Negra (Figure 3; Floody and Huete, 1998), and from a few kilometers south of the mine in the Coya and Matadero River valleys (Floody and Huete, 1998; Floody, 2000), but not within the El Teniente mine itself. However, their presence in the mine is indicated by the recovery of magnetite crystals up to 30 cm in length in the mine plant, and also the common occurrence of magnetite-actinolite stockwork veins and alteration within mafic igneous rocks in the deposit. The matrix minerals in the breccias at Laguna La Negra include magnetite, actinolite, tourmaline, quartz, apatite, and K-feldspar, and secondary minerals in clasts and wall rock include magnetite, actinolite, chlorite, quartz, and feldspar.

Biotite breccias

Brown biotite is the dominant mineral in biotite breccias, but they also contain variable amounts of tourmaline, quartz, feldspars, chlorite, anhydrite, gypsum, apatite, chalcopyrite, bornite, pyrite, rutile, and magnetite (Figure 13D). Biotite crystals in the matrix of biotite breccias can be fine-grained, or as much as several centimeters in length. Biotite breccias usually are monolithic, with clasts dominated by either mafic (Figure 13D) or felsic intrusive rocks, but in some cases they can have both. Biotite-rich breccias usually have high copper content. Biotite-altered mafic clasts in biotite breccias are often barely recognizable as such. Biotite breccias are associated with the development of a stockwork of biotite-rich veins in the surrounding host rock.

Biotite breccias, and associated biotite veins and alteration, post-date magnetite-actinolite alteration. Fragments of biotite breccias and biotite-altered mafic rocks have been found in igneous (Figure 14), anhydrite, tourmaline (Figure 13B), and rock-flour breccias, indicating that biotite breccias, veins, and pervasive biotite alteration occurred early in the formation of the El Teniente deposit. Biotite breccias, veins, and biotite-altered mafic rocks are cut by felsic intrusions (Figure 12). Generally, neither of the two large felsic plutons, the Sewell Tonalite and the Teniente Dacite Porphyry, nor the latite dikes associated with the Braden Pipe, are biotite-altered, except locally where biotite breccias and veins cut these intrusions, or where they are included as clasts in breccias (Figure 13C). These relations suggest that biotite breccias were emplaced repeatedly in the evolution of the deposit, and in many cases clearly prior to emplacement of the felsic intrusions (Figure 7). Biotite is often altered to chlorite and/or sericite (Figure

13B) by later alteration events associated with the intrusion of both younger breccias and felsic plutons, and this has further added to the difficulties involved in recognizing and mapping these breccias and veins.

Biotite breccias and associated veins in El Teniente resemble those in Los Pelambres (Skewes and Atkinson, 1985; Atkinson et al., 1996) and in the Río Blanco breccia complex of Río Blanco-Los Bronces (Serrano et al., 1996). They formed relatively early in the development of the deposit, and occur in areas of potasssic alteration associated with high-copper hypogene grade. Biotite breccias at El Teniente have been identified in zones of high-grade hypogene copper surrounding the Braden Pipe, but distant from the Teniente Dacite Porphyry (Figure 4). These include a 400 by 400 m area located east of the Braden Pipe (section 124N; Figure 4), where copper grades exceed 2% (Figure 5) within a complex of biotite, igneous, anhydrite and tourmaline breccias, which both cut the Sewell Tonalite and are transected by Porphyry A (Arredondo, 1994). They also occur in an area of high-grade hypogene copper northeast of the Braden Pipe (400-600N, 1000-1200E, Figures 4 and 5; Arredondo, 1994; Morales, 1997), where the Esmeralda sector of the mine is currently being developed. Biotite breccias occur both west and east of the Teniente Dacite Prophyry (section 83N; Figure 4). They may have a much greater extent in the deposit than has been recognized up to the current time, as indicated by the spatial extent of pervasive biotitization.

Igneous breccias

Igneous breccia is the name given to breccias in which the matrix contains biotite, quartz, feldpars, anhydrite, chalcopyrite and iron oxides, and has a typically fine-grained, equigranular, holocrystalline “igneous” appearance (Figure 14). If the matrix is dominated by a dark biotite-rich cement, then they are often called andesitic igneous breccia. Alternatively, if the matrix is lighter in color, because it contains less biotite and more anhydrite, feldspars and quartz, then they are termed dacitic or diorite igneous breccia. Igneous breccias have mineralogy similar to biotite breccias, but in general contain less biotite, and in some areas appear to grade into biotite breccias.

Igneous breccias often contain clasts of biotite-altered mafic rocks (Figure 14). In some cases they may post-date biotite alteration of these clasts (Guzmán, 1991), as indicated by the lack of biotite alteration of felsic clasts in the same breccia (Figure 14A). In some areas of the mine they are associated with high-grade copper mineralization. For example, in the Esmeralda sector of the mine, northeast of the Braden Pipe (400-600N, 1000-1200E, Figure 4; Morales, 1997), one igneous breccia, containing rounded clasts of both tonalite and biotite-altered mafic rocks in a chalcopyrite-rich “igneous” matrix, occurs in an area more than 60 m wide. This breccia contains grades of >1.5% Cu, widens at depth, has a recognized vertical extent of at least 200 m below its present level of exploitation, and its roots have yet to be encountered. Igneous breccias also are associated with biotite and anhydrite breccias east of the Braden Pipe (section 124N), and both west and east of the Teniente Dacite Porphyry (section 83N).

Anhydrite breccias

Anhydrite is the dominant mineral, often occurring along with biotite, tourmaline, quartz, gypsum, apatite, chalcopyrite, pyrite, bornite and rutile, in the matrices of many breccia bodies in El Teniente (Figure 13C). Anhydrite breccias are commonly heterolithic, with clasts of both biotite-altered mafic rocks and felsic intrusive rocks, as well as igneous and tourmaline breccias, in a matrix that comprises as much as 20-30% of the volume of the breccia. Anhydrite breccias formed after many of the biotite and igneous breccias, and they commonly occur in areas that have been previously brecciated by biotite and igneous breccias. Veins containing anhydrite, biotite, quartz, feldspars and sulfide minerals surround these anhydrite breccias. According to Arredondo (1994), another generation of anhydrite breccias was emplaced in association with tourmaline breccias. These contain sericitized and silicified clasts, and are surrounded by veins containing tourmaline, anhydrite, quartz plus sulfide minerals.

Anhydrite breccias are usually easily recognized and mapped, and they are widely distributed in the deposit (Figure 4). In the Esmeralda sector of the mine, northeast of the Braden Pipe (400-600N, 1000-1200E), a 25-m-wide zone of anhydrite breccia surrounds the igneous breccia (Morales, 1997). They also occur, in association with biotite and igneous breccias, in a large breccia complex east of the Braden Pipe (section 124N). Another large anhydrite-quartz breccia occurs north of the Braden Pipe, along the eastern margin of the Teniente Dacite Porphyry (section 83N). This breccia is monolithic, containing clasts of previously biotite-altered and mineralized mafic rocks, but not felsic rocks, which suggests that it formed prior to the intrusion of the dacite porphyry (Arredondo, 1994).

Tourmaline breccias

Tourmaline is an abundant component, along with anhydrite, quartz, chalcopyrite, bornite, and pyrite, in the matrices of many breccias at El Teniente, including most prominently, the Marginal Breccia of the Braden Pipe (Figures 4 and 13B). Occasionally biotite is present with tourmaline in the matrix of some of these breccias. Tourmaline breccias can be monolithic or heterolithic. Clasts in tourmaline breccias are silicified and sericitized, either completely or, if they are large, only along their borders, which produces a characteristic bleaching, particularly in previously biotite-altered mafic clasts (Figure 13B). Tourmaline breccias generate a stockwork of veins with cores of tourmaline, quartz, chalcopyrite, bornite and pyrite, and sericite and/or chlorite halos that bleaches the host rock (Fig. 15B). Tourmaline breccias can be either mineralized, such as the Marginal Breccia of the Braden Pipe, or barren.

The Marginal Breccia of the Braden Pipe (Figure 4), dated by K-Ar as 4.7 Ma (Cuadra, 1986), is the largest tourmaline breccia in El Teniente. Other tourmaline breccias south of the Braden Pipe (near 500E, 700S; Figure 4) have vertical extensions of over 1 km and their roots have not yet been intercepted. The matrices of these breccias are composed of tourmaline, anhydrite, biotite, chalcopyrite, bornite and molybdenite, and locally they contain copper grades of >6% and >1% molybdenum. Tourmaline breccias also occur with biotite, igneous and anhydrite breccias in the areas of high grade hypogene copper east and northeast of the Braden Pipe (sections 83N and 124N).

Tourmaline breccias in El Teniente resemble those from Río Blanco-Los Bronces (Serrano et al., 1996), such as the Donoso (Warnaars et al., 1985; Skewes et al., 2003) and Sur-Sur (Vargas et al., 1999) copper-rich tourmaline breccias, with respect to both their matrix mineralogy and associated veins and sericitic alteration effects. Both fluid inclusion and stable isotope data indicate that matrix minerals in these breccias precipitated from high-temperature magmatic fluids (Figure 16; Skewes et al., 2002)

Rock-flour breccias

Some breccias, such as the center part of the Braden Pipe, have a matrix of small, finely ground fragments (<1 mm) of minerals and rocks, in addition to cement consisting of anhydrite, biotite, quartz, tourmaline and/or copper sulfide minerals (Figure 13A). These breccias are hetherolithic, with clasts of previously biotite-altered mafic rocks, felsic intrusive rocks, and pre-existing breccias. The Braden Pipe contains fragments of all rock types recognized in the deposit, and also of some rocks that not been mapped in the area of the mine and that presumably were derived from buried basement rocks (Floody, 2000). In some rock-flour breccias, biotite or tourmaline is abundant as cement in the matrix, which gives them a dark color. In others, the rock-flour fragments are cemented by sericite and quartz, often with pyrite, and the matrix is light colored.

The presence of biotite-altered mafic rocks, felsic intrusive rocks and pre-existing breccia fragments indicates that these breccias were emplaced at a late stage of brecciation. The central rock-flour part of the Braden Pipe has been dated by K-Ar at 4.5 Ma (Cuadra, 1986), and as 4.75 Ma by an $^{40}Ar/^{39}Ar$ age (Figure 7; Maksaev et al., 2002), both in sericite from altered rock fragments within the pipe. Rock-flour breccias have also been recognized and mapped in other areas of the deposit east, northeast and north of the Braden Pipe (Skewes et al., 2002).

Alteration

All rocks in the area of hypogene copper mineralization at El Teniente show indications of multiple alteration events. Each alteration event responsible for emplacement of hypogene copper mineralization has occurred together with development of a specific group of vein types associated spatially and temporally with the emplacement of different breccias and/or felsic intrusions. Intensity of alteration is generally related to the density of veins.

The mafic intrusive rocks, which host 80% of the hypogene copper mineralization in the deposit, are the most affected by these multiple, superimposed alteration events. Pervasive biotite alteration is the most widespread, affecting the mafic intrusive rocks in an area of roughly 2.7 by 2 km that coincides with the area of high copper grades (Villalobos, 1975). Secondary biotite, the most abundant alteration mineral in the deposit, occupies between 20 to more than 50 percent of the volume of the altered mafic rocks (Camus, 1975; Arévalo et al., 1998). Biotite alteration is the first major stage of alteration associated with copper mineralization, and the stage upon which all subsequent alteration and mineralization events are superimposed. It was preceded by a magnetite-actinolite alteration event, but neither sulfide minerals nor copper deposition are associated with this earlier stage of alteration.

Biotite alteration of both the mafic rocks (Figure 10) and felsic intrusions is related to emplacement of biotite breccias and veins. Early biotite veins, despite their importance, have received little attention, because they are difficult to recognize (Figure 10B), they have often reopened and had other, later vein types form within them (Figure 10A), and they commonly are altered to chlorite and/or sericite. Drill core frequently fractures along thin biotite veins, masking their presence.

Traditionally, four “stages” of alteration and hypogene mineralization have been described at El Teniente; the Late Magmatic (Tardimagmática), Principal Hydrothermal (Hidrotermal Principal), Late Hydrothermal (Hidrotermal Tardía), and Póstuma stages (Ojeda et al., 1980; Cuadra, 1986; Arévalo et al., 1998). Late Magmatic alteration has been characterized as “potassic” alteration associated spatially and temporally with intrusion of the Sewell Tonalite, tonalite porphyry apophyses and the Teniente Dacite Porphyry. Pervasive potassic alteration of the mafic rocks in the El Teniente mine is characterized by abundant biotite, chalcopyrite, Fe-oxides, and anhydrite, but with only minor amounts of K-feldspar. Biotite alteration has been considered an early event of Late Magmatic alteration. Typical Late Magmatic veins cut pervasively biotite-altered rocks, and contain quartz, anhydrite, potassium feldspar, biotite, chlorite, magnetite, apatite and sulfides, including chalcopyrite, pyrite, bornite, and molybdenite (Figure 15A). Although these typical Late Magmatic veins generally lack halos, earlier biotite veins have biotite-rich halos (Figures 10B and 10D), and pervasive biotite alteration is related to the density of these early biotite veins.

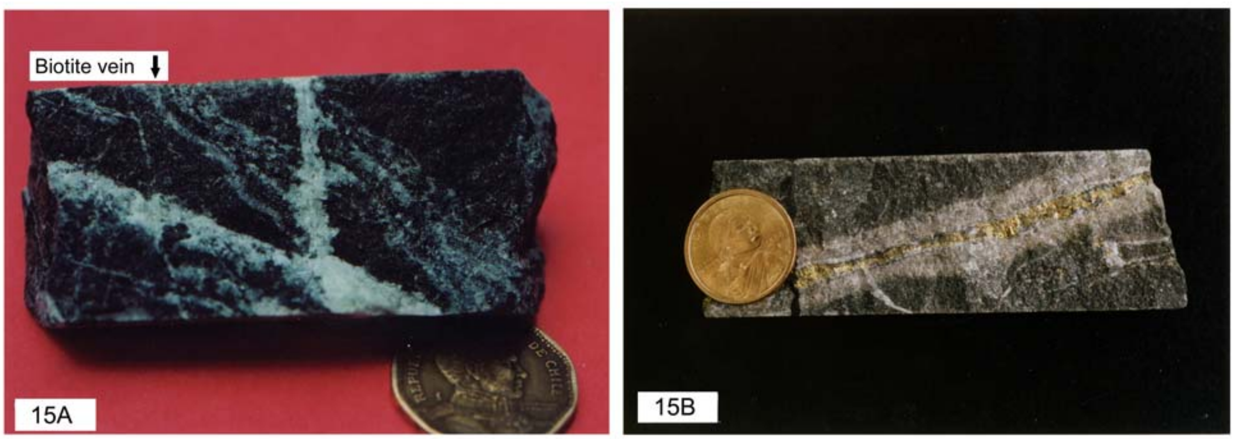


Figure 15. A) Late Magmatic quartz veins, without halos, in a biotite-altered mafic rock. The vertical quartz vein in the center of the photo cuts earlier thin biotite veins, which run from the lower right toward the upper left corner of the core section, across a displacement in these veins (sample DDH1659-563’; from a near vertical drill hole initiated on level Teniente 6, northeast of the Braden Pipe; 593N, 835E, 1,954 m above sea level). B) Principal Hydrothermal pyrite and quartz vein, with a sericite, chlorite and quartz halo, cutting a previously biotite-altered mafic rock (sample DDH1529-490’; sample from a drill hole initiated on level Teniente 5, east of the Braden Pipe; 123N, 1640E, 2,130 m above sea level; section 124N).

It is clear that biotite-alteration occurred in conjunction with multiple independent events, possibly over a period of time as long as >2 million years, from prior to, or in association with, the intrusion of the Sewell Tonalite at 7.1 Ma (Cuadra, 1986), through the time of the intrusion of the later porphyries, which occurred until 4.8 Ma (Figure 7). Other “stages” of alteration traditionally recognized in the deposit also have resulted from multiple independent events related to the emplacement of different breccias and felsic intrusions. Principal Hydothermal alteration, for example, has been associated spatially with the Sewell Tonalite, tonalite porphyry apophyses and Teniente Dacite Porphyry, implying that this type of alteration also occurred over an extended period and at different times in different areas of the deposit. Subsequent Late Hydrothermal alteration is best developed in a zone concentric to the Marginal Breccia of the Braden Pipe (Villalobos, 1975; Ojeda et al., 1980), but similar alteration also occurs surrounding other tourmaline breccias in the deposit (Arredondo, 1994), associated with latite ring-dikes around the Braden Pipe (Arévalo et al., 1998), and even in a tourmaline-cemented sector within the central rock-flour portion of the Braden Pipe (Floody, 2000). Available $^{40}Ar/^{39}Ar$ dating confirm the occurrence of multiple alteration events during the development of the deposit, with peaks near 5.3 Ma (equivalent to the 5.28 Ma U-Pb in zircon age of the Teniente Dacite Porphyry) and 4.7 Ma (similar to the 4.82 Ma U-Pb zircon age of one latite ring-dike) based on a statistical analysis of biotite and sericite dates, which range from 6.4 to 4.4 Ma (Maksaev et al., 2001, 2002).

Veins and associated alteration assemblages within the central copper-rich portion of the deposit are described here in an approximate chronological sequence, similar to the "stages" of alteration traditionally described at El Teniente. However, it is important to stress that, as in the case of emplacement of different breccia types, different alteration assemblages and veins developed repeatedly during the formation of the deposit, and there is no simple chronological sequence of vein types and/or alteration assemblages.

Magnetite-actinolite alteration

Magnetite-actinolite alteration, in association with magnetite-actinolite veins, is strongly overprinted by subsequent biotite alteration. Because of this, little is known about the distribution of magnetite-actinolite alteration at El Teniente. In the mine, it affects mainly the gabbros, diabases and basaltic porphyry intrusions. It is observed only locally in the Sewell Diorite, and may have occurred in the mafic rocks prior to the intrusion of the felsic plutons. It has also been reported from various areas surrounding the mine (Floody and Huete, 1998).

In the mafic rocks, magnetite and actinolite, or actinolitic hornblende, replaces clinopyroxene, usually pseudomorphically (Figure 10C). Calcic plagioclase exhibits normal zoning and apparently has not been albitized, but may contain many tiny (< 8 microns) magnetite and actinolite inclusions. Small amounts of chlorite associated with magnetite, epidote and subordinate amounts of quartz and anhydrite can also be present. Rocks affected by magnetite-actinolite alteration usually preserve original textures, are highly magnetic, and have low amounts of copper and few copper sulfide minerals.

Magnetite breccias and associated magnetite-actinolite alteration in and surrounding El Teniente are similar to alteration associated with magnetite-actinolite breccias in the Río Blanco-Los Bronces copper deposit (Skewes et al., 1994; Serrano et al., 1996). This type of alteration has been attributed to high-temperature (>350°C), highly saline fluids (Skewes et al., 1994, 2002), which may be either of magmatic origin or connate formation waters. It is similar to the magnetite-amphibole-plagioclase alteration described by Arancibia and Clark (1996) in the Island Copper porphyry deposit in British Columbia, Canada, which involved significant iron metasomatism by highly oxidizing, high-temperature fluids.

Biotite alteration

Biotite alteration, traditionally considered an early event of Late Magmatic alteration, and the first major stage of alteration associated with copper mineralization, preferentially affects the mafic intrusions that host most of the copper mineralization. The intensity of biotite alteration has obscured original petrologic characteristics of these mafic intrusions (Figure 10D). Original textures of the biotite-altered mafic rocks often are nearly totally destroyed, and fine-grained biotite has replaced pre-existing mafic minerals, and in some cases plagioclase. Disseminated biotite is often associated with anhydrite, chlorite, magnetite, rutile, chalcopyrite and sometimes bornite. Magnetite is very abundant in zones of biotite alteration, but it is not clear how much magnetite was emplaced during the earlier magnetite-actinolite alteration, prior to biotite alteration, and how much is contemporaneous with biotite.

Biotite alteration appears to be pervasive and have an isotropic distribution in most mafic rocks (Figure 10A), but in fact is related to a dense stockwork of biotite veins, ranging from <0.5 millimeters (Figure 10B) to several centimeters across, and with biotite-rich halos of variable width. Density of biotite veins is often so high that alteration halos overlap with each other and recognition of individual veins becomes difficult. Density of biotite-rich veins is greatest surrounding biotite breccias, where mafic rocks turn into a massive aggregate of secondary brown biotite. Here, recognition of the breccias themselves, and the distinction between breccias and surrounding biotite-altered mafic rocks, is often obscured by lack of mineralogic, textural and color differences between the biotite-rich breccia matrix and intensely biotite-altered mafic clasts (Figure 13D) and wall rocks surrounding the breccias. Intense biotite alteration occurs surrounding breccia complexes to the east and northeast of the Braden Pipe (sections 83N and 124N; Figure 4). Biotites from the area of intense biotite alteration intruded by Porphyry A, east of the

Braden Pipe (section 124N), have been dated by K-Ar as between 6.0 to 4.7 Ma (SERNAGEOMIN, 1986), and $^{40}Ar/^{39}Ar$ ages for biotite in various areas of the deposit range from 5.50 to 4.69 Ma (Maksaev et al., 2001).

Biotite veins can consist exclusively of brown biotite and sulfide minerals, but others may also have green biotite, quartz, anhydrite, feldspar, chlorite, sericite, magnetite, rutile, and apatite. These minerals may co-precipitate with biotite, or precipitate after biotite, when early formed veins are reopened by later hydrothermal fluids. Sequential fracture fillings produce concentric zoning, with an anhydrite, quartz, feldspar, chlorite and sulfide-rich center, grading out to biotite (Figure 10A). As the proportion of quartz, feldspar, chlorite and/or anhydrite increases, these veins are more readily recognizable in the mine and in drill core. Some biotite veins also have distinct grey halos of feldspar, quartz, anydrite and lesser amounts of biotite (Figure 12B). Sulfide minerals in biotite veins include chalcopyrite, with lesser bornite, pyrite and molybdenite, and these veins carry a significant part of the copper mineralization in the deposit. Biotite veins precipitated from highly saline, boiling and non-boiling magmatic fluids (Figure 16), at depths of 1 to 3 km below the paleosurface (Skewes et al., 2002).

Although biotite alteration has traditionally been considered coeval with the emplacement of felsic intrusions, in general felsic plutons have only minor, local biotite alteration. In many places, it is clear that felsic intrusions cut pre-existing biotite breccias, veins and biotite-altered mafic rocks (Figure 12). The Teniente Dacite Porphyry lacks biotite alteration. Biotite breccias occur on both flanks of this porphryry (section 83N; Figure 4), and two generations of biotite formation are recognized in the mafic rocks in this area (Arévalo et al., 1998), suggesting multiple stages of biotite alteration preceding the intrusion of this porphyry. In other areas of the deposit, felsic intrusions are clearly altered by biotite veins and breccias (Figure 13C). These relations imply that biotite alteration took place repeatedly over an extended time period in different areas of the deposit, in part preceding and in part subsequent to the emplacement of different felsic intrusions in the deposit (Figure 7).

Subsequent Late Magmatic alteration

Subsequent Late Magmatic alteration involved formation of veins of quartz, anhydrite, K-feldspar, biotite, chlorite and sulfide minerals, generally without halos, that cut, but do not alter, the earlier formed pervasive biotite (Figure 15A; Zuñiga, 1982; Arévalo et al., 1998). Distinguishing some of these veins from earlier biotite veins can be somewhat arbitrary, as the same minerals often fill the central portion of biotite veins. Most Late Magmatic veins are simply quartz, anhydrite and sulfide veins, without any biotite, internal zonation, or halos. Sulfide minerals in these veins are chalcopyrite, bornite, pyrite and molybdenite, and account for a significant part of the mineralization in the deposit, particularly in the area near the Teniente Dacite Porphyry where bornite is abundant. Late Magmatic veins, like earlier biotite veins, precipitated from highly saline, high-temperature, magmatic fluids, both boiling and non-boiling (Kusakabe et al., 1984, 1990; Skewes et al., 2002).

Principal Hydrothermal alteration

This alteration is characterized by destruction and replacement of pre-existing minerals by quartz and sericite, with lesser chlorite and anhydrite, in halos surrounding sulfide mineral-rich veins that also contain quartz, chlorite and anhydrite (Figure 15C; Zuñiga, 1982). Chalcopyrite and pyrite and are the main sulfide minerals, and bornite is absent from the Principal Hydrothermal alteration. Zuñiga (1982) described various Principal Hydrothermal veins. Within their halos, that vary from mineralogically homogeneous to zoned and/or banded, original plagioclase in mafic rocks, and feldspars and ferromagnesian minerals in felsic rocks, are replaced by sericite, quartz and chlorite, and original igneous textures are generally destroyed.

Intensity of this sericitic alteration is controlled by the density of veins and widths of their halos (Arévalo et al., 1998). It can vary from absent to pervasive, producing rocks composed totally of sericite and quartz, with minor chlorite, anhydrite and sulfide minerals. This type of alteration is most intense in the upper levels of the deposit surrounding the Teniente Dacite Porphyry stock, at a distance of a few hundred meters from the stock. It also is strongly developed in the upper levels of the deposit surrounding the contacts of the Sewell Tonalite and the porphyritic tonalite apophyses to the east of the Braden Pipe (Arévalo et al., 1998). Deeper in the deposit, the intensity of Principal Hydrothermal alteration decreases. $^{40}Ar/^{39}Ar$ ages for sericite from various areas of the deposit range from 6.35 to 4.39 Ma (Figure 7; Maksaev et al., 2001).

For Principal Hydrothermal veins, abundant vapor-rich fluid inclusions in quartz indicate boiling (Skewes et al., 2002). Highly saline, halite-bearing inclusions occur, but are not common. Quartz in veins and sericite in the vein halos precipitated from fluids with magmatic $\delta^{18}O$ and δD values, similar to the fluids from which Late Magmatic veins formed (Figure 16; Kusakabe et al., 1990; Skewes et al., 2002).

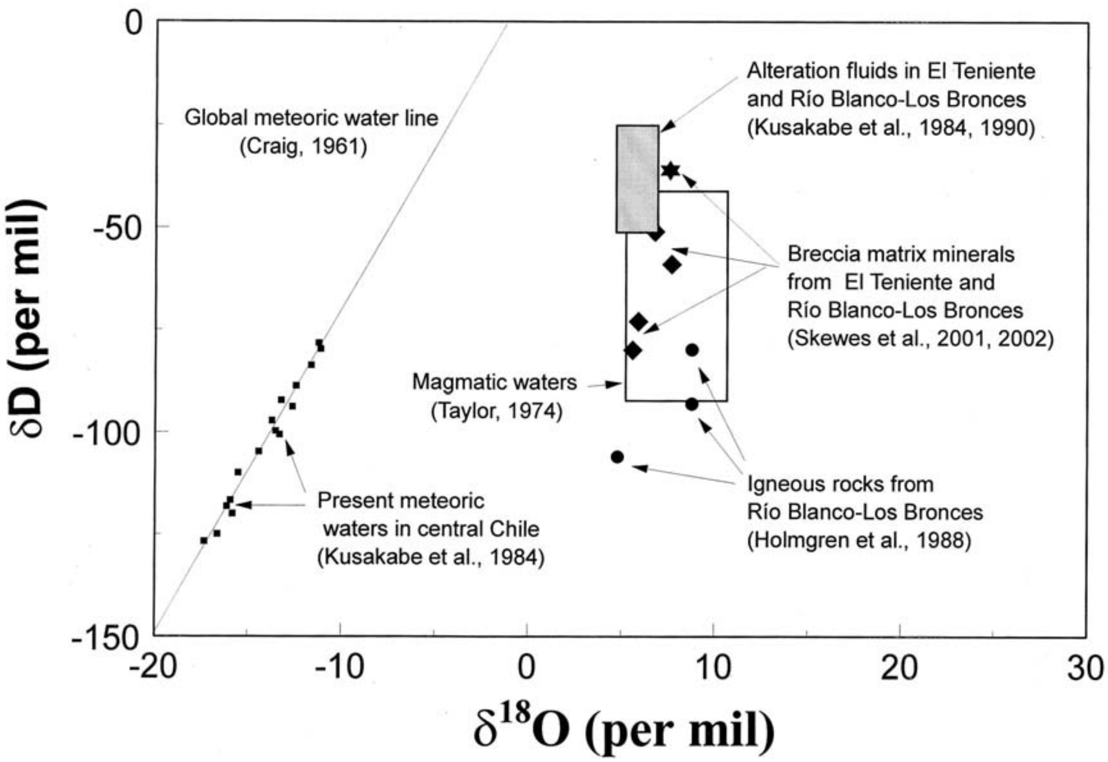


Figure 16. Plot, modified after Skewes et al. (2001, 2002, 2003), of $\delta^{18}O$ versus δD, in parts-per-mil, for hydrothermal fluids from which the minerals in the matrices of breccias at both El Teniente (stars) and Río Blanco-Los Bonces (diamonds) precipitated. The figure also shows the field for 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 Rio 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 a 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 in central Chile.

Late Hydrothermal alteration

Late Hydrothermal veins contain quartz, tourmaline, anhydrite, sericite, chlorite, gypsum, carbonates, chalcopyrite, bornite, pyrite, molybdenite, tenantite-tetrahedrite, and minor scheelite, stibnite, galena and sphalerite. These veins tend to be thicker than those associated with the Principal Hydrothermal alteration (Zuñiga, 1982). They also have wider alteration halos characterized by an aggregate of quartz, sericite and chlorite, and the destruction of the original igneous texture of the rock.

Late Hydrothermal alteration, the "tourmaline stage" of Howell and Malloy (1960), is spatially related to formation of the Braden Pipe, and in particular to the Marginal Breccia, a tourmaline-rich unit of the pipe. The Marginal Breccia contains clasts altered to the same quartz-sericite assemblage as produced by the Late Hydrothermal veins around the pipe (Figure 13B). This alteration also affects the latite ring-dike intrusions surrounding the pipe, and forms a concentric ring 150 m wide surrounding the pipe, within which bornite and tennantite are most abundant close to the pipe, zoning outwards to a greater abundance of chalcopyrite. Late Hydrothermal alteration also occurs in areas of the deposit where other tourmaline breccias have been emplaced, including in an area surrounding a large, strongly mineralized, tourmaline and anhydrite breccia complex south of the Braden Pipe (Figure 4; Arévalo et al., 1998), and around tourmaline breccias cutting the Sewell Tonalite and associated with the tonalite porphyry apophyses east of the Braden Pipe. A front of tourmalinization within the central rock-flour portion of the Braden Pipe also has characteristics similar to Late Hydrothermal alteration (Floody, 2000). As with Principal Hydrothermal alteration, the extent of pervasive sericitic alteration associated with Late Hydrothermal veins decreases with increasing depth in the deposit.

Abundant vapor-rich fluid inclusions, indicating boiling, occur in Late Hydrothermal veins (Skewes et al., 2002). Highly saline, halite-bearing inclusions occur, but are not common. $\delta^{18}O$ of the aqueous fluids that precipitated quartz in Late Hydrothermal veins is within the range of magmatic fluids and similar to the fluids from which both Late Magmatic and Principal Hydrothermal veins formed (Kusakabe et al., 1984, 1990).

Póstuma alteration

Póstuma alteration, traditionally considered the last stage of hypogene alteration, is restricted to the central rock-flour breccia of the Braden Pipe. It affects both the clasts and rock-flour matrix, and played an important role in the consolidation of the pipe. Although Póstuma alteration clearly post-dates the formation of the central rock-flour part of the Braden Pipe, it may have preceded Late Hydrothermal alteration associated with the formation of the Marginal Breccia unit of the pipe (Floody, 2000). Secondary minerals associated with Póstuma alteration are sericite, calcite and chlorite, with disseminated pyrite and locally chalcopyrite. Gypsum, carbonates, quartz, apatite, tennatite-tetrahedrite, sphalerite, and galena also fill cavities in the pipe, including some very large cavities that contain euhedral gypsum crystals that are >4 m in length (Floody, 2000).

Alteration around the deposit

Alteration surrounding the zone of pervasive biotite-altered rocks has not been studied in detail, mainly because these rocks lack economic amounts of copper. A transition zone of alteration to green biotite and chlorite, in which the abundance of chalcopyrite decreases relative to pyrite and copper grades drop below 0.5%, occurs immediately adjacent to the deposit (Villalobos, 1975; Zuñiga, 1982). Altered rocks in this zone also contain quartz, anhydrite, sericite, plagioclase, sphene, apatite, tourmaline and abundant Fe-Ti oxides, including magnetite, rutile, ilmenite and leucoxene, and veins contain chlorite, anhydrite, quartz and pyrite. Camus (1975) considered the inner part of this transition zone, in which the igneous textures of the original mafic rocks have been significantly affected, to result from chloritization of secondary biotite. Villalobos (1975), in contrast, considered the chlorite zone surrounding the deposit as a “basic front” beyond which iron-rich chlorite rather than biotite was the stable phase during Late Magmatic alteration. It is also possible that the chlorite alteration surrounding the deposit formed during the early magnetite-actinolite alteration within the deposit, but this has not yet been investigated.

The outer limits of the chlorite zone may, possibly, grade into a propylitic zone (Villalobos, 1975; Camus, 1975; Zuñiga, 1982), which has been characterized as the weak replacement of primary minerals by chlorite, magnetite, epidote and hematite, with subordinate amounts of tourmaline, sericite, quartz, calcite, siderite and pyrite. However, just as within the deposit, numerous small centers of felsic intrusions, hydrothermal breccias and alteration zones, such as at Lagunas La Negra and La Huifa, Olla Blanca, Agua Amarga and other regional prospects (Figure 3; Cuadra, 1986; Floody and Huete, 1998; Floody, 2000), occur in a region a few tens of kilometers wide surrounding the deposit, particularly to the north, and each of these centers has produced variable types and intensities of alteration and mineralization. The outer limits of this zone are difficult to determine, because the regional metamorphic mineral assemblages in rocks of the Farellones and Coya Machalí Formations have not been defined in this area.

Supergene alteration

A zone of supergene alteration coincides with complete leaching of anhydrite and is mapped above the upper limit of the presence of anhydite, which also corresponds to the deepest appearance of supergene chalcocite (Camus, 1975). Kaolinite, montmorillonite, alunite and sericite are the most abundant supergene alteration minerals. Original copper sulfide minerals have been replaced by limonite (goethite and jarosite) and hematite in the upper leached zone. A zone of copper enrichment 100- to 500-m thick, in which copper grades have locally doubled (Cuadra, 1986), underlies the leached zone. The upper part of the enriched zone, typically 80-m-thick, is an oxidized zone with chrysocolla, malachite, azurite, cuprite, native copper and copper pitch (Zuñiga, 1982; Cuadra, 1986; Arredondo, 1994). Below this oxidized layer, chalcocite is the dominant supergene copper bearing mineral, partly replacing hypogene copper sulfide minerals (bornite and chalcopyrite), along with covellite, native copper and cuprite. The uppermost part of the supergene enrichment zone, including the oxidation layer, may have as much as 15% copper (Zuñiga, 1982).

Depth of penetration and intensity of supergene alteration is controlled by topography, as well as the location of the Braden Pipe and Teniente Dacite Porphyry, which affect the permeability of the rocks they intrude (Zuñiga, 1982). The supergene alteration zone is thickest in regions of highest topography east of the Teniente Dacite Porphyry and Braden Pipe, but supergene enrichment attains its greatest depth of penetration in the highly fractured area surrounding the dacite porphyry (section 83N; Figure 4). Supergene enrichment on the flanks of the dacite porphyry (Figure 5) has further contributed to the erroneous impression that this stock was the main source of copper mineralization in El Teniente.

Copper mineralization

Most hypogene copper mineralization occurs within the pervasively biotite-altered mafic intrusives of the deposit, with grades between 0.75 and 1.5% over a 2.7 by 2 km area (Figure 5). Anomalous high copper grades of >1.5% are distributed irregularly surrounding the copper-poor cores of the Teniente Dacite Porphyry and Braden Pipe. High copper grades occur on both flanks of the dacite porphyry. In part, this is the result of supergene enrichment, which penetrated to below Teniente level 6 (2,165 m above sea level) on the west side of the porphyry and to below Teniente level 5 (2,284 m above sea level) on the east side of the porphyry (section 83N; Figure 4). However, it also reflects the presence of mineralized biotite and anhydrite breccias, which flank the area intruded by the dacite porphyry (Figures 4 and 5). High hypogene copper grades also occur in various other areas where breccia complexes were emplaced. These occur to the east and northeast of the Braden Pipe, as a NW-SE-trending group of biotite, igneous, anhydrite and tourmaline breccias, in some cases intruded by apophyses of porphyritic tonalite (Figure 4). They also occur to the south of the pipe, as a NE-SW-trending group of tourmaline and anhydrite breccias. In the Esmeralda sector of the mine (400-600N, 1000-1200E; Figures 4 and 5), which is developed around just one group of breccias, there is an estimated 3.5 million metric tonnes of fine copper at an average grade of 1% (Morales, 1997), and there are more than 10 such breccia complexes identified to date in the deposit! A narrow zone of relatively high copper also occurs in the tourmaline-rich Marginal Breccia unit of the Braden Pipe, and some copper occurs within a tourmalinized part of the central rock-flour breccia of this pipe (>1 million metric tonnes with an average grade of 1.16% Cu; small by El Teniente's standards; Floody, 2000).

Clearly, copper mineralization at El Teniente was emplaced in a series of independent events. These events occurred over an extended period, from the time of biotite alteration, beginning prior to the crystallization of the Sewell Tonalite, to the time of tourmalinization after emplacement of the central part of the Braden Pipe. Molybdenite Re-Os ages indicate at least four distinct mineralization events, which span an approximately 2 million year period, at 6.3, 5.6, 4.9 and 4.4 Ma (Figure 7; Maksaev et al., 2001, 2002; Munizaga et al., 2002). However, the Re-Os ages are all for molybdenite associated with mineralization in felsic rocks and they do not date the mineralization in the mafic intrusive rocks, which host 80% of the Cu in the deposit and into which the younger felsic rocks intrude. Furthermore, molybdenite appears in significant quantity relatively late in the paragenetic sequence of mineralization in the deposit, and early copper-sulfides occur without molybdenite. Therefore, these ages are considered to represent only a minimum time span for mineralization events in the deposit (Figure 7). Significantly, although the 6.3 and 4.9 Ma mineralization ages do correspond to U-Pb in zircon crystallization ages of felsic plutons in the deposit, the 5.6 and 4.4 Ma ages do not. Also, none of these four episode of mineralization correspond with, nor are within ±300,000 years of the 5.28 Ma U-Pb zircon crystallization age of the Teniente Dacite Porphyry (Figure 7), which has often been considered the "productive" pluton in the deposit, but is clearly not.

Chalcopyrite is the dominant copper sulfide mineral in the deposit. Concentric zonation of copper sulfide minerals around the copper-poor cores of both the Teniente Dacite Porphyry and Braden Pipe consist of a narrow bornite-rich (bornite > chalcopyrite) zone grading out into a broad chalcopyrite-rich (chalcopyrite >> bornite + pyrite) zone. Further outwards, where copper grades are less than 0.5% (Figure 5), is a pyrite-rich zone (pyrite >> chalcopyrite +

bornite; Howell and Molloy, 1960; Camus, 1975, Ojeda et al., 1980; Arévalo et al., 1998). Intrusion of both the copper-poor Teniente Dacite Porphyry stock and the Braden rock-flour breccia pipe during the last stages of development of the deposit truncated previously mineralized rocks, and the "barren" core of the deposit is simply superimposed, at a late stage, on previously emplaced copper mineralization. Although intrusion of both the dacite porphyry and the Marginal Breccia unit of the Braden Pipe generated bornite-rich zones surrounding their borders, thereby producing the concentric zonation in sulfide mineral distribution, this zonation also post-dates the early emplacement of chalcopyrite, and is the result of telescoping of different events in the formation of the deposit.

Osmium, and by implication other metals such as copper and molybdenum, are all derived from the 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 during formation of the deposit (Freydier et al., 1997). If these metals had been derived from the surrounding country rocks, greater variability in the $^{187}Os/^{188}Os$ ratios would be expected. Lead isotope ratios, measured in galena ($^{206}Pb/^{204}Pb$=18.57, $^{207}Pb/^{204}Pb$=15.60, and $^{208}Pb/^{204}Pb$=38.49; Puig, 1988; Zentilli et al., 1988), also exhibit little variability, and lead isotopes are the same as the lead isotopic compositions of recent Andean volcanic rocks erupted in central Chile, implying that lead in these galenas was also derived exclusively from the igneous rocks in the deposit. Furthermore, these lead isotopic ratios, as well as the osmium isotopic ratios, which are more similar to mantle (0.13) than crustal (>>1.0) values, indicate that these metals, and the magmas they were derived from, formed in the sub-Andean mantle contaminated by the subduction of a small amount of pelagic and terrigenous sediment, and continental crust tectonically eroded off the continental margin. A calculated total sulfur isotopic composition $\delta^{34}S$ of +4.5 per mil (Kusakabe et al., 1984) is also similar to $\delta^{34}S$ values of non-mineralized Andean granitoids, which range from +3.3 to +6.1 per mil (Sasaki et al., 1984), and these are in turn similar to Japanese granitoids generated from mantle contaminated by subducted marine sulfur.

Discussion

Magmatic evolution of the deposit

Prior to uplift and erosion this giant deposit contained >100x10^6 metric tonnes of Cu (Skewes and Stern, 1995). It would require a minimum volume of >300 km^3 of magma with 100 parts-per-million (ppm) Cu to supply this quantity of Cu ore, even if the extraction of Cu from the magma by the exsolution of saline magmatic fluids was 100% efficient, which it is not. Therefore the minimum volume of magma must have been significantly larger. A volume of >600 km^3 would be consistent with the 60 km^3 of magma, with 62 ppm Cu, calculated to have produced the 6x10^6 metric tonnes of Cu in the Yerington deposit in Nevada (Cline and Bodnar, 1991).

The very small volume of the Teniente Dacite Porphyry, <<10 km^3, precludes this late, weakly mineralized felsic stock from being the "productive" pluton in the deposit. In fact, mafic igneous rocks are volumetrically more significant that felsic rocks in the vicinity of El Teniente (Figures 4 and 8B). Mafic igneous intrusive rocks host the El Teniente deposit, and after an episode of intrusion of felsic plutons between 7.1 and 4.8 Ma, intermediate dikes and mafic lavas were again emplaced in and surrounding the deposit (Figure 7). 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 (Hildreth and Moorbath, 1988; Stern et al., 1990). Even during the period when felsic plutons intruded the mafic intrusive rocks that host the deposit, volatile-rich mafic magmas continued to be generated in the sub-arc mantle and rise into the crust, as indicated by the intrusion of mafic Porphyry A (Figure 7) into the Sewell Tonalite between 6.6 and 6.0 Ma. Other mafic magmas may have mixed with or underplated magmas in the deeper parts of the evolving magma chamber below the deposit, rather than reaching the surface. This process of open-system behavior 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 at El Teniente. 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 sulfur (Hattori, 1996; Pallister et al., 1996, Kress, 1997; Candela, 1997; Hattori and Keith, 2001), as well as copper, iron, boron, osmium and other elements derived from the sub-arc mantle, to felsic magmas forming near the top of the chamber that otherwise might be poor in sulfur (Nagashima and Katsura, 1973) and chalcophile elements. Evidence for open-system behavior 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).

We propose that El Teniente formed above a large open-system magma chamber (Figure 17), fed by mantle-derived mafic magmas, that persisted for the >2 million year time period of the multiple episodes of breccia emplacement and mineralization that formed the deposit (Figure 7). This magma chamber was cooling at >4 km below the paleosurface. This is implied by the fact that the larger breccias in El Teniente are rooted >2 km below the current surface, below the deepest exploration drill holes that reach 800 meters below the lowest level of mine operations, and because >1 km of erosion has likely occurred since the last episodes of breccia emplacement and mineralization at 4.4 Ma (Figure 7; Skewes and Holmgren, 1993). El Teniente formed above the roof of this long lived, open-system magma chambers during dynamic conditions of crustal uplift and erosion (Stern and Skewes, 1994). As mafic mantle-derived magmas replenished the base of the open-system magma chamber, exsolution of sulfur and metal-rich aqueous brines and vapor from the crystallizing upper part of the chamber produced brecciation, alteration and mineralization of the roof rocks above the chamber (Burnham, 1985; Cloos, 2001). During the multistage development of the El Teniente deposit, exsolution of magmatic-hydrothermal fluids created first the early biotite, igneous and anhydrite breccia complexes and associated pervasive biotite alteration and copper mineralization. Subsequently, tourmaline, anhydrite and rock-flour breccias, both mineralized and barren, were emplaced in association with sericitic alteration as well as the addition and redistribution of copper mineralization.

Eventually the magma chamber cooled and crystallized to form the felsic magmas that produced the Sewell Tonalite, porphyritic felsic apophyses, and ultimately the Teniente Dacite Porphyry and latite dikes. The cooling and crystallization of this chamber occurred as the input of mantle-derived mafic magma into the base of the magma chamber below the deposit decreased, from late Miocene to Pliocene, due to the progressive decrease in subduction angle that ultimately lead to the eastward migration of the locus of Andean magmatic activity (Stern, 1989; Skewes and Stern, 1994, 1995; Stern and Skewes, 1995, 1997). The youngest felsic porphyry stocks -- the Pliocene Teniente Dacite Porphyry and latite dikes -- that intruded the already biotite-altered and mineralized mafic rocks in the deposit, contained less input of sulfur and copper from mantle-derived mafic magmas, and were copper-poor. These small, late felsic dikes and stocks cut and redistributed previously emplaced copper mineralization, but were not the main source of the copper in this deposit.

A significant temporal chemical trend that is observed among igneous rocks related to the deposit is towards higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios (Figure 9). The youngest, most radiogenic rocks in the region are the post-mineralization intermediate andesite dikes and basaltic andesite lavas in the Cachapoal River valley (Figure 9). Therefore, this temporal trend is independent of the SiO_2 content of the rocks, and is likely the result of progressively greater contamination of their mantle source by subducted sediments and continental crust due to the decrease in angle of subduction prior to the eastward migration of the arc (Stern, 1989, 1991, 2001; Stern and Skewes, 1995, 1997). The isotopic data for both igneous rocks and ore minerals associated with the El Teniente do not support the involvement of continental crust in the formation of the deposit other than those continental components subducted into the underlying subarc mantle magma-source region.

Similar isotopic changes also occurred during the development of the other giant copper deposits in central Chile (Figure 6). The southwards temporal migration of these changes reflects the southward migration of the locus of subduction of the Juan Fernández Ridge (Stern and Skewes, 1995; Yáñez et al., 2001, 2002), and the timing of formation of El Teniente and other giant copper deposits in central Chile was clearly related to the late Miocene changes in subduction geometry that accompanied subduction of the ridge (Skewes and Stern, 1994, 1995). Ridge subduction also enhances rates of tectonic erosion of the continental margin and the subduction, into the mantle source region of Andean magmas, of both terrigenous and pelagic sediments (Stern, 1991), and presumably also water and chlorine, which are of fundamental importance in the removal of Cu from crystallizing magmas and its transport and deposition in the crust.

The La/Yb ratios of the more mafic rocks associated with the deposit also increase, but only approximately two-fold, from ≤5 in the early Miocene Coya-Machalí volcanic rocks, to ≤8 in the late Miocene gabbros, diabases and basaltic porphyries in the mine, to ≈10 for the Pliocene basaltic andesite lava flows in the Cachapoal River valley (Figure

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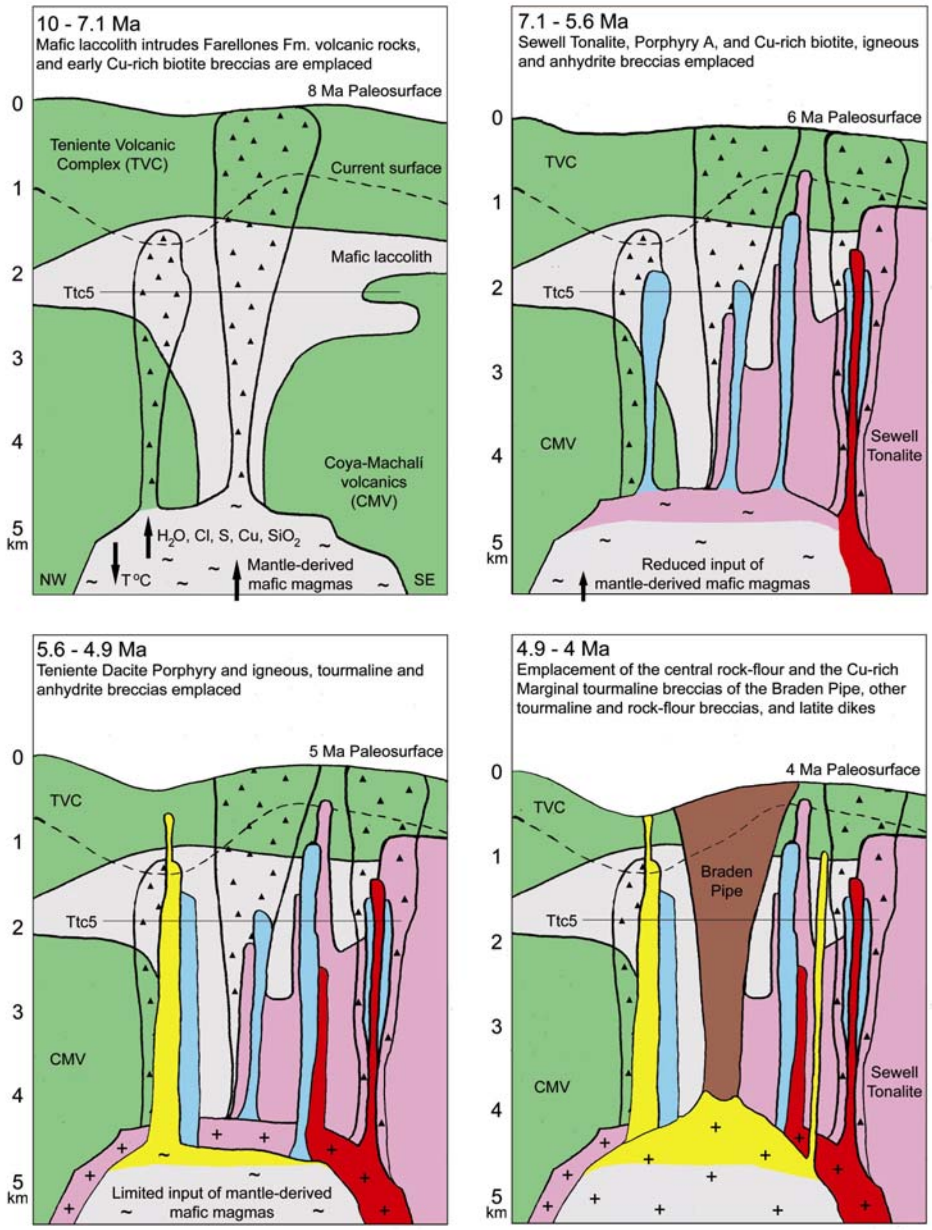

Figure 17. Schematic illustration of the sequential stages in the development of the El Teniente deposit, as described in the text. Colors of rock units are essentially the same as in Figures 3 and 4, with green representing both Teniente Volcanic Complex (TVC) and Coya-Machalí (CMV) volcanic rocks, grey the mafic laccolith, pink the Sewell Tonalite, red for Porphyry A, yellow the Teniente Dacite Porphyry and latite dikes, triangles for biotite breccias, blue for anhydrite breccias, and brown for the Braden Pipe. For simplicity, neither igneous nor tourmaline breccias are depicted.

8A). This change may reflect a decrease in the degree of partial melting of the mantle as subduction angle decreased prior to eastward arc migration (Stern, 1989, 1991; Stern and Skewes, 1995). Kay et al. (1999) and Rabbia et al. (2000) suggest that the high La/Yb values for felsic rocks related to the deposit imply a shift to fractional crystallization or melting in the deeper crust, involving garnet rather than amphibole. However, these high ratios can also be explained by fractionation of minor and trace mineral phases within and extraction of saline magmatic fluids from the roof of a shallow crustal magma chamber during the final stages of its solidification. This is consistent with the very small relative volume of the late Teniente Dacite Porphyry and other small felsic stocks (Figure 8B).

Genesis of the deposit

Formation of the giant El Teniente deposit began with intrusion of a mafic complex, with the form of a laccolith, into extrusive rocks of the Miocene Teniente Volcanic Complex (Figure 17A). The center of this mafic laccolith, more than 2,000 m thick, is presumably located over its feeder dikes, as well as where the Sewell Tonalite and Teniente Dacite Porphyry subsequently intruded and the copper deposit ultimately was developed. What focused magmatism and mineralization in such a specific area over an extended 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. Important N-S, NE-SW and NW-SE crustal structures intersect at the deposit, and in the active southern Andean arc, the largest long-lived (>1 million years) magmatic systems, producing giant, >10 km in diameter calderas, such as the Maipo caldera at 34°S (Stern et al., 1984), 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 all occur where the generally N-S trending Andean arc is intersected by NW-SE arc segments (see Figures 1 and 2 in Muñoz and Stern, 1988).

After formation of the mafic laccolith that hosts the deposit, magnetite-actinolite alteration occurred as the result of circulation of either magmatic fluids or connate formation water. This pre-mineralization stage of alteration is poorly constrained, but involved the emplacement of breccias and associated stockwork vein systems, and significant iron metasomatism, and was clearly not merely auto-metamorphism or uralitization.

Subsequently, multiple biotite breccia complexes, associated biotite veins, pervasive biotite alteration and the first stage of copper mineralization developed above the evolving open-system magma chamber (Figure 17A) that ultimately crystallized to form the Sewell Tonalite (Figure 17B). This tonalite, and younger porphyritic mafic (Porphyry A) and felsic apophyses, intruded these breccias and the biotite-altered and copper-mineralized mafic rocks, beginning possibly as early as 7.1 Ma (Cuadra, 1986), and certainly before 6.6 Ma (Maksaev et al., 2001). Biotite, igneous and anhydrite breccias also continued to form and contribute copper to the system even after the crystallization of the Sewell Tonalite, to at least 4.7 Ma (Maksaev et al., 2002). Some of these breccias cut the Sewell Tonalite, implying the continued persistence as the source of mineralizing fluids of the deep open-system magma chamber below the evolving deposit. The main group of these breccia complexes, which are the areas of highest grade hypogene copper in the deposit (Figure 5), are located east and northeast of the Braden pipe, along a NW-SE trend that parallels or is within the Puquios/Codegua fault zone (Figures 3 and 4). Other biotite breccias also formed west of the area later intruded by the Teniente Dacite Porphyry (section 83N; Figure 4), and presumably in the area cut by the Braden Pipe, because this breccia contains abundant clasts of previously biotite-altered mafic rocks (Figure 13B).

The youngest porphyry intrusions, including the Teniente Dacite Porphyry and latite dikes, are associated in time with the emplacement of both mineralized and unmineralized tourmaline, anhydrite and rock-flour breccias, and sericitic alteration in the upper levels of the deposit between 6.4 and 4.4 Ma (Figures 17C and 17D; Maksaev et al., 2001). One group of these breccias occurs south of the Braden Pipe, along a NE-SW trend paralleling the strike of the Teniente fault zone (Figures 3 and 4). The largest tourmaline and rock-flour breccias is the Braden Pipe (Figure 17D). This pipe clearly formed in multiple stages, but the exact chronology is difficult to determine. The central rock-flour part of the pipe contains clasts of both latite and tourmaline breccia, and this central part is surrounded by the tourmaline-rich Marginal Breccia and latite ring-dikes. Howell and Molloy (1960) suggested that the Marginal Breccia formed first, and then the central part of this tourmaline breccia was obliterated by the emplacement of rock-flour breccia. Floody (2000) has suggested that the rock-flour breccia formed in an area where earlier tourmaline breccias had been emplaced, but that the Marginal Breccia formed after the central rock-flour unit, by tourmalinization of the fractured wall surrounding the rock-flour breccia pipe. Tourmalinization, and associated mineralization, has also affected the central rock-flour portion of the pipe (Floody, 2000). Whatever the chronology, it is clear that, like the deposit itself, formation of this single large and complex breccia pipe involved mutiple intrusions of latite, tourmaline and rock-flour breccias, and cannot be explained by the simple step-wise intrusion of first latite, then tourmaline breccia and finally rock-flour breccia.

Fluid inclusion and stable isotope data indicate that at El Teniente, the 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 the input of significant amounts of meteoric water into the deposit (Figure 16; Kusakabe et al., 1984, 1990; Skewes et al., 2001, 2002). Although the influx of meteoric water has been invoked to explain sericitic alteration in many porphyry copper deposits (Hedenquist and Lowenstern, 1994), it was not the fundamental cause of this type of alteration in El Teniente. This temporal shift in alteration effects is associated with the appearance of tourmaline rather than biotite breccias. This shift was possibly caused by changes, from mafic to more felsic, in the chemistry of the magmas from which the fluids that formed these different breccia types exsolved. Alternatively, temporal changes may have occurred in the depth and nature of the fluids exsolved from these magmas. In El Teniente, as well as in the other giant copper deposits in central Chile, early biotite breccias and biotite alteration formed from fluids exsolved from deeper magma chambers, while later tourmaline breccias and sericitization resulted from fluids derived from shallower magma chambers, due to both progressive uplift and erosion (Skewes and Holmgren, 1993), and the progressive intrusion of younger plutons to higher levels in the deposit. Biotite breccias and alteration may have formed from saline brines exsolved from magmas under lithostatic conditions, at sufficiently high pressures to prevent either extensive boiling or simultaneous exsolution of an immiscible vapor phase (Cline and Bodnar, 1994). As high pressure lithostatic conditions gave way to later lower pressure hydrostatic conditions, due to a combination of uplift and erosion, and also progressive fracturing in the later stages of development of the deposit, simultaneous exsolution of brine and immiscible vapor phase may have occurred from the same magma chambers that previously had exsolved only brines. This would increase the amount of vapor formed, and the extent of mixing between saline brines and condensed vapors, thereby increasing the potential for sericitic alteration (Skewes et al., 2003).

Most copper mineralization in the deposit was emplaced as chalcopyrite during the early stage of pervasive biotite-alteration of mafic host rocks, associated with the emplacement of biotite breccias and veins. Both enrichments and depletions in the nearly uniform, original copper distribution appear to be the result of subsequent magmatic-hydrothermal events. Intrusion of mineralized igneous, anhydrite and tourmaline breccia complexes to the east, northeast and south of the Braden Pipe added copper to the deposit to produce localized areas of high (>1.5%) copper grade (Figure 5). Emplacement of both the Teniente Dacite Porphyry and the central rock-flour unit of the Braden Pipe truncated previously pervasively biotite-altered and copper-mineralized rocks in the areas now occupied by their barren cores, and in the case of the dacite porphyry, concentrated copper in a bornite-rich zone on the flanks of the porphyry. Emplacement of the tourmaline-rich Marginal Breccia of the Braden Pipe contributed copper to the deposit, and Late Hydrothermal alteration related to this breccia created a bornite-rich zone surrounding the barren core of the pipe. Finally, supergene enrichment further enhanced copper grades, particularly on the flanks of the dacite porphyry (Figure 5).

Classification of the deposit

A barren, or copper-poor core, is a characteristic of many copper porphyry deposits (Lowell and Guilbert, 1970). However, in El Teniente, the barren core was clearly produced at a late stage, when the copper-poor Teniente Dacite Porphyry and Braden rock-flour breccia pipe were emplaced into previously biotite-altered and mineralized rocks (Figure 17). Concentric zoning of bornite > chalcopyrite > pyrite surrounding the barren cores of the Teniente Dacite Porphyry and Braden Pipe, which Howell and Molloy (1960) cited as the typical "circular configuration" of mineralization "arrayed concentrically around a common center" characteristic of "a model porphyry copper deposit", is, in El Teniente, actually just an artifact of the late intrusion of these copper-poor bodies into the previously pervasively biotite-altered and mineralized mafic rocks, within which chalcopyrite is the dominant sulfide. This concentric zoning reflects only the multistage development of the deposit rather than a temperature gradient or fluid-rock alteration pattern surrounding a single felsic porphyry intrusion.

In contrast to porphyry deposits. Howell and Molloy (1960) note that in some copper deposits the orebody itself occupies the central core, and specifically that "the mineralized breccia deposits belong to this group" and "strictly speaking, many of them cannot be classified as porphyry copper." We agree 100% with the implications of this comment with regard to El Teniente. Although copper porphyry deposits commonly contain breccias, El Teniente is clearly an enourmous magmatic-hydrothermal breccia deposit. Classification of El Teniente as either a giant copper "porphyry" or "breccia" deposit may be considered by some to be largely a semantic problem, but if this classification has genetic significance, it becomes an important distinction, and it is clear that El Teniente is a breccia deposit. El Teniente may have many aspects of a porphyry deposit, including the presence of porphyritic igneous rocks, large tonnage, potassic and sericitic alterations zones associated with stockwork veins, and concentric zonation of copper sulfide minerals around a barren core. However, most of these key features, in particular the deposition of the large amount of copper and the barren core, are directly related to multiple breccias in the deposit.

El Teniente has much in common with the other two giant copper deposits in central Chile, Los Pelambres and Río Blanco-Los Bronces (Figure 1; Skewes and Stern, 1994, 1995). Their Miocene and Pliocene ages, large tonnage, and the presence of multiple mineralized biotite, igneous, anhydrite, and tourmaline magmatic-hydothermal breccias in each deposit are the most obvious similarities. One important difference, however, is that in both Los Pelambres and Río Blanco-Los Bronces, biotite breccias and veins in the central zone of potassic alteration and high-grade copper were emplaced in felsic plutonic rocks, and these biotite breccias and veins are easily recognized and mapped. High copper content in Los Pelambres has been correlated directly with the density of biotite veins (Atkinson et al., 1996), and in Río Blanco-Los Bronces with the presence of biotite breccias, veins and alteration in and surrounding the central Río Blanco breccia complex (Serrano et al., 1996). In El Teniente, the rocks cut by biotite breccias and veins are themselves dark colored, biotite-altered mafic intrusions. The biotite breccias and veins lack color and mineralogic contrast with their host rocks, and they have not been recognized and mapped until recently.

Furthermore, in the Río Blanco-Los Bronces deposit, the multiple mineralized breccias are distributed over a >6 x 2 km zone, and many of the late, large tourmaline-rich breccias, such as Donoso (Skewes et al., 2003) and Sur-Sur (Vargas et al., 1999), and rock-flour breccias such as La Americana, flank the central biotite-altered zone associated with the Río Blanco breccia complex (Serrano et al., 1996). This makes the multiplicity of independent events that formed this deposit relatively clear. In El Teniente, the multiple breccias are more closely spaced, in a 2 x 2.7 km area, and the enormous copper-poor Braden rock-flour breccia pipe, as well as the tourmaline-rich Marginal Breccia of this pipe, occur directly in what has been considered the center of the deposit. This has resulted in concentric zonations in copper content and sulfide mineral distribution that have obscured the association of high-grade hypogene copper with early biotite breccias, veins, and pervasive biotite alteration. In Río Blanco-Los Bronces, where late tourmaline and rock-flour breccias, and dacite porphyries, were emplaced along the margins of the Río Blanco breccia complex, this concentric zonation does not occur.

From both a genetic and exploration point of view, these three giant deposits are all better considered megabreccia deposits, not porphyry deposits. The Los Bronces breccia deposit, for example, with >10 million metric tonnes of fine copper, does not include a single porphyry stock (Warnaars et al., 1985; Skewes et al., 2002)! The larger Río Blanco-Los Bronces deposit does, but as in El Teniente, these are late, copper-poor intrusions that have redistributed, rather than contributed, copper to the system. Such porphyries may focus later supergene alteration by creating fractures and enhanced permeability around their margins. However, they do not themselves provide evidence for the possible extent of hypogene mineralization in a megabreccia deposit such as El Teniente or the other giant deposits in central Chile. Therefore, the suggestion of Howell and Molloy (1960) that felsic porphyries should be the main target in the exploration for Andean deposits needs to be reconsidered as a primary exploration strategy, at least in the Andes of central Chile.

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References

Arancibia, O., and Clark, A., 1996 - Early magnetite-amphibole-plagioclase alteration-mineralization in the Island porphyry copper-gold molybdenum deposit, British Columbia, *Economic Geology* 91, 402-438.

Arévalo, A., Floody, R., and Olivares, A., 1998 - Modelo Geometalúrgico. Estudio geometalúrgico del mineral a explotar a mediano y largo plazo. *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Internal Report* GL-133/98, 76p.

Arredondo, C.S., 1994 - Distribución caracterización y génesis de los cuerpos de brechas ubicados en el sector central-este del yacimiento El Teniente. Memoria de Título, *Universidad de Chile, Departamento de Geología y Geofísica, Santiago*, 99p.

Atkinson, W.W. Jr, Souviron, S., Vehrs, T.I., and Faunes, A., 1996 - Geology and mineral zoning of the Los Pelambres porphyry copper deposit, Chile; *in* Camus, F., Sillitoe, R.H., and Petersen, R.,(Eds.), Andean Copper Deposits, *Society of Economic Geologists Special Publication* 5, 131-155.

Baros, M.C., 1996 - El Teniente, Los Hombres del Mineral, *Gráfica Andes, Santiago*, 500p.

Burnham, C.W., 1985 - Energy release in subvolcanic environments: implications for breccia formation, *Economic Geology* 80, 1515-1522.

Camus, F., 1975 - Geology of the El Teniente orebody with emphasis on wall-rock alteration, *Economic Geology* 70, 1341-1372.

Candela, P.A., 1977 - A review of shallow, ore related granites: textures, volatiles, and ore metals, *Journal of Petrology* 38, 1619-1633.

Charrier, R., and Munizaga, F., 1979 - Edades K-Ar de volcanitas cenozoicas del sector cordillerano del río Cachapoal (34°15' Lat. Sur.), *Revista Geológica de Chile* 7, 41-51.

Charrier, R., Baeza, O., Elgueta, S., Flynn, J.J., Gans, P., Kay, S.M., Muñoz, N., Wyss, A.R., and Zurita E., 2002 - Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile 33°-36°S.L., *Journal of South American Earth Sciences* 15, 117-139.

Clark, A.H., 1993 - Are outsize porphyry copper deposits either anatomically or environmentally distinctive?; *in* Whiting B.H., Mason, R., and Hodgson, C..J., (Eds.), Giant Ore Deposits, *Society of Economic Geologist Special Publication* 2, 213-283.

Cline, J., and Bodnar, R.J., 1991 - Can economic porphyry copper mineralization be generated by typical calc-alkaline melt, *Journal of Geophysical Research* 96, 8113–8126.

Cline, J., and Bodnar, R.J., 1994 - Direct evolution of saline brine from a crystallizing silicic melt at the Questa, New Mexico, molybdenum deposit, *Economic Geology* 89, 1780-1802.

Cloos, M., 2001 - Bubbling magma chambers, cupolas, and porphyry copper deposits, *International Geology Review* 43, 285-311.

Cornejo, P., Tosdal, R.M., Mpodozis, C., Tomlinson, A.J., Rivera, O., and Fanning, C.M., 1997 - El Salvador, Chile, porphyry copper revisited: geologic and geochronologic framework, *International Geology Review* 39, 22-54.

Craig, H., 1961 - Isotopic variations in meteoric waters, *Science* 133, 1702-1703.

Cuadra, P., 1986 - Geocronología K-Ar del yacimiento El Teniente y areas adyacentes, *Revista Geológica de Chile* 27, 3-26.

Cuadra, P., 1992 - Geocronología yacimiento El Teniente y áreas adyacentes: informe de situación, *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Internal Report* GL-397, 34 p.

Floody, R., 2000 - Estudio de vulnerabilidad geológica-geotecnia de Chimenea de Brecha Braden. Fase 1, Geología de Brechas Braden, *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Internal Report* GL-044/00, 90p.

Floody, R., and Huete, C., 1998 - Potencial distrito Teniente, *Report to the Gerencia de Exploraciones, CODELCO-CHILE*, 49p.

Freydier, C., Ruiz, J., Chesley, J., Candless, T., and Munizaga, F., 1997 - Re-Os isotope systematics of sulfides from felsic igneous rocks: application to base metal porphyry mineralization in Chile, *Geology* 25, 775-778.

Garrido, I., Riveros, M., Cladouhos, T., Espiñeira, D., and Allmendinger, R., 1994 - Modelo geológico estructural yacimiento El Teniente, *VII Congreso Geológico Chileno, Concepción, Actas* 2, 1553-1558.

Garrido, I., Cembrano, J., Siña A., Stedman, P., and Yáñez, G.A., 2002 – High magma oxidation state and bulk crustal shortening: key factors in the genesis of Andean porphyry copper deposits, central Chile (31-34°S), *Revista Geológica de Chile* 29 (1), 43-54.

Gerlach, D.C., Frey, F.A., Moreno-Roa, H., and López-Escobar, L., 1988 - Recent volcanism in the Puyehue-Cordón Caulle region, southern Andes, Chile (40.5°S); petrogenesis of evolved lavas, *Journal of Petrology* 29, 333-382.

Godoy, E., Yáñez, G.A., and Vera, E., 1999 - Inversion of an Oligocene volcanic-tectonic basin and uplifting of its superimposed Miocene magmatic arc in the Chilean Central Andes: first seismic and gravity evidences, *Tectonophysics* 306, 217-236.

Guzmán, C., 1991 - Alteración y mineralización de los pórfidos dioríticos del sector central del yacimiento El Teniente. Memoria de Título*, Universidad de Chile, Departamento de Geología y Geofisica, Santiago*, 145p.

Hattori, K.H., 1996 - Occurrence of sulfide and sulfate in the 1991 Pinatubo eruption products and their origin; *in* Newhall, C.G., and Punogbayan, R.S., (Eds.), Fire and Mud; Eruptions and Lahars of Mount Pinatubo, Philippines, *University of Washington Press*, 807-824.

Hattori, K.H., and Keith, J.D., 2001 - Contribution of mafic melt to porphyry copper mineralization: evidence from Mount Pinatubo, Phillipines, and Bingham deposit, Utah, *Mineralium Deposita* 36 (8), 799–806

Hedenquist, J.W., and Lowenstern, J.B., 1994 - The role of magmas in the formation of hydrothermal ore deposits, *Nature* 370, 521-527.

Hildreth, W., 1981 - Gradients in silicic magma chambers: implications for lithospheric magmatism, *Journal of Geophysical Research* 86, 10,153-10,192.

Hildreth, W., and Moorbath, S., 1988 - Crustal contributions to arc magmatism in the Andes of central Chile, *Contributions to Mineralogy and Petrology* 103, 361-386.

Hildreth, W., Grunder, A.L., and Drake, R.E., 1984 - The Loma Seca Tuff and the Calabozos Caldera: a major ash-flow and Caldera complex in the Southern Andes of Central Chile, *Geological Society of America Bulletin* 95, 45-54.

Holmgren, C., Marti, M., Skewes, M.A., Schneider, A., and Harmon, R.S., 1988 - Análisis isotópicos y de inclusiones fluidas en el yacimiento Los Bronces, Chile Central. *V Congreso Geológico Chileno, Santiago, Actas* 1, B299-B313.

Howell, F.H., and Molloy, S., 1960 - Geology of the Braden orebody, Chile, South America, *Economic Geology* 55, 863-905.

Jordan, T.E., Isacks, B.L., Allmendinger, R.W., Brewer, J.A., Ramos, V.A., and Ando, C.J., 1983 - Andean tectonics related to geometry of subducted Nazca plate, *Geological Society of America Bulletin* 94, 341-361.

Kay, S.M., and Mpodozis, C., 2002 - Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab, *Journal of South American Earth Sciences* 15, 39-57.

Kay, S.M., Mpodozis, C., and Coira, B., 1999 - Neogene magmatism, tectonism and mineral deposits of the Central Andes (22°-33°S Latitude); *in* Skinner, B.J., (Ed.), Geology and Ore Deposits of the Central Andes*, Society of Economic Geologists Special Publication* 7, 27-59.

Kress, V., 1997 - Magma mixing as a source of Pinatubo sulphur, *Nature* 389, 591-593.

Kurtz, A.C., Kay, S.M., Charrier, R., and Farrar, E., 1997 - Geochronology of Miocene plutons and exhumation history of the El Teniente region, Central Chile (34-35°S), *Revista Geológica de Chile* 16, 145-162.

Kusakabe, M., Hori, M., Nakagawa, S., Matsuhisa, Y., Ojeda, J.M., and Serrano, L.M., 1984 - Oxygen and sulfur isotopic compositions of quartz, anhydrite and sulfide minerals from the El Teniente and Río Blanco porphyry copper deposits, Chile, *Bulletin of the Geological Survey of Japan* 35, 583-614.

Kusakabe, M., Hori, M., and Matsuhisa, Y., 1990 - Primary mineralization-alteration of the El Teniente and Río Blanco porphyry copper deposits, Chile; stable isotope, fluid inclusion and Mg^{+2}/ Fe^{+2}/ Fe^{+3} ratios of hydrothermal fluids; *in* Herbert, H.K., and Ho, S.E., (Eds.), Stable Isotopes and Fluid Processes in Mineralization,*, University of Western Australia Press*, *Perth,* 244-259.

Lavenu, A., and Cembrano, J., 1999 - Compressional- and transpressional-stress pattern for Pliocene and Quaternary brittle deformation in fore arc and intra-arc zones (Andes of Central and Southern Chile), *Journal of Structural Geology* 2, 1669-1691.

Lindgren, W., 1933 - Mineral Deposits, *4th Edition, McGraw-Hill Book Company, Inc.*, *New York,* 930 p.

Lindgren, W., and Bastin, E.S., 1922 - Geology of the Braden mine, Rancagua, Chile, *Economic Geology* 17, 75-99.

Lowell, J.D., and Guilbert, J.M., 1970 - Lateral and vertical alteration-mineralization zoning in porphyry ore deposits, *Economic Geology* 65, 373-408.

Macfarlane, A.W., 1999 - Isotopic studies of northern Andean crustal evolution and ore metal sources; *in* Skinner, B.J., (Ed.), Geology and Ore Deposits of the Central Andes, *Society of Economic Geologists Special Publication* 7, 195-217.

Maksaev, V., and Zentilli, M., 1988 - Marco metalogénico de los megadepositos de tipo pórfido cuprífero del norte grande de Chile, *V Congreso Geológico Chileno, Santiago*, *Actas,* 1, B181-B212.

Maksaev, V., Munizaga, F., McWilliams, M., Theile, K., Arévalo, A., Zuñiga, P., and Floody, R., 2001 - $^{40}Ar/^{39}Ar$ geochronology of the El Teniente porphyry copper deposit, *III Simposio Sudamericano de Geologia Isotopica, Extended Abstracts (CD)*, *Pucón, Chile,* 496-499.

Maksaev , V. Munizaga, F. McWilliams, M, Fanning, M. Mathur, R., Ruiz, J. and Thiele, K., 2002 - El Teniente Porphyry copper deposit in the Chilean Andes, New geochronological timeframe and duration of hydrothermal activity, *Geological Society of America Abstracts with Programs* 34 (6), 336.

Morales, A, 1997 - Geología y geotecnia del sector norte del proyecto Esmeralda, División El Teniente, CODELCO-CHILE, *VIII Congreso Geológico de Chile, Antofagasta*, *Actas* 2, 1068-1072.

Morel, R., and Spröhnle, C., 1992 - Mapa de la geología distrital, Hoja Sewell, *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Map* GL88-7548.

Munizaga, F., Maksaev, V., Fanning, M., Mathur, R., Ruiz, J., and Thiele, K., 2002 – Understanding molybdenite Re-Os ages from the El Teniente porphyry copper deposit, Chile, *Geological Society of America Abstracts with Programs* 34 (6), 336.

Muñoz, J., and Stern, C.R., 1988 - The quaternary volcanic belt of the southern continental margin of South America: transverse structural and petrochemical variations across the segment between 38°S and 39°S, *Journal of South American Earth Sciences* 1, 147-161.

Nagashima, S., and Katsura, T., 1973 - The solubility of sulfur in Na_2O-SiO_2 melts under various oxygen partial pressures at 1100°C, 1250°C and 1300°C, *Bulletin Chemical Society of Japan* 46, 3099-3103.

Nystrom, J., Parada, M.A., and Vergara, M., 1993 - Sr-Nd isotope compositions of Cretaceous to Miocene volcanic rocks in Central Chile: a trend towards a MORB signature and a reversal with time, *Second International Symposium of Andean Geodynamincs, Oxford, Extended abstracts*, 411-414.

Ojeda, J.M., Hernández, E., Ossandón, G., Enrione, A., and Mestre, A., 1980 - El pórfido cuprífero El Teniente, *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Internal Report*, 72p.

Pallister, J.S., Hoblitt, R.P., Meeker, G.P., Knight, R.J., and Siems, D.F., 1996 - Magma mixing at Mount Pinatubo: petrographic and chemical evidence from the 1991 deposits; *in* Newhall, C.G., and Punogbayan, R.S., (Eds.), Fire and Mud; Eruptions and Lahars of Mount Pinatubo, Philippines, *University of Washington Press*, 687-731.

Pardo-Casas, F., and Molnar, P., 1987 - Relative motion of the Nazca (Farallón) and South American plates since Late Cretaceous times, *Tectonics* 6, 233-248.

Puig, A., 1988 - Geologic and metallogenic significance of the isotopic composition of lead in galenas of the Chilean Andes, *Economic Geology* 83, 843-858.

Rabbia, O.M., Reich, M., Hernández, L., King, R., and López-Escobar, L., 2000 - High-Al TTG-like suite at the El Teniente porphyry copper deposit, Chile, *IX Congreso Geológico Chileno, Puerto Varas*, *Actas* 1, 326-330.

Rivano, S., Godoy, E., Vergara, M.,and Villaroel, R., 1990 - Redefinición de la Formación Farellones en la Cordillera de los Andes de Chile Central (32-34°S), *Revista Geológica de Chile* 17, 205-214.

Rivera, O., and Falcón, M.F., 1998 - Estudio geológico distrital de la División El Teniente de Codelco-Chile, Escala 1:25.000, *Report to Vicepresidencia de Exploraciones y Asociaciones Mineras, CODELCO-CHILE*, 268p.

Riveros, M., 1991 - Geología del pórfido latítico del sector sur del yacimiento El Teniente. Memoria de Título, *Universidad de Chile, Departamento de Geología y Geofísica*, *Santiago,*142p.

Rojas, A., 2002 - Petrografía y geoquímica del pórfido dacítico Teniente, yacimiento El Teniente, Provincia de Cachopoal, VI Región, Chile. Memoria de Titulo*, Universidad de Concepción,, Departamento de Geología, Concepción*, 118p.

Rowland, M.G., and Wilkinson, J.J., 1998 - A hybrid origin for porphyritic magmas sourcing mineralizing fluids, *9th International Symposium of water-rock interaction, Taupo, New Zealand, Proceedings*, 569-573.

Sasaki, A., Ulriksen, E., Sato, K. and Ishihara, S. 1984 - Sulfur isotope reconnaissance of porphyry copper and manto-type deposits in Chile and the Philippines, *Bulletin of the Geological Survey of Japan* 35 (11), 615-622.

SERNAGEOMIN, 1986 - Dataciones K-Ar en El Teniente, *Superintendencia Geología de El Teniente, CODELCO-CHILE*, *Report* 115/86, 1p.

Serrano, L., Vargas, R., Stambuk, V., Aguilar, C., Galeb, M., Holmgren, C., Contreras, A., Godoy, S., Vela, I., Skewes, M.A., and Stern, C.R., 1996 - The late Miocene to early Pliocene Río Blanco-Los Bronces copper deposit, central Chilean Andes; *in* Camus, F, Sillitoe, R.H., and Petersen, R., (Eds.), Andean Copper Deposits, *Society of Economic Geologist Special Publication* 5, 120-129.

Sillitoe, R.H., 1988 - Epochs of intrusion-related copper mineralization in the Andes, *Journal of South American Earth Sciences* 1, 89-108.

Skewes, M.A., and Arévalo, A.G., 2000 - El complejo de gabros y diabasas que hospeda a las brechas mineralizadas del depósito de cobre El Teniente, Chile central, *IX Congreso Geológico Chileno, Puerto Varas*, *Actas* 1, 380-384

Skewes, M.A., and Atkinson, W.W. Jr., 1985 - Petrology of the early formed hydrothermal veins within the central potassic alteration zone of Los Pelambres porphyry copper deposit, *Revista Geológica de Chile* 25-26, 39-56.

Skewes, M.A., and Holmgren, C., 1993 - Solevantamiento Andino, erosión y emplazamiento de brechas mineralizadas en el depósito de cobre porfídico Los Bronces, Chile Central (33°S): aplicación de termometría de inclusiones fluidas, *Revista Geológica de Chile* 20, 71-84.

Skewes, M.A., and Stern, C.R., 1994 -Tectonic trigger for the formation of late Miocene Cu-rich breccia pipes in the Andes of central Chile, *Geology* 22, 551-554.

Skewes, M.A., and Stern, C.R., 1995 - Genesis of the giant Late Miocene to Pliocene copper deposits of central Chile in the context of Andean magmatic and tectonic evolution, *International Geology Review* 37, 71-84.

Skewes, M.A., and Stern, C.R., 1996 - Late Miocene mineralized breccias in the Andes of central Chile: Sr- and Nd-isotopic evidence for multiple magmatic sources; *in* Camus, F., Sillitoe, R.H., and Petersen, R., (Eds.), Andean Copper Deposits, *Society of Economic Geologist Special Publication* 5, 119-130.

Skewes, M.A., Holmgren, C., and Vargas, R., 1994 - Alteración a anfíbola y magnetita en el megayacimiento Río Blanco- Los Bronces, Chile Central, *VII Congreso Geológico de Chile. Concepción, Actas*, 1, 1623-1626.

Skewes, M.A., Arévalo, A., Holmgren, C., and Stern, C.R., 2001- Stable isotope evidence for the formation from magmatic fluids of the mineralized breccias in the Los Bronces and El Teniente copper deposits, Central Chile, *III Simposio Sudamericano de Geología Isotópica, Pucón, Chile, Extended Abstracts (CD)*, 531-534.

Skewes M.A., Arévalo A.G., Floody R., Zuñiga, P., and Stern C.R., 2002 - The giant El Teniente breccia deposit: hypogene copper distribution and emplacement; *in* Goldfarb R, and Nielsen R (Eds.), Integrated methods for discovery: global exploration in the 21st Century, *Society of Economic Geologists Special Publication* 9, 299–332.

Skewes, M.A., Holmgren, C., and CR Stern, C.R., 2003 - The Donoso copper-rich, tourmaline-bearing breccia pipe in central Chile: petrologic, fluid inclusion and stable isotope evidence for an origin from magmatic fluids, *Mineralium Deposita* 38: 2-21.

Sparks, S.R.J., Sigurdson, H., and Wilson, L., 1977 - Magma mixing: a mechanism for triggering acid explosive eruptions, *Nature* 267, 315-318.

Stern, C.R., 1989 - Pliocene to present migration of the volcanic front, Andean Southern Volcanic Zone, *Revista Geológica de Chile* 16, 145-162.

Stern, C.R., 1991 - Role of subduction erosion in the generation of Andean magmas, *Geology* 19, 78-81.

Stern, C.R., 2001 - The subduction erosion and mantle source region contamination model of Andean arc magmatism: isotopic evidence from igneous rocks of central Chile, *III Simposio Sudamericano de Geología Isotópica, Extended Abstracts (CD)*, *Pucón, Chile,* 348-351.

Stern, C.R., and Skewes, M.A., 1995 - Miocene to present magmatic evolution at the northern end of the Andean Southern Volcanic Zone, central Chile, *Revista Geológica de Chile*, 22, 261-272.

Stern, C.R., and Skewes, M.A., 1997 - Subduction of the Juan Fernández Ridge below central Chile: effects on subduction geometry, rates of subduction erosion, arc migration and magma chemistry, and genesis of copper deposits, *VIII Congreso Geológico de Chile, Antofagasta*, *Actas*, 3, 1724-1728.

Stern, C.R., Amini, H., Charrier, R., Godoy, E., Hervé, F., and Varela, J., 1984 - Petrochemistry and age of rhyolitic pyroclastics flows which occur along the drainage valleys of the Río Maipo and Río Cachapoal (Chile) and the Río Chaucha and Río Papagayos (Argentina), *Revista Geológica de Chile* 23, 39-52.

Stern, C.R., Frey, F.A., Futa, K., Zartman, R.E., Peng, Z., and Kyser, T.K., 1990 - Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian Plateau lavas of southernmost South America, *Contributions to Mineralogy and Petrology* 104, 294-308.

Taylor, H.P., 1974 - The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition, *Economic Geology* 69, 843-883.

Vargas, R., Gustafson, L., Vukasovic, M., Tidy, E., and Skewes, M.A., 1999 - Ore breccias in the Río Blanco-Los Bronces porphyry copper deposit, Chile; *in* Skinner, B., (Ed.), Geology and Ore Deposits of the Central Andes, *Society of Economic Geologists Special Publication* 7, 281-297.

Vergara, M., Charrier, R., Munizaga, F., Rivanos, S., Sepúlveda, P., Thiele, R., and Drake, R., 1988 - Miocene volcanism in the Central Chilean Andes (31°30’-34°35’S), *Journal of South American Earth Sciences* 1, 199-209.

Villalobos, J., 1975 - Alteración hidrotermal en las andesitas del yacimiento El Teniente. Ph.D. Thesis*, Universidad de Chile, Departamento de Geología y Geofísica, Santiago,* 125p.

Warnaars, F.W., Holmgren, C., and Barassi, S., 1985 - Porphyry copper and tourmaline breccias at Los Bronces-Río Blanco, Chile, *Economic Geology* 80, 1544-1565.

Yáñez, G.A., Ranero, C.R., von Huene, R., and Díaz, J., 2001 - Magnetic anomaly interpretation across the southern central Andes (32°-34°S): the role of the Juan Fernández Ridge in the late Tertiary evolution of the margin, *Journal of Geophysical Research* 106(B4), 6325-6345.

Yáñez, G.A., Cembrano, J., Pardo, M., Ranero, C.R. and Selles, D., 2002 - The Challenger-Juan Fernández–Maipo major tectonic transition of the Nazca-Andean subduction system at 33–34°S: geodynamic evidence and implications, *Journal of South American Earth Sciences* 15, 23-38.

Zentilli, M., Doe, B.R., Hedge, C.E., Alvarez, C., Tidy, E., and Daroca, J.A., 1988 - Isótopos de plomo en yacimientos de tipo pórfido cuprífero comparados con otros depósitos metalíferos en los Andes del norte de Chile y Argentina, *V Congreso Geológico Chileno, Santiago*, *Actas,* 1, B331-B369.

Zuñiga, P., 1982 - Alteración y mineralización hipógenas en el sector oeste del yacimiento El Teniente. Memoria de Título, *Universidad de Chile, Departamento de Geología y Geofísica, Santiago*, 102p.