Chapter 14

The Giant El Teniente Breccia Deposit: Hypogene Copper Distribution and Emplacement

M. Alexandra Skewes,‡
Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0399

Alejandra Arevalo, Ricardo Floody, Patricio H. Zuniga,
Superintendencia Geología, El Teniente, CODELCO-Chile, Rancagua, Chile

AND Charles R. Stern
Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0399

Abstract

The giant El Teniente copper-molybdenum deposit, located in the Andes of central Chile, is one of the world’s largest known copper deposits, containing estimated resources of \(>75 \times 10^6\) t of fine copper in ore with grades greater than 0.67 percent. El Teniente has been described in the past as a porphyry deposit developed around a Paleocene dacite porphyry stock, with 80 percent of its copper mineralization hosted in Miocene andesites. However, new mapping—both regional and in underground mine workings—along with petrological studies, indicates that El Teniente, like the other giant Miocene and Pliocene copper deposits in central Chile, is actually best classified as a breccia deposit. Most of the high-grade hypogene copper at El Teniente occurs in and surrounding multiple magmatic-hydrothermal breccia pipes. Mineralized breccia complexes, with copper content >1 percent, 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 porphyritic basalts and basaltic andesites, and not in andesite extrusive rocks. The multiple breccias in El Teniente include copper- and sulfide-rich biotite, igneous, tourmaline, and anhydrite breccias, generated by the exsolution of magmatic fluids from cooling plutons, and also magnetite and rock-flour breccias. Surrounded by biotite breccias, a dense stockwork of biotite-dominated veins has produced pervasive biotite alteration, and copper mineralization characterized by chalcopyrite >> bornite + pyrite. Later veins, with various proportions of quartz, anhydrite, sericite, chlorite, tourmaline, feldspars, and copper sulfide minerals, formed in association with the 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 copper to the deposit, but in other cases eliminated or redistributed preexisting mineralization. Both the Teniente Dacite porphyry and the central rock-flour breccia of the Braden pipe, the dominant lithostratigraphic unit in the deposit, are copper 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 multistage development of breccia emplacement, alteration and copper mineralization at El Teniente occurred over a time span that was greater than 2 m.y., between >6.4 and 4.4 Ma, at the end of a more than 10-m.y. episode of Miocene and Pliocene magmatic activity, and just prior to the eastward migration of the Andean magmatic arc as a consequence of decreasing subduction angle. 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 north-south, northwest-southeast, and northeast-southwest Andean structures, but what actually focused magmatic activity and mineralization at this one locality for so long remains an unsolved problem, the solution of which would provide an important tool for exploration of similar giant deposits.

Introduction

The giant El Teniente deposit, located in the Andes of central Chile, 70 km southeast of Santiago (Fig. 1), is one of the world’s largest known copper-molybdenum deposits. It originally contained an estimated total copper content of \(>93 \times 10^6\) metric tonnes (t), of which \(18 \times 10^6\) t have already been extracted, leaving current resources of \(>75 \times 10^6\) t of copper (Fig. 2) in ore with grades greater than 0.67 percent, and \(>1.4\) \(\times 10^6\) t of fine molybdenum in ore with grades greater than

‡Corresponding author: e-mail, Skewes@colorado.edu
0.019 percent. This deposit is exploited by the world’s biggest underground mine, which encompasses an area of approximately 3 km² and has a vertical extent of >1,000 m, between 1,983 (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 by 2 km, and has a known vertical extent of >2,000 m, from between the surface at 3,200 m, and the deepest point intersected by drill holes at 1,200 m, 800 m below the current deepest level of mine operations. The actual depth to which copper mineralization extends is unknown.

Since Lindgren and Bastin (1922) first described El Teniente, known between 1904 and 1967 as the Braden deposit, it has been recognized that this deposit formed by multiple hydrothermal events associated with a sequence of igneous intrusions. Distinguishing the various stages during which the hypogene copper ore has been deposited and redistributed and determining the nature of the lithologies that host the hypogene ore are important not only for understanding the genesis of El Teniente, but also for reserve calculation and mine planning, operation and safety, and for developing exploration strategies to discover other giant copper deposits.

This paper presents new information, made available as the mine develops to deeper levels, that helps us understand...
the nature and genesis of this deposit. El Teniente has been described in the past as a porphyry copper deposit formed around a Pliocene dacite porphyry stock, with 80 percent of its copper mineralization hosted in Miocene andesitic intrusive rocks (Howell and Molloy, 1960; Camus, 1975; Cuadra, 1986). During the last decade, however, regional mapping (Fig. 3; Morel and Spröhnle, 1992; Floody and Huete, 1998), and mapping in extensive new underground mine workings in the deeper hypogene zone (Figs. 4 and 5), along with petrological studies, have together provided new information about the host rocks (Skewes, 1997a, 1999, 2000; Skewes and Arévalo, 1997, 2000; Skewes et al., 1999), hypogene ore distribution (Fig. 6; Arévalo et al., 1998), and history of ore emplacement at El Teniente. These studies indicate that most high-grade hypogene copper at El Teniente occurs in and surrounding multiple magmatic-hydrothermal breccia pipes, hosted in a mafic intrusive complex composed of gabbros, diabases, and porphyritic basaltic, but not andesitic intrusive rocks.

The copper-poor central rock-flour breccia of the Braden pipe, the most distinctive lithostructural unit in the deposit (Figs. 3–6; Floody, 2000), and the Teniente Dacite porphyry, both cut preexisting 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. In fact, where this dacite porphyry outcrops north of the Teniente River (Fig. 3), the intrusive rocks it intrudes are altered, but not mineralized (Floody and Huete, 1998). Therefore, Howell and Molloy’s (1960, p. 903) suggestion that “in the Chilean portion of the Andean Cordillera . . . the mining geologist who failed to investigate carefully a dacite or latite intrusion would indeed be negligent” may be true, but needs to be reconsidered as the principal exploration strategy for copper deposits in the Andes of central Chile.

**General Background**

According to Baros (1996), who has compiled a detailed history of the development of the El Teniente mine, the deposit was exploited on a small scale before 1760, but first was referred to by this name in that year as a result of a legend that a fugitive Spanish lieutenant (El Teniente) discovered the deposit. The first official records of ownership and production are from the year 1819. In 1904, William Braden bought the property and formed the Braden Copper Company, which in 1915 was acquired by Kennecott Copper Corporation. The Braden Copper Company installed a 250-ton per day concentrator in 1906, and by 1960 the Kennecott 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 t of ore a day, with an average grade of 1.2 percent copper and 0.026 percent molybdenum.

The first comprehensive geologic description of the deposit was that of Lindgren and Bastin (1922). 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 several periods of intrusion, brecciation, and mineralization at El Teniente, and concluded that this mine preserves a record of alternating igneous activity and ore deposition, and affords convincing evidence of the intimate genetic connection between igneous rocks and ore deposits. Lindgren and Bastin (1922) considered El Teniente, along with Rio Blanco-Los Bronces (Fig. 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 (Fig. 1A), dominated by enargite, also along with pyrite and quartz.

Howell and Molloy (1960, p. 902) described El Teniente as a model porphyry copper deposit with “a circular configuration of alteration” and mineralization “arrayed concentrically around a common center.” They concluded that mineralization in El Teniente was emplaced around the barren core of a dacite porphyry intrusion within the hypogene rocks of the Farellones Formation, and not in a sill as described by Lindgren and Bastin (1922).

Ossandon (1974) conducted a detailed study of the petrology and alteration associated with the Teniente Dacite porphyry, and Villalobos (1975) described alteration of the “andesite” host rocks of the deposit. Camus (1975) summarized wall-rock alteration and sulfide mineral distribution in the deposit, and 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 (Posthumous). Zuñiga (1982) detailed different vein types associated with these stages of alteration.

Clark et al. (1983) determined a 4.6 Ma K-Ar age for the Teniente Dacite porphyry, and Cuadra (1986, 1992) 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 the Miocene extrusive rocks of the Farellones Formation in the vicinity of El Teniente ranged 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 and 4.8 Ma, and the Teniente Dacite porphyry between 4.7 and 4.6 Ma. Both of these felsic intrusive units predate the emplacement of the Braden pipe, which he
dated between 4.7 and 4.5 Ma. He dated two postmineralization lamprophyre (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.

New studies in the last 10 years, many of the results of which are only available in internal mine reports, theses, and/or abstracts, form the basis of this updated description and interpretation of the genesis of the giant El Teniente copper deposit. These new studies have provided a substantial amount of additional information concerning the chronology of the igneous rocks in the vicinity of the El Teniente deposit (Godoy, 1993; Rivera and Falcón, 1998) and the chemistry of these rocks (Stern and Skewes, 1995; Kay and Kurtz, 1995). Also, new information has become
Fig. 4. Geologic map of level Teniente 5 (2,284 m above sea level) in the mine. Apophyses of porphyritic tonalite north of the Sewell Diorite are mapped as distal parts of this pluton, although they may possibly be younger and have an independent origin (Guzmán, 1991). Cross sections 124N and 85N are shown in Figure 5. Spatial extent of biotic breccias are projected onto this level from where they have been recognized between levels Teniente 4 and 8 in sections 124N and 85N, 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 biotic alteration.
available concerning the timing and rates of deformation, uplift, and erosion (Skewes and Holmgren, 1993; Kurtz et al., 1997; Godoy et al., 1999), and the general tectonic setting affecting the genesis of both the Miocene to recent igneous rocks and the giant copper deposits in the Andes of central Chile (Stern, 1989, 1991, 2001; Skewes and Stern, 1994, 1995, 1996; Stern and Skewes, 1995, 1997; Kay et al., 1999; Yáñez et al., 2001). Detailed descriptions have been published of the other two giant deposits in central Chile (Fig. 1), Los Pelambres (Atkinson et al., 1996), and Río Blanco-Los Bronces (Serrano et al., 1996; Vargas et al., 1999; Skewes et al., 2002), interpreting the formation of these deposits, both of which are very similar to El Teniente in many respects, in the context of the current understanding of the magmatic and tectonic processes in the Andes of central Chile.

With respect to El Teniente itself, new results concerning the "Andesites of the Mine," which host >80 percent of the copper mineralization in this deposit (Camus, 1975), have been obtained from field mapping in the immediate vicinity of the mine (Fig. 3; Morel and Spöhrle, 1992) and from mapping and petrologic studies of igneous rocks inside the mine (Skewes, 1996a, 1997a, 1997b, 2000; Skewes and Arévalo, 1997, 2000; Skewes et al., 1999). New studies have also been conducted concerning the Sewell Diorite (Rabbia et al., 2000), Teniente Dacite porphyry (Rojas, 2002), latite dikes (Riveros, 1991), and other felsic porphyries in the mine (Guzmán, 1991); the Braden pipe (Floody, 2000) and other breccias in and surrounding the mine (Arredondo, 1994; Morales, 1997; Floody and Huete, 1998; Skewes, 1999); the distribution of sulfide minerals and copper in the deposit (Fig. 6; Arévalo and Floody, 1995; Arévalo et al., 1998); and the structural controls in the vicinity of the deposit (Garrido et al., 1994; Garrido, 1995; Rivera and Falcon, 1998). The lithologic units, as well as alteration and mineralization events, have been dated by both 40Ar/39Ar (Maksaev et al., 2001) and Re-Os techniques (Mathur et al., 2001). Results from fluid inclusion studies (Ip, 1987; Kusakabe et al., 1990; Skewes, 1996b, 1997c), and both stable (O, H, and S; Kusakabe et al., 1984, 1990; Skewes et al., 2001) and radiogenic (Rb-Sr, Sm-Nd, Re-Os, and U-Pb; Puig, 1988; Zentilli et al., 1988; Stern and Skewes, 1995; Kay and Kurtz, 1995; Skewes and Stern, 1996; Freydiere et al., 1997) isotopic studies, have constrained the origin of igneous rocks, alteration, and mineralization associated with the genesis of the El Teniente deposit.

**Regional Geologic, Tectonic, and Structural Setting**

El Teniente, along with Los Pelambres (32° S; >25 × 10⁶ t of copper; Sillitoe, 1973; Atkinson et al., 1996) and Río Blanco-Los Bronces (33° S; >50 × 10⁶ t of copper; Warnaars et al., 1985; Serrano et al., 1996), formed during the Miocene and Pliocene in the Andes of central Chile (Fig. 1), and are among the youngest and largest (Fig. 2) copper deposits in the Andes. They are copper-, sulfur-, iron-, calcium-, molybdenum-, and boron-rich, but gold-poor deposits that share important features. These include 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.

Another distinctive feature these three deposits have in common is the presence of large magmatic-hydrothermal breccias, both mineralized and unmineralized (Skewes and Stern, 1994, 1995). As noted by Howell and Molloy (1960,
p. 902), "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 (Figs. 3–5; Floody, 2000), and possibly as much as 700 to 1,400 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-hydrothermal breccias at El Teniente (Figs. 4, 5; Arredondo, 1994; Morales, 1997; Skewes, 1999).
The multiple breccias in each of the three giant deposits in central Chile include copper- and sulfide-poor magnetite-actinolite breccias, copper- and sulfide-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 fluids from cooling plutons (Warnaars et al., 1985; Skewes and Stern, 1994, 1995, 1996; Vargas et al., 1999; Skewes et al., 2001, 2002). 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 igneous intrusions in each deposit are weakly mineralized dacite porphyries, the emplacement of which has redistributed, both cutting and concentrating, preexisting 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 (Fig. 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, 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). As with the older copper deposits in northern Chile, such as Chupicamata and El Salvador (Fig. 1A), copper mineralization was emplaced during a relatively restricted time interval (~3 m.y.), at the end of a more extended period of magmatic activity (~10 m.y.), just prior to the eastward migration of the locus of the Andean volcanic arc (Maksav and Zentilli, 1988; 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). 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 Broncos, and 1.8 Ma for El Teniente, decreases southerly (Fig. 7), reflecting the southward sweep of the locus of subduction of the Juan Fernández Ridge (Yáñez et al., 2001). 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 $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these magmas (Fig. 7). Subduction of oceanic crust, pelagic and terrigenous sediments, and continental crust tectonically eroded off the edge of the continent, into the mantle source region of Andean magmas, may provide the large amounts of water, sulfur, copper, and boron involved in the generation of the giant copper deposits of central Chile (Stern, 1989, 1991; Macfarlane, 1999).

As the subduction angle decreased, beginning in the middle Miocene, the crust in central Chile was deformed and thinned (Jordan et al., 1983; Godoy et al., 1999), and uplifted and eroded (Skewes and Holmgren, 1993; Kurtz et al., 1997). The three giant Miocene and Pliocene copper deposits are strongly telescoped, with multiple magmatic-hydrothermal breccias superimposed, one on top of the other, within the extrusive and intrusive igneous rocks of the Farellones Formation, and intruded in turn by copper-poor porphyry stocks. Continued 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 Andes (Fig. 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 (Fig. 2) have been attributed in part to these 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), indicates maximum shortening oriented N 94° ± 9° E, consistent with the direction of convergence of the Nazca plate with the South American plate at approximately N 82° ± 4° E (Pardo-Casas and Molnar, 1987). Godoy et al. (1999) have suggested that, between 9 and 3.5 Ma, rocks of the Farellones Formation that host the El Teniente deposit were uplifted and transported eastward along the Fierro thrust. This thrust may be the eastern extension of a detachment which underlies El Teniente at a depth, they
suggest, of only 2.3 km, although it has not been penetrated by exploration drill holes.

According to Garrido et al. (1994), the deposit is emplaced within the El Teniente fault zone, which consists of anastomosing strike-slip faults, trending N 65° 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 (Fig. 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 a postmineralization lamprophyre dike with the same northeast-southwest strike (Fig. 4). Garrido (1995) also recognized regional N 48° ± 11° W 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 (Fig. 3; Garrido et al., 1994). In the mine, the northwest-southeast–trending northernmost part of the Teniente Dacite porphyry, and a group of mineralized breccia complexes located east and northeast of the Braden pipe (Fig. 4), each intruded by small felsic porphyry apophyses, lie along or close to the northwest-southeast–trending Puquios/Codegua fault. Finally, regionally significant north-south structures may also have played a role in controlling the emplacement of the north-south–striking part of the Teniente Dacite porphyry and a north-south zone of tourmalization within the Braden pipe (Floody, 2000). Generally, subvertical faults in all three of these directions (northwest-southeast, northwest-southeast, and north-south) were active before, during, and after the formation of the deposit (Garrido et al., 1994; Garrido, 1995). Inside the area of the mine, the emplacement of the Braden pipe also exerted an important local structural control, resulting in radial and concentric stockwork of hydrothermal veins, latite ring-dikes, and pebble-dikes.

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 40Ar/39Ar mineral dating of exhumed plutons (Kurtz et al., 1997), range from 150 to 300 m per m.y. over the last 4.9 m.y., and erosion rates were probably in this range over the last approximately 15 m.y. These erosion rates are an order of magnitude higher than the 30 m per m.y. estimated by Camus (1975).

Igneous Host Rocks

El Teniente is located in middle to late Miocene extrusive and intrusive igneous rocks that are part of the Farellones Formation (Fig. 3). Extrusive rocks of the Farellones Formation overlie older continental igneous rocks of the Oligocene to early Miocene Coya-Machalí (Abancay) Formation, 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 Cordiller along the drainage divide between Chile and Argentina (Fig. 1B). These older rocks may occur in the deep crust below El Teniente, but they do not crop out within the mine or in the immediate vicinity surrounding the deposit (Figs. 3, 4).

Farellones Formation extrusive rocks

Extrusive rocks of the Miocene Farellones Formation, locally referred to as the Teniente volcanic complex (Godoy, 1993; Kay and Kurtz, 1995; Rivera and Falcón, 1998), are the oldest rocks exposed in the immediate area surrounding the deposit (Fig. 3). The Farellones Formation is a sequence of >2,500 m of lavas, volcaniclastic 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 (Charrier and Munizaga, 1979; Cuadra, 1986; Vergara et al., 1988; Godoy, 1993; Rivera and Falcón, 1998). Based on location of specific volcanic centers and their chemistry, this complex has been subdivided by Godoy (1993) and Kay and Kurtz (1995) into rocks of the 15.2 to 12 Ma Maquí Chico Group, which erupted from centers to the northwest of the El Teniente deposit, and rocks of the 10 to 9 Ma Lower Sewell and 9 to 7 Ma Upper Sewell Groups, both of which erupted from centers located immediately adjacent to the deposit, as well as other centers to the east and south. Extrusive rocks of the Teniente volcanic complex were intruded by gabbro, diabase, diorite, tonalite, latite, and dacite porphyry plutons between 12.4 and 4.4 Ma (Cuadra, 1986, 1992; Godoy, 1993; Kurtz et al., 1997; Rivera and Falcón, 1998; Maksaev et al., 2001).

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 Kurtz, 1995), in contrast to the rocks of the older Coya-Machalí Formation, which are low and medium K tholeiitic arc igneous rocks. 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 (Fig. 8; Kay and Kurtz, 1995), and also higher initial 87Sr/86Sr and lower initial 143Nd/144Nd ratios (Fig. 9; Nyström et al., 1993; Kay and Kurtz, 1995). 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, to conditions of thickened continental crust when the Teniente volcanic complex formed in the Miocene.

El Teniente mafic intrusive complex

The oldest rocks within the mine are dark colored, with aphanitic to porphyritic appearance (Fig. 10A), and are locally known as the "Andesites of the Mine." These rocks, which host 80 percent 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 and Molloy, 1960; Villalobos, 1975; 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 (Table 1; Villalobos, 1975; Camus, 1975; Skewes, 1997a) show SiO₂ contents that range from 47 to 57 wt percent (Fig. 11A), indicating these rocks are more basic than andesites. Recent geologic mapping (Fig. 3; Morel and Spröhnle, 1992), and petrological studies (Skewes, 1997a; 2000; Skewes and Arévalo, 1997, 2000; Skewes et al., 1999), indicate that the Andesites of the Mine are mafic intrusives rocks, including gabbros, 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 northwest of the mine (Fig. 3), and in the Diálogo Canyon along the Puquios River to the southeast of the mine (Lindgren and Bastin, 1922; Skewes, 2000). The central part of this mafic complex, within which the mine is located, has a vertical extent or more than 2,000 m.

Although mafic rocks of this complex have important textural variations (Fig. 10), 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 relatively large crystals (1–6 mm) of calcic plagioclase (An₉₂₋₉₄), 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; Camus, 1975; Villalobos, 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.

Gabbros (Fig. 10B) have a hypidiomorphic granular texture, with crystals that range in size from 2 to 6 mm, of mainly (50–80%) calcic plagioclase, with subordinate amounts of clinopyroxene and magnetite. Diabases (Fig. 10C) are formed by smaller (0.5–2 mm) calcic plagioclase crystals, typically with tabular shapes and often with flow orientation, and occasionally relic clinopyroxene. Porphyritic basalt and basaltic andesites (Fig. 10D) have a variable percent (10–35%) of phenocrysts (0.5–2 cm) of calcic plagioclase. In each of these texturally different rock types, 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 (Fig. 10B), but in most by secondary biotite, along with anhydrite, chloropyrite, 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 SiO₂ contents that generally range between 47 and 54 wt percent, and chemically they correspond to basalts and basaltic andesites (Table 1; Fig. 11A; Camus, 1975; Villalobos, 1975; Skewes, 2000; Skewes and Arévalo, 2000). They have between 6 and 11 wt percent CaO, and 16 to 22 wt percent Al₂O₃, which are consistent with their high calcic plagioclase content. The FeO (6–11.7 wt %) is high with respect to MgO (<6.2 wt %), and TiO₂ and P₂O₅ contents are relatively low, consistent with tholeiitic affinities for these mafic rocks. There is no chemical distinction between gabbros, diabases, and basaltic porphyries (Table 1; Skewes, 2000). These mafic rocks have low rare earth elements (REE) concentrations, with light REE not very
<table>
<thead>
<tr>
<th>Sample</th>
<th>Gabbro</th>
<th>Basaltic porphyry</th>
<th>Diabase</th>
<th>Sewell Diorite</th>
<th>Porphyry A</th>
<th>Latite dike</th>
<th>Teniente Porphyry</th>
<th>Teniente Porphyry</th>
<th>Teniente Porphyry</th>
<th>Lamprophyre dike</th>
<th>Cachapoal lava</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actinolite</td>
<td>Biotite</td>
<td>Actinolite</td>
<td>Chlorite</td>
<td>Biotite</td>
<td>Sericite</td>
<td>Chlorite</td>
<td>Chlorite</td>
<td>Chlorite</td>
<td>Chlorite</td>
<td>Chlorite</td>
</tr>
<tr>
<td>DDH1411-1680</td>
<td>59.08</td>
<td>12.20</td>
<td>8.30</td>
<td>63.70</td>
<td>51.14</td>
<td>64.73</td>
<td>62.93</td>
<td>65.76</td>
<td>61.10</td>
<td>55.40</td>
<td></td>
</tr>
<tr>
<td>DDH1826-367</td>
<td>1.00</td>
<td>1.01</td>
<td>1.20</td>
<td>0.59</td>
<td>1.02</td>
<td>0.45</td>
<td>0.46</td>
<td>0.40</td>
<td>0.67</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>DDH1607-700</td>
<td>17.85</td>
<td>19.11</td>
<td>28.36</td>
<td>17.02</td>
<td>18.66</td>
<td>17.58</td>
<td>17.00</td>
<td>17.03</td>
<td>17.20</td>
<td>17.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.11</td>
<td>9.83</td>
<td>9.97</td>
<td>1.90</td>
<td>6.88</td>
<td>1.02</td>
<td>2.64</td>
<td>2.07</td>
<td>2.60</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.05</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.32</td>
<td>4.17</td>
<td>5.04</td>
<td>1.50</td>
<td>3.47</td>
<td>1.14</td>
<td>1.39</td>
<td>0.72</td>
<td>3.20</td>
<td>4.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.44</td>
<td>7.80</td>
<td>7.96</td>
<td>3.90</td>
<td>5.69</td>
<td>3.82</td>
<td>4.02</td>
<td>3.19</td>
<td>5.50</td>
<td>7.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.62</td>
<td>1.68</td>
<td>2.30</td>
<td>4.93</td>
<td>5.08</td>
<td>4.93</td>
<td>5.63</td>
<td>5.47</td>
<td>5.14</td>
<td>3.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.22</td>
<td>2.23</td>
<td>1.43</td>
<td>2.20</td>
<td>2.04</td>
<td>2.37</td>
<td>2.29</td>
<td>2.41</td>
<td>2.09</td>
<td>1.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>0.21</td>
<td>0.25</td>
<td>0.21</td>
<td>0.14</td>
<td>0.16</td>
<td>0.19</td>
<td>0.13</td>
<td>0.21</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>1.76</td>
<td>1.96</td>
<td>1.80</td>
<td>4.70</td>
<td>1.20</td>
<td>3.41</td>
<td>1.66</td>
<td>0.90</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100.42</td>
<td>98.54</td>
<td>100.96</td>
<td>100.03</td>
<td>99.76</td>
<td>99.17</td>
<td>99.98</td>
<td>98.85</td>
<td>100.57</td>
<td>99.07</td>
<td></td>
</tr>
</tbody>
</table>

K-Ar age >7.4 >7.4 >7.4

<table>
<thead>
<tr>
<th></th>
<th>Ca</th>
<th>Rb</th>
<th>Sr</th>
<th>Ba</th>
<th>La</th>
<th>Ce</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Tb</th>
<th>Y</th>
<th>Zr</th>
<th>Hf</th>
<th>Tb</th>
<th>Sc</th>
<th>Cr</th>
<th>Ni</th>
<th>Lanth./Yb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.7</td>
<td>95</td>
<td>9.2</td>
<td>102</td>
<td>95</td>
<td>110</td>
<td>528</td>
<td>981</td>
<td>311</td>
<td>11</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>12</td>
<td>27</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>71</td>
<td>159</td>
<td>113</td>
<td>472</td>
<td>392</td>
<td>447</td>
<td>699</td>
<td>569</td>
<td>742</td>
<td>915</td>
<td>825</td>
<td>129</td>
<td>561</td>
<td>100</td>
<td>60</td>
<td>35</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.8</td>
<td>9.3</td>
<td>17.4</td>
<td>19.5</td>
<td>23.6</td>
<td>40.5</td>
<td>34.7</td>
<td>18</td>
<td>30.9</td>
<td>27.7</td>
<td>26.0</td>
<td>35.1</td>
<td>52.2</td>
<td>12.3</td>
<td>4.0</td>
<td>6.5</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.3</td>
<td>2.89</td>
<td>25.4</td>
<td>3.5</td>
<td>3.6</td>
<td>6.4</td>
<td>3.4</td>
<td>2.3</td>
<td>2.8</td>
<td>2.3</td>
<td>2.1</td>
<td>4.0</td>
<td>6.3</td>
<td>1.0</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.08</td>
<td>1.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
<td>1.1</td>
<td>1.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.6</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>1.7</td>
<td>5.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.26</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>


Strongly enriched relative to heavy REE (La/Yb < 8; Fig. 8; Table 1), and in these respects they resemble the tholeiitic basalts of the Maqui Chico Group of the Teniente volcanic complex (Skewes, 1997a, 2000).

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 K2O (0.5-1.5 wt %) and H2O (typically <1.5 wt %) contents. The samples with more intense biotite alteration have higher K2O content, as much as 4 wt percent (Fig. 11A). Villalobos (1975) and Camus (1975) evaluated chemical gains and losses caused by various types of alteration based on comparison of the chemistry of altered samples from within the mine to fresh andesites from outside the mine. However, these results are not valid because the mafic intrusive rocks in the mine are clearly not equivalent to typical Teniente volcanic complex andesite extrusive rocks.

The age of the mafic intrusive rocks in the mine has not been determined. They are intruded by all the different felsic intrusions and breccias in the mine (Fig. 4), including the Sewell Diorite 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 relatively large felsic plutons intrude the mafic rocks in the area of the mine (Figs. 4, 5). Their spatial distribution, published ages, and general petrologic characteristics suggest that these represent two independent bodies intruded at different times. The larger Sewell Diorite, which occurs to the southeast of the Braden pipe, is a tonalite stock, dated between 7.4 and 7.1 Ma by K-Ar (Cuadra, 1986). Maksaev et al. (2001) determined a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 5.7 Ma for this pluton, but conclude that this younger date corresponds to hydrothermal/mineralization events superimposed on the stock. The smaller and younger Teniente Dacite porphyry, dated by K-Ar between 4.7 and 4.6 Ma (Clark et al., 1983; Cuadra, 1986), occurs north of the Braden pipe and has been truncated by the emplacement of this breccia. Other smaller felsic bodies include apophyses of porphyritic diorite, tonalite, and/or dacite, which occur east of the Braden pipe (Guzmán, 1991). Latites dated between 5.3 and 4.8 Ma by K-Ar (Riveros, 1991; Cuadra, 1992), and between 4.8 and 4.4 by $^{40}\text{Ar}/^{39}\text{Ar}$ (Maksaev et al., 2001), also occur, both as ring-dikes concentric to the Braden pipe and as blocks within this breccia.

The Sewell Diorite is one among a number of plutons of the Teniente plutonic complex that intruded the Teniente volcanic complex rocks between 12.4 and 7.0 Ma (Cuadra, 1986, 1992; Godoy, 1993; Kay and Kurtz, 1995; Kurtz et al., 1997; Rivera and Falcón, 1998). The Sewell Diorite is not a diorite, but rather a tonalite (Villalobos, 1975; Skewes, 2000), formed by rocks with textures that vary from medium-grained (1–5 mm) equigranular (Fig. 12A) to porphyritic. The equigranular Sewell Diorite consists of andesine-labradorite plagioclase, altered amphiboles, biotite, quartz, and minor potassium feldspar. The porphyritic part of the Sewell Diorite pluton contains phenocrysts of plagioclase, biotite, and relic amphibole in a groundmass of quartz, plagioclase microlites and minor potassium feldspar, but lacks “quartz eyes,” which distinguishes it from both the Teniente Dacite porphyry and some of the porphyritic diorite and tonalite apophyses (Fig. 12B) that occur to the north of the Sewell Diorite pluton (Fig. 4; Guzmán, 1991).

Although mineralogically similar, it is not clear if the equigranular and porphyritic portions of the Sewell 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, and also possibly to the Teniente Dacite porphyry. Cuadra (1986) determined a K-Ar age of 7.0 Ma, confirmed by $^{40}\text{Ar}/^{39}\text{Ar}$ (Maksaev et al., 2001), for a porphyritic quartz-diorite pluton from Laguna La Huifa, located a few kilometers northeast of the deposit (Fig. 3). Another K-Ar age of 6.0 Ma (SERNAGEOMIN, 1986) has been obtained for a mafic porphyry, Porphyry A (section 124N; Figs. 4, 5, Table 1), in the deposit. Taken together, these ages suggest that the porphyritic tonalite apophyses either intruded together with the central, equigranular part of the Sewell Diorite pluton, or possibly as independent small bodies between the times that the Sewell Diorite pluton and younger Teniente Dacite porphyry were emplaced, and suggest that they are not all simply marginal portions of either one or the other of these two large plutons.

The Teniente Dacite porphyry is an elongated dikelike body, extending 1.5 km to the north of the Braden pipe, with a maximum width of 300 m (Figs. 4, 5). It has been consid-
ered by many authors to be the “productive” igneous intrusion responsible for mineralization at El Teniente (Howell and Molloy, 1960; Ossandón, 1974; Camus, 1975; Ojeda et al., 1980; Cuadra, 1986). However, its core is practically barren, it clearly cuts copper mineralized mafic rocks, veins, and breccias in the deposit, and its northernmost extension, north of the Teniente River valley (Fig. 3), is unmineralized (Floody and Huete, 1998). According to both Ossandón (1974) and Rojas (2002), the Teniente Dacite porphyry 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.

Major element chemical analyses do not distinguish the Sewell Diorite and Teniente Dacite porphyry (Table 1, Fig. 11B). The available analyses of these two stocks range between 61.5 and 67.3 wt % SiO₂, with K₂O content between 1.8 and 6.3 wt percent (Ossandón, 1974; Camus, 1975; Guzmán, 1991; Stern and Skewes, 1995; Kay and Kurtz, 1995; Skewes, 2000; Rojas, 2002). Rare earth elements in the Teniente Dacite porphyry are strongly fractionated (La/Yb = 15.0-61.6; Fig. 8; Kay and Kurtz, 1995; Rojas, 2002), whereas for the equigranular Sewell Diorite, this ratio ranges between both lower, less fractionated values, and highly fractionated values (La/Yb = 9.9 to 44; Fig. 8; Stern and Skewes, 1995; Kay and Kurtz, 1995; Skewes, 2000; Rabbia et al., 2000). According to Kay and Kurtz (1995), other plutons of the Teniente plutonic complex have a more restricted range of La/Yb ratios (8 to 22), causing them to suggest that the samples of the Sewell Diorite with higher La/Yb values are actually Teniente Dacite porphyry. However, this is not the case, as some of the samples of the Sewell Diorite with more highly fractionated REE are equigranular tonalite (Skewes, 2000). Rabbia et al. (2000) also report high La/Yb ratios (27 to 44) for both the Sewell Diorite and 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 Diorite from the Teniente Dacite porphyry.

The Teniente Dacite porphyry is truncated by the south end of the Braden pipe. It is not clear if this porphyry also occurs south of the pipe. Guzmán (1991) suggests that the porphyritic phase of the Sewell Diorite, and the porphyry apophyses to the north of this pluton, may be related to the Teniente Dacite porphyry and not the equigranular Sewell Diorite pluton. The porphyry apophyses, however, are chemically more variable than either the Teniente Dacite porphyry or Sewell Diorite, with SiO₂ ranging between 51 and 72 wt percent (Table 1, Fig. 11B; Guzmán, 1991). This suggests that the porphyry apophyses are independent small intrusions, and not all simply marginal portions of either the Sewell Diorite or Teniente Dacite porphyry.

The Sewell Diorite, and other plutons of the Teniente plutonic complex, have Sr and Nd isotopic compositions similar to extrusive rocks from the Teniente volcanic complex (Fig. 8; Stern and Skewes, 1995; Kay and Kurtz, 1995). Their ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd 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 (Fig. 4) and may have intruded after the emplacement of the breccia pipe as indicated by ⁴⁰Ar/³⁹Ar ages of between 4.8 and 4.4 Ma (Maksaev et al., 2001). However, their K-Ar age (5.3-4.8 Ma; Cuadra, 1992), and the
occurrence of blocks of this rock type in the pipe, suggest that that at least some latite porphyry also intruded prior to the formation of the Braden pipe and may have played a role in the formation of the pipe (Floody, 2000). 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 Diorite, with between 62.5 and 66.7 wt percent SiO₂ and 1.2 to 4.8 wt percent K₂O (Table 1, Fig. 11B; Riveros, 1991; Kay and Kurtz, 1995; Skewes, 2000), and a high La/Yb ratio of about 30 (Fig. 8; Kay and Kurtz, 1995; Skewes, 2000).

Postmineralization lamprophyre dikes and lava flows

The youngest igneous rocks in the deposit are postmineralization lamprophyre (hornblende andesite) dikes, dated as 3.8 to 2.9 Ma (Cuadra, 1986; Godoy, 1993). They contain phenocrysts of amphiboles and andesine plagioclase in a fine-grained groundmass of plagioclase, amphibole, iron oxides, and glass. They correspond chemically to andesites, with SiO₂ between 55.8 and 64.7 wt percent (Table 1, Fig. 11B; Stern and Skewes, 1995; Kay and Kurtz, 1995). They have La/Yb values of 14.1 to 25.7 (Fig. 8; Stern and Skewes, 1995; Kay and Kurtz, 1995), and their 87Sr/86Sr ratios are slightly higher and 143Nd/144Nd ratios slightly lower than rocks of the older Teniente volcanic and plutonic complexes (Fig. 9; Stern and Skewes, 1995; Kay and Kurtz, 1995).

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 (Charrier and Munizaga, 1979). These are two-pyroxene basaltic andesites with 55.4 to 56.5 wt percent SiO₂ (Table 1, Fig. 11B). They have lower La/Yb ratios (9.7) than the older lamprophyre dikes in the mine (Fig. 8; Stern and Skewes, 1995), but higher 87Sr/86Sr and lower 143Nd/144Nd ratios (Fig. 9; Stern and Skewes, 1995).

Breccias

General

El Teniente deposit contains many different magmatic-hydrothermal breccias, both mineralized and unmineralized. The Braden pipe, the largest breccia pipe and the central lithostructural unit in the deposit (Figs. 3–6, 13B, C), biotite-rich breccias cutting the Sewell Diorite (Fig. 12A), and anhydrite breccias (Fig. 13A) 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 (Fig. 14A), are difficult to recognize both in the mine and in drill core. This is because (1) the matrix of these breccias lacks 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, have become evident (Morales, 1997; Skewes, 1999).

Breccias at El Teniente are both monolithic (Figs. 12A, 14A) and/or heterolithic (Fig. 13C, D). The nature of their clasts depends in part on the location of the breccias in the deposit, and in part on 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 (Fig. 13B), anhydrite (Fig. 13A), biotite (Fig. 14A), gypsum, magnetite, and igneous (Fig. 14C) and rock-flour (Fig. 13C, D) breccias (Arredondo, 1994; Morales, 1997; Skewes, 1999; 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.

Classification of breccias by matrix minerals is not always rigorous, because the proportion of different matrix minerals may vary, even within one breccia pipe. Also, 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 and a central core of copper-poor rock-flour breccia, which may have formed at several different stages during the development of this single large breccia pipe (Fig. 4; Howell and Molloy, 1960; Camus, 1975; 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 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 (Arredondo, 1994; Morales, 1997; Skewes, 1999; Floody, 2000).

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.
Fig. 13. A. 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 in level Teniente 6, within the Esmeralda project (Morales, 1994), just northeast of the Braden pipe; 500N, 1090E, 2,210 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 (325N, 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. Heterolithic rock-flour breccia from the central “bolones” portion of the Braden pipe (Fig. 4; Floody, 2000). The 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). D. Another heterolithic rock-flour breccia, with biotite, anhydrite, quartz, and sulfide minerals cementing the matrix, and with clasts of felsic and biotite-altered mafic rocks, the latter in the lower left corner (sample DDH1659-257; from a near vertical drill hole initiated on level Teniente 6, northeast of the Braden pipe; 595N, 855E, 2,047 m above sea level). Both the fragment and breccia are cut by Late Magmatic veins containing quartz and sulfide minerals, without halos, and Principal Hydrothermal veins with quartz, sericite, and sulfide minerals, and with sericitic halos. This rock-flour breccia formed independent of, and based on the types of veins, earlier than the Braden pipe.

Magnetite breccias

Magnetite breccias have been described from a few kilometers north of the El Teniente deposit in the area of Laguna La Negra (Fig. 3; Cuadra, 1985; 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 by 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 (Figs. 12A, 14B). Biotite crystals in the matrix of biotite breccias can be fine-grained (Fig. 14A), or as much as several centimeters in length (Fig. 12A). Biotite breccias usually are monolithic, with clasts dominated by either mafic (Fig. 14A) or felsic (Fig. 12A) intrusive rocks, but in some cases

---

**Fig. 14.** A. Biotite breccia containing clasts of biotite-altered and mineralized porphyritic basalt (sample DDH1951-71); from a horizontal drill hole initiated at level Teniente 8, northeast of the Braden pipe; 810N, 1400E, 1,983 m above sea level. Similar biotite breccias have been mapped in the past as part of the Andesites of the Mine. Both the breccias and clasts are cut by quartz-anhydrite Late Magmatic veins, with variable proportions of chlorite (after biotite), chalcopyrite, and pyrite. B. Photomicrograph (crossed polarizers, 5.8 x 3.7 mm) of fine-grained biotite breccia, with biotite-rich matrix containing anhydrite, quartz, feldspar, and chalcopyrite, and biotite-altered gabbro clasts (sample DDH11698-174); 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, Figs. 4 and 5). C. Two heterolithic igneous breccias with different proportions of felsic and biotite-altered mafic clasts (samples on the right—DDH1103-100; 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—DDH11937-349; from drill hole initiated at level Teniente 4-Production, east of the Braden pipe; 109N, 1600E, 2,200 m above sea level; section 121N, Fig. 5). The lack of secondary biotite in the felsic clasts suggests that the mafic clasts were altered prior to their incorporation in these breccias. D. Photomicrograph (crossed polarizers, 5.8 x 3.7 mm) of the matrix of an igneous breccia, containing biotite, anhydrite, quartz, feldspar, and sulfide minerals, and also a difficult-to-see clast (outlined by dashed line) of biotite-altered gabbro in which the plagioclase and opaque minerals are slightly larger than grains in the matrix of the breccia (sample DDH11686-257; from a drill hole initiated at level Teniente 4-Production, southeast of the Braden pipe; 375S, 1550E, 2,280 m above sea level). Such breccias have often been described and mapped as fine-grained diorites.
they can have both. Biotite-rich breccias usually have high copper content.

Biotite-altered mafic clasts in biotite breccia are often barely recognizable as such (Fig. 14B). Biotite breccias are associated with the development of a stockwork of biotite-rich veins in the surrounding host rock. In their centers, these veins contain brown and/or green biotite, as well as anhydrite, feldspars, quartz, chalcopyrite and magnetite; they also have biotite-rich halos (Fig. 15A).

Biotite breccias, and associated biotite veins and alteration, postdate magnetite-actinolite alteration. Fragments of biotite breccias and biotite-altered mafic rocks have been found in igneous (Fig. 14C), anhydrite, tourmaline (Fig. 13B), and rock-flour (Fig. 13D) 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 (Fig. 12B). Generally, neither of the two large felsic plutons, the Sewell Diorite 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 (Fig. 12A), or where they are included as clasts in breccias (Fig. 13A). These relations suggest that biotite breccias were emplaced repeatedly in the evolution of the deposit, but in most cases, clearly prior to emplacement of the felsic intrusions. Biotite is often altered to chlorite and/or sericite (Figs. 13B, 15C) 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 are clearly identifiable when they are hosted in felsic intrusive rocks (Fig. 12A). They are, however, very difficult to recognize when they are hosted in mafic rocks (Fig. 14A), unless another light-colored mineral such as anhydrite, apatite, feldspar, or quartz is associated with biotite in their matrix. For this reason, mine geologists began mapping biotite breccias as a separate unit only recently. On most maps of the mine, as well as in core logs, biotite breccias are still considered as part of the biotite-altered mafic intrusions because of their color and textural resemblance to these rocks. In some cases, where they occur in complex breccia zones associated with later igneous, anhydrite, and tourmaline breccias, they have been mapped as “hydrothermal” breccias (Arredondo, 1994).

Biotite breccias have been identified in zones of high-grade hypogene copper surrounding the Braden pipe, and distant from the Teniente Dacite porphyry (Fig. 4). These include a 400 x 400 m area located east of the Braden pipe (section 124N; Figs. 4, 5; Skewes, 1997b, 1999), where copper grades exceed 2 percent (Fig. 6) within a complex of biotite, igneous, anhydrite, and tourmaline breccias, which both cut the Sewell Diorite (Fig. 12A) 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, Figs. 4, 6; 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 porphyry (section 83N; Figs. 4, 5; Skewes, 1996a, 1999). 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, feldspars, anhydrite, chalcopyrite, and iron oxides, and has a typically fine-grained, equigranular, holocrystalline igneous appearance (Fig. 14C, D). 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. As with biotite breccias, they have also often been mapped in El Teniente as “hydrothermal” breccias, and in some areas of the mine as fine-grained diorites. They are associated with veins of similar mineralogy to that within the breccias themselves.

Igneous breccias often contain clasts of biotite-altered mafic rocks (Fig. 14C, D). In some cases they may postdate biotite alteration of these clasts (Guzmán, 1991), as indicated by the lack of biotite alteration of felsic clasts in the same breccia (Fig. 14C). In some areas of the mine they are intimately associated with high-grade copper mineralization. For example, in the Esmeralda sector of the mine, northeast of the Braden pipe (400-600N, 1000-1200E, Fig. 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 percent Cu, widens in 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; Figs. 4, 5; Skewes, 1999), and both west and east of the Teniente Dacite porphyry (section 83N; Figs. 4, 5).

Anhydrite breccias

Anhydrite is the dominant mineral, often occurring along with biotite, tourmaline, quartz, gypsum, apatite, chalcopyrite, pyrite, bornite and rutilite, in the matrices of many breccia bodies in El Teniente (Fig. 13A; Arredondo, 1994). 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 to 30 percent of the volume of the breccia. Anhydrite breccias clearly 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 seritized and silicified clasts, and are surrounded by veins containing tourmaline, anhydrite, and quartz, plus sulfide minerals.

Anhydrite breccias are usually easily recognized and mapped, and they are widely distributed in the deposit (Fig. 4). In the Esmeralda sector of the mine, northeast of the Braden pipe (400–600N, 1000–1200E, Fig. 4), 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; Figs. 4, 5; Arredondo, 1994; Skewes, 1997b, 1999). Another large anhydrite-quartz breccia occurs north of the Braden pipe, along the eastern margin of the Teniente Dacite porphyry (section 83N; Figs. 4, 5; Skewes, 1996a, 1999). 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 (Figs. 4,
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 (Fig. 13B). Tourmaline breccias generate a stockwork of veins with cores of tourmaline, quartz, chalcopyrite, bornite, and pyrite, and sericite and/or chlorite halos that bleach the host rock (Fig. 15C). Tourmaline breccias can be either mineralized, such as the Marginal breccia of the Braden pipe, or barren.

The Marginal breccia of the Braden pipe (Fig. 4), dated by the potassium-argon age method (K-Ar) as 4.7 Ma (Cuadra, 1986), is the largest tourmaline breccia in El Teniente. Other recently explored tourmaline breccias in the mafic intrusions south of the Braden pipe (near 500E, 700S; Fig. 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 percent and >1 percent molybdenum (O. Quezada; oral commun., 2001). 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; Figs. 4, 5; Arredondo, 1994; Skewes, 1999).

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. These breccias are heterolithic, with clasts of previously biotite-altered mafic rocks, felsic intrusive rocks, and preexisting breccias (Fig. 13C, D). The Braden pipe contains fragments of all rock types recognized in the deposit, and also of some rocks that have 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 (Fig. 13C, D). 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 preexisting 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). Rock-flour breccias have also been recognized and mapped recently in other areas of the deposit east, northeast, and north of the Braden pipe (Fig. 13D; Skewes, 1999).

Alteration

General

All rocks in the area of hypogene copper mineralization at El Teniente show indications of multiple alteration events. Each of the alteration events 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 percent 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 km × 2 km that coincides with the area of high copper grades (Villalobos, 1975). Secondary biotite, the most abundant alteration mineral in the deposit, occupies from 20 to more than 50 percent of the volume of the altered mafic rocks (Camus, 1975; Arévalo et al., 1998). According to 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 (Fig. 10) and felsic intrusions (Fig. 12A) is related to emplacement of biotite breccias (Fig. 14A, B) and veins (Figs. 10A, 15A). Early biotite veins, despite their importance, have received little attention, because they are difficult to recognize (Fig. 10A), they have often reopened and had other, later vein types form within them, 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 Diorite, 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 (Arévalo et al., 1998). 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 (Fig. 15B). Although these typical Late Magmatic veins generally lack halos, earlier biotite veins have biotite-rich halos (Figs. 10A, 15A), and pervasive biotite alteration is related to the density of these early biotite veins.

It is clear that biotite alteration occurred in conjunction with multiple independent events, possibly over a period of time as long as >2 m.y., from prior to, or in association with, the intrusion of the Sewell Diorite at 7.1 Ma
(Cuadra, 1986), through the time of the intrusion of the later porphyries, which occurred until 4.4 Ma. Available Re-Os (Mathur et al., 2001) and $^{40}$Ar/$^{39}$Ar (Maksaev et al., 2001) dating indicate multiple major alteration and mineralization events, with peaks near 5.6 and 4.8 Ma (Re-Os), and/or 5.3 and 4.7 Ma ($^{40}$Ar/$^{39}$Ar), the latter based on a statistical analysis of biotite and sericite dates that range from 6.4 to 4.4 Ma. 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 Hydrothermal alteration, for example, has been associated spatially with the Sewell Diorite, 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); however, similar alteration also occurs surrounding other tourmaline breccias in the deposit (Arredondo, 1994), associated with latite ring-dikes around the Braden pipe (Arevalo et al., 1998), and even in a tourmaline-cemented sector within the central rock-flour portion of the Braden pipe (Floody, 2000).

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 (Cuadra, 1985; Floody and Huet, 1998).

In the mafic rocks, magnetite and actinolite, or actinolitic hornblende (Skewes, 1996a), replaces clinopyroxene, usually pseudomorphically (Fig. 10). Calcic plagioclase exhibits normal zoning and apparently has not been albited, but may contain many tiny (< 8 µm) magnetite and actinolite inclusions (Skewes, 1997a). 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.

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. Original textures of the biotite-altered mafic rocks often are nearly totally destroyed, and fine-grained biotite has replaced preexisting mafic minerals, and in some cases plagioclase (Fig. 10). 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, but in fact is related to a dense stockwork of biotite veins, ranging from <0.5 mm (Fig. 10A) to several cm across, and with biotite-rich halos of variable width (Figs. 10A, 15A). 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 (Fig. 14B) 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; Figs. 4, 5). Biotites from the area of intense biotite alteration intruded by Porphyry A, east of the Braden pipe (section 124N; Figs. 4, 5), have been dated by K-Ar as between 6.0 and 4.7 Ma (SERNAGEOMIN, 1986), and $^{40}$Ar/$^{39}$Ar ages for biotite in various areas of the deposit range from 5.5 to 4.7 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. 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 gray halos of feldspar, quartz, anhydrite, and lesser amounts of biotite (Fig. 12B). Sulfide minerals in biotite veins include chalcopyrite, with lesser bornite, pyrite, and molybdenite. These veins carry a significant part of the copper mineralization in the deposit.
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 preexisting biotite breccias, veins, and biotite-altered mafic rocks (Fig. 12B). The Teniente Dacite porphyry lacks biotite alteration. Biotite breccias occur on both flanks of this porphyry (section 83N; Figs. 4, 5; Skewes, 1999), 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 (Figs. 12A, 13A). These relations imply that biotite alteration took place over an extended time period, at various times in different areas of the deposit, in part preceding and in part subsequent to the emplacement of different felsic intrusions in the deposit.

**Subsequent Late Magmatic alteration**

Subsequent main 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 (Fig. 15B; 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 (Fig. 15B). 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 alteration concentrated in the northern part of the deposit, on the western and eastern flanks of the Teniente Dacite porphyry, has been attributed to intrusion of this porphyry (Villalobos, 1975; Ojeda et al., 1980; Zuñiga, 1982; Arévalo et al., 1998). It also occurs locally in the Sewell Diorite (Fig. 12A), and associated with breccia complexes east and northeast of the Braden pipe (sections 83N and 124N; Figs. 4, 5), where some anhydrite-rich veins, containing chalcopyrite, are associated with anhydrite breccias (Arredondo, 1994). In the southern portion of the deposit, Late Magmatic alteration has been largely overprinted by subsequent alteration events (Arévalo et al., 1998).

**Principal Hydrothermal alteration**

This alteration is characterized by destruction and replacement of preexisting minerals by quartz and sericite, with lesser chlorite and anhydrite, in halos surrounding sulfide mineral-rich veins that also contain quartz, chlorite, and anhydrite (Fig. 15C; Zuñiga, 1982). Chalcopyrite, pyrite, and molybdenite 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 Diorite 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. $^{40}\text{Ar}/^{39}\text{Ar}$ ages for sericite from various areas of the deposit range from 6.4 to 4.4 Ma (Maksaev et al., 2001).

**Late Hydrothermal alteration**

Late Hydrothermal veins contain quartz, tourmaline, anhydrite, sericite, chlorite, gypsum, carbonates, chalcopyrite, bornite, pyrite, molybdenite, tennantite-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 Molloy (1960), is spatially related to formation of the Braden pipe, and in particular to the Marginal breccia, a tourmaline-rich unit of the pipe (Villalobos, 1975; Ojeda et al., 1980). The Marginal breccia contains clasts altered to the same quartz-sericite assemblage as produced by the Late Hydrothermal veins around the pipe (Fig. 13B). This alteration also affects the late ring-dike intrusions surrounding the pipe, and forms a concentric ring 150 m wide surrounding the pipe, within which bornite and tenantite 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 (Fig. 4; Arévalo et al., 1998), and around tourmaline breccias cutting the Sewell Diorite 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.

**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 postdates 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, tennantite-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 percent, occurs immediately adjacent to the deposit (Villalobos, 1975; Zúñiga, 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; Zúñiga, 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 (Fig. 3; Cuadra, 1985, 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 Farelones and Coya-Machalí Formaciones 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 anhydrite, 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 (Zúñiga, 1982; Cuadra, 1986; Arendondo, 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 percent copper (Zúñiga, 1982).

Depth of penetration and intensity of supergene alteration are 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 (Zúñiga, 1982). The supergene alteration zone is thickest in regions of highest topography cast 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; Fig. 5). Supergene enrichment on the flanks of the dacite porphyry (Fig. 6) has further contributed to the erroneous impression that this stock was the main source of the 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 percent over a 2.7 × 2 km area (Fig. 6). Anomalous high copper grades of >1.5 percent 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; Fig. 5). However, it also reflects the presence of mineralized biotite and anhydrite breccias, which flank the area intruded by the dacite porphyry (Figs. 4, 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 northwest-southeast–trending group of biotite, igneous, anhydrite, and tourmaline breccias, in some cases intruded by apophyses of porphyritic tonalite (Fig. 4). They also occur to the south of the pipe, as a northeast-southwest–trending group of tourmaline and anhydrite breccias. In the Esmeralda sector of the mine (400–600N, 1000–1200E; Figs. 4, 6), which is developed around just one group of breccias, there are an estimated
3.5 Mt of fine copper at an average grade of 1 percent (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 tourmalized part of the central rock-flour breccia of this pipe (>1 Mt 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 Diorite, to the time of tourmalization after emplacement of the central part of the Braden pipe.

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 consists of a narrow bornite-rich (bornite > chalcopyrite) zone grading out into a broad chalcopyrite-rich (chalcopyrite > bornite + pyrite) zone. Farther outward, where copper grades are less than 0.5 percent (Fig. 6), is a pyrite-rich zone (pyrite > chalcopyrite + bornite; Howell and Molloy, 1960; Villalobos, 1975; Camus, 1975, Ojeda et al., 1980; Arévalo et al., 1998). Intrusion of both the copper-poor 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 postdates 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 $^{187}\text{Os}/^{188}\text{Os}$ 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 $^{187}\text{Os}/^{188}\text{Os}$ ratios would be expected. Lead isotopic ratios, measured in galena ($^{206}\text{Pb}/^{204}\text{Pb} = 18.57$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.60$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.49$; Puig, 1988; Zentilli et al., 1988), also exhibit little variability, and 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 isotope 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.

**Hydrothermal Fluids**

Fluid inclusion and stable isotope studies of minerals in matrices of different types of breccias, and in veins associated with different alteration assemblages, both at El Teniente and in the other giant copper deposits of central Chile, provide constraints on the nature of the fluids involved in the generation of breccias, veins, alteration, and mineralization in these deposits (Table 2).

Magnetite breccias and 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). In Río Blanco-Los Bronces, these breccias and this alteration also occur early in the development of the deposit, and are generally preserved around its periphery, possibly because they have been overprinted by later alteration events within the central portion of the deposit. This type of alteration has been attributed to high-temperature (>350°C), highly saline fluids (42 to 50 wt % NaCl equiv; Table 2; Skewes et al., 1994), which may be either of magmatic origin or connate formation waters. It is similar to the magnetite-actinolite-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 breccias and 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 association with other igneous, anhydrite, and tourmaline breccias in areas of potassic alteration associated with high-copper hypogene grade. Skewes et al. (2001) report temperatures of homogenization of 525°C for high-salinity fluid inclusions in quartz from a biotite breccia northeast of the Braden pipe. Based on this temperature, they calculate δ¹⁸O of 6.8 per mil for aqueous fluid that precipitated this quartz, consistent with the generation of this fluid from a cooling magma (Table 2). Biotite veins at both Los Pelambres and Río Blanco-Los Bronces also precipitated from highly saline, boiling, and nonboiling magmatic fluids, at depths of 1 to 3 km below the paleosurface (Skewes and Atkinson, 1985; Serrano et al., 1996). Minimum temperatures of formation of biotite veins at Los Pelambres, determined based on fluid inclusions, biotite chemistry, and mineralogical assemblages (Skewes and Atkinson, 1985), are between 280° and >550°C (Table 2). Brimhall (1977) estimated the temperature of formation of similar early "pre-Main stage" biotite veins at Butte, Montana, to be as high as 600° to 700°C.

Fluid inclusions in quartz-bearing Late Magmatic veins, which cut biotite veins (Fig. 13B), indicate precipitation from highly saline (29 to 48% NaCl equiv), high-temperature fluids (Table 2), both boiling and nonboiling (Clark et
Table 2. Homogenization temperatures (°C) and salinities (weight % NaCl equivalent) of halite-bearing fluid inclusions, and calculated δ¹⁸O and δD (per mil), of the fluids that generated the different types of breccias, veins and alteration in the three giant Miocene and Pliocene copper deposits of central Chile.

<table>
<thead>
<tr>
<th>El Teniente</th>
<th>Rio Blanco-Los Bronces</th>
<th>Los Pelambres</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAGNETITE-ACTINOLITE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breccias</td>
<td>Present</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Veins</td>
<td>Present</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>BIOTITE (± K-FELDSPAR)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early Late Magmatic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biotite Breccias</td>
<td>525°C; 37-49.3% NaCl; Yes</td>
<td>+6.8</td>
<td>–</td>
</tr>
<tr>
<td>Biotite Veins</td>
<td>Present</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Igneous Breccias</td>
<td></td>
<td>Present</td>
<td>–</td>
</tr>
<tr>
<td>Main Late Magmatic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veins</td>
<td>280-480°C; 29-45.5% NaCl; Yes</td>
<td>+6.0</td>
<td>–</td>
</tr>
<tr>
<td><strong>SERICITE (± CHLORITE ± QUARTZ)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Principal Hydrothermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veins</td>
<td>295-480°C; 29.8-54.1% NaCl; Yes</td>
<td>+5.9</td>
<td>-35</td>
</tr>
<tr>
<td>Late Hydrothermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anhydrite Breccias</td>
<td>500°C; 30.8-49.1% NaCl; Yes</td>
<td>+8.4</td>
<td>–</td>
</tr>
<tr>
<td>Tourmaline Breccias</td>
<td>250 - 400°C; 30-45.1% NaCl; Yes</td>
<td>+8.5 to +10.8</td>
<td>-38</td>
</tr>
<tr>
<td>Veins</td>
<td>280-350°C; 30.3-37.4% NaCl; Yes</td>
<td>+5.8</td>
<td>–</td>
</tr>
<tr>
<td><strong>CARBONATES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pópomina</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Braden Rock-Flour Breccias</td>
<td>Absent</td>
<td>+6 to +6.5</td>
<td>–</td>
</tr>
</tbody>
</table>

Data from Clark et al. (1983); Kussakabe et al. (1984, 1990); Skewes and Atkinson (1985); Ip (1987); Holmgren et al. (1988), Skewes (1996b, 1997c), and Skewes et al. (1994, 2001, 2002).
al., 1983; Ip, 1987; Kusakabe et al., 1990; Skewes, 1996b, 1997c). The anhydrite-chalcopyrite sulfur isotope geothermometer indicates temperatures of 456° ± 41°C for the formation of these veins (Kusakabe et al., 1984). Calculated at this temperature, the δ¹⁸O of the fluids from which quartz and anhydrite precipitated was 6 per mil, similar to aqueous fluids derived from cooling magmas (Table 2; Kusakabe et al., 1984, 1990).

Highly saline fluid inclusions in quartz from the Marginal tourmaline-rich unit of the Braden pipe also homogenize at high temperatures (400°C; Skewes et al., 2001). Based on this temperature, stable isotope analysis of tourmaline and anhydrite from the matrix of this breccia indicates precipitation from magmatic fluids with δ¹⁸O of 6.9 to 10.6 per mil and δD of −36 per mil (Fig. 16, Table 2; Skewes et al., 2001). Tourmaline breccias in El Teniente resemble those from Rio Blanco-Los Bronces (Serrano et al., 1996), such as the Donoso (Warnaars et al., 1985; Skewes et al., 2002) 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. Fluid inclusion and stable isotope studies of Donoso and Sur-Sur breccias indicate that they also formed from highly saline (30 to 57 wt % NaCl equiv) fluids at high temperature (400°C to 660°C), magmatic fluids (δ¹⁸O = 5.9 to 9.1 per mil; δD = −51 to −80 per mil; Fig. 16, Table 2; Vargas et al., 1999; Skewes et al., 2001, 2002).

In Principal Hydrothermal veins, abundant vapor-rich fluid inclusions in quartz indicate boiling (Skewes, 1996b, 1997c). Highly saline, halite-bearing inclusions occur, but are not common. Inclusions with variable salinity (4 to 54% NaCl equiv) homogenize between 295°C and 480°C (Table 2; Skewes, 1996b, 1997c), consistent with sulfur isotope temperatures of 410°C (Kusakabe et al., 1984). Calculated at this temperature, δ¹⁸O of the aqueous fluids that precipitated quartz and anhydrite is approximately 5.9 per mil, and the δD of fluids that precipitated sericite in the vein halos is −35 per mil, both within the range of magmatic fluids and similar to the fluids from which Late Magmatic veins formed (Fig. 16; Table 2; Kusakabe et al., 1990). Abundant vapor-rich fluid inclusions, indicating boiling, also occur in Late Hydrothermal veins (Skewes, 1996b, 1997c). Highly saline, halite-bearing inclusions occur, but are not common. High and intermediate salinity inclusions (30 to 37 wt. % NaCl equiv) homogenize between 285°C and 360°C (Table 2; Skewes, 1996b, 1997c). Calculated at sulfur isotope temperatures of 410°C (Kusakabe et al., 1984), δ¹⁸O of the aqueous fluids that precipitated quartz and anhydrite is approximately 5.8 per mil, within the range of magmatic fluids and similar to the fluids from which both Late Magmatic and Principal Hydrothermal veins formed (Table 2; Kusakabe et al., 1984, 1990).

These 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 (Fig. 16, Table 2; Kusakabe et al., 1984, 1990; Skewes et al., 2001). Although the influx of meteoric water has been invoked to explain sericitic alteration in many 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, whereas later tourmaline breccias and sericitization resulted from fluids derived from shallower magma chambers, due to both progressive uplift and erosion (Skewes and Holmgren, 1998), and the progressive intrusion of younger plutons to higher levels in the deposit. Biotite breccia 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 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 previ-
ously 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., 2002).

Even the fluids responsible for Póstuma alteration within the central portion of the Braden pipe have a magmatic isotopic signature. Halite-free fluid inclusions in quartz and barite from cavities in the pipe homogenize between 250° and 350°C (Kusakabe et al., 1990; Skewes et al., 2001). Calculated at 350°C, quartz precipitated from aqueous fluids with δ¹⁸O between 6 and 8.5 per mil, similar to the magmatic fluids involved in the earlier and more widespread stages of alteration at El Teniente (Table 2; Kusakabe et al., 1990; Skewes et al., 2001).

**Discussion**

El Teniente has much in common with the other two giant copper deposits in central Chile, Los Pelambres and Río Blanco-Los Bronces (Fig. 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-hydrothermal breccias in each deposit are the most obvious similarities. An 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 × 2 km zone, and many of the late, large tourmaline-rich breccias, such as Donoso (Skewes et al., 2002) and Sur-Sur (Vargas et al., 1999), and rock-flower 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 × 2.7 km area, and the enormous copper-poor Braden rock-flower 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.

Here we summarize first the evolution of the igneous rocks within which the deposit was emplaced and from which the copper was derived, then the main stages of development of the El Teniente deposit (Fig. 17), and finally the implications for the exploration for other giant Andean copper deposits.

**Magmatic evolution of the deposit**

Mafic igneous intrusive rocks host the deposit, and after an episode of intrusion of felsic pluttons between 7.1 and 4.6 Ma, intermediate dikes and mafic lavas were again emplaced in and surrounding the deposit. This is consistent with the dominantly mafic nature of Andean magmatism, which is generated by melting in the mantle wedge above a subducting, dehydrating slab (Hickey et al., 1986; Hickey-Vargas et al., 1989; Hildreth and Moores, 1988; Stern et al., 1990; Kay et al., 1999; Dungan et al., 2001). During the period when felsic pluttons 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 (Table 1, Figs. 4, 5) into the Sewell Diorite at approximately 6.0 Ma (SERNAGEOMIN, 1986). Other mafic magmas may have mixed with or underplated magmas in the deeper parts of the evolving felsic pluttons, rather than reaching the surface (Skewes and Stern, 1994, 1995). This process has been well demonstrated for magma chambers below many active and ancient volcanic systems (Sparks et al., 1977; Hildreth, 1981; Pallister et al., 1996). Mafic magmas emplaced into the base of an evolving, open-system felsic pluton provide heat to allow this pluton to grow and intrude to higher levels in the crust; it also supplies 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 that otherwise might be poor in sulfur (Nagashima and Katsura, 1973) and chalcophile elements. Indirect evidence for open-system behavior involving mixing of mafic and felsic magmas during evolution of Andean porphyry copper deposits has been presented by Cornejo et al. (1997) and Rowland and Wilkinson (1998), and direct evidence for mixing between felsic and more mafic magmas has recently been reported from proton-induced X-ray excitation (PIXE) microprobe analysis of melt inclusions in quartz phenocrysts within a porphyry stock at El Salvador (Fig. 1; Palacios et al., 2002).

As volatile-rich mafic mantle-derived magmas replenish the base of a growing and/or cooling open-system felsic pluton, exsolution of sulfur and metal-rich aqueous brines and vapor from the crystallizing upper part of the pluton produce brecciation, alteration, and mineralization of the rocks into which the pluton intrudes (Burnham, 1985). During development of the El Teniente deposit, exsolution of magmatic-hydrothermal fluids created first the early biotite, igneous, and anhydrite breccia complexes and associate pervasive biotite alteration and copper mineralization. Subsequently, tourmaline and anhydrite breccias, both mineralized and barren, formed. This produced multiple independent breccia complexes above the magma chambers that eventually crystallized to form the Sewell Diorite, related porphyritic tonalite apophyses, and ultimately the Teniente
Fig. 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, 4, and 5.
Dacite porphyry. However, input of mantle-derived mafic magma into the base of the felsic magma chamber below the deposits decreased, from middle to late Miocene, 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 late dikes and stocks cut and redistributed previously emplaced copper mineralization, but were not the main source of the copper in this deposit.

The most significant temporal chemical trend that is observed among igneous rocks related to the deposit is that towards higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 9). This may be due in part to progressively greater intracrustal contamination of mantle-derived magmas as the crust thickened during the Miocene (Kay and Kurtz, 1995; Kay et al., 1999). However, the felsic Sewell Diorite has the same isotopic composition as the more mafic rocks of the Teniente volcanic complex, whereas the youngest, most radiogenic rocks in the region are the postmineralization intermediate lamprophyre dikes and basaltic andesite lavas in the Cachapoal River valley (Fig. 9). Therefore, this temporal trend is independent of the $\text{SiO}_2$ content of the rocks, and is more likely a 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). Similar isotopic changes also occurred during the development of the other giant copper deposits in central Chile (Fig. 7), and the southward temporal migration of these changes reflects the southward migration of the locus of subduction of the Juan Fernández Ridge (Yañez et al., 2001).

The La/Yb ratios of the more mafic rocks associated with the deposit also increase, but only approximately twofold, from $\leq 5$ in the early Miocene Coya-Machalí volcanic rocks, to $\leq 7$ in the late Miocene gabbros, diabases, and basaltic porphyries in the mine, to $\approx 10$ for the Pliocene basaltic andesite lava flows in the Cachapoal River valley (Fig. 8). 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 and Kurtz (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 in shallow crustal magma chambers.

**Genesis and classification of the deposit**

Formation of the giant El Teniente deposit began with intrusion of a mafic complex, in the form of a laccolith, into extrusive rocks of the Miocene Teniente volcanic complex (Fig. 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 Diorite 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.

We suggest three interrelated possibilities for the genesis of this world-class copper system. First, important north-south, northeast-southwest, and northwest-southeast crustal structures intersect at the deposit. In the active southern Andean arc, the largest long-lived (>1 m.y.) 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 occur where the generally north-south-trending Andean arc is intersected by northwest-southeast arc segments (see figs. 1 and 2 in Muñoz and Stern, 1988). Alternatively, focusing of magmatic activity and mineralization may reflect segmentation of the subducted slab. Los Pelambres and El Teniente deposits, for example, occur on the northern and southern boundaries, respectively, of the segment of the Nazca plate that has ruptured to produce large earthquakes in central Chile every 83 ± 9 years for the last 500 years (Comte et al., 1986), and the Rio Blanco-Los Bronces deposit occurs on the boundary between the Flat-Slab and Southern volcanic zones segments of the Andes (Fig. 1). A third possibility is that long-term focusing of magmatic activity may result from rheological contrasts between the areas below each deposit and the intervening areas, due to the diapirc rise of magmas, either within the crust (Damon, 1986; Yañez and Maksae, 1994), or as deep as immediately above the subducted slab (Marsh, 1979).

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 premineralization 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 autometamorphism 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 that ultimately crystallized to form the Sewell Diorite (Fig. 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 (Fig. 17C; Cuadra, 1986), and certainly before 5.7 Ma (Maksae 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 Diorite, to at least 4.7 Ma (Fig. 17D; Maksaev et al., 2001). Some of these breccias cut the Sewell Diorite (Fig. 12A), implying they were generated by fluids from magma chambers that solidified to form plutons still not encountered even in the deepest drill holes below the mine. The main group of these breccia complexes, which are the areas of highest grade hypogene copper in the deposit (Fig. 6), are located east and northeast of the Braden pipe, along a northwest-southeast trend that parallels or is within the Puquios-Codegua fault zone (Figs. 3, 4). Other biotite breccias also formed west of the area later intruded by the Teniente Dacite porphyry (section 83N; Figs. 4, 5), and presumably in the area cut by the Braden pipe, because this breccia contains abundant clasts of previously biotite-altered mafic rocks (Fig. 13B).

The youngest porphyry intrusions, including the latite dikes and Teniente Dacite porphyry, 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 (Fig. 17E; Maksaev et al., 2001). One group of these breccias occurs south of the Braden pipe, along a northeast-southwest trend paralleling the strike of the Teniente fault zone (Figs. 3, 4). The largest of the tourmaline and rock-flour breccias is the Braden pipe (Fig. 17F). 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 multiple 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. Magmatic-hydrothermal fluids that formed the mineralized tourmaline-rich Marginal breccia of the pipe were derived from the cooling of a pluton that must exist at significant depth below the deepest drill holes into the Braden pipe.

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 (Fig. 6). 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 (Fig. 6).

Concentric zoning of barren > chalcopryte > pyrite surrounding the barren cores of the Teniente Dacite porphyry and Braden pipe, which Howell and Molloy (1960, p. 902) cited as the typical "circular configuration" of mineralization "arrayed concentrically around a common center" characteristic of a model porphyry copper deposit, is actually an artifact of the late intrusion of these copper-poor bodies into the previously pervasively biotite-altered and mineralized mafic rocks, within which chalcopryte is the dominant sulfide. This concentric zoning reflects the multistage development of the deposit rather than a temperature gradient or fluid-rock alteration pattern surrounding a single felsic porphyry intrusion. In Río Blanco-Los Bronces, where late tourmaline and rock-flour breccias, and dacite porphries, were emplaced along the margins of the Río Blanco breccia complex, this concentric zonation does not occur.

A barren, or copper-poor core, is a characteristic of many 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 (Fig. 17). Howell and Molloy (1960, p. 902) note that in some copper deposits the orebody itself occupies the central core, and specifically that "the mineralized breccia pipe deposits belong to this group, although, strictly speaking, many of them cannot be classified as porphyry copper." We agree strongly with the implications of this comment with regard to El Teniente. Although copper porphyry deposits commonly contain breccias, El Teniente and the other giant copper deposits in central Chile are clearly enormous magmatic-hydrothermal breccia deposits. 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.
Implications for exploration

Implications for exploration for other giant copper deposits include, first and foremost, the fact that the Teniente Dacite porphyry is not the “productive” pluton in this deposit. 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. The Los Bronces breccia deposit, for example, with >10 Mt of fine copper, does not include a single porphyry stock (Warmaars et al., 1985; Skewes et al., 2002). The larger Río Blanco-Los Bronces deposit does, but as in El Teniente, these are relatively small, late, shallow copper-poor intrusions that have redistributed, rather than contributed, copper to the system. Such porphyries may also 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 breccia deposit such as El Teniente or the other giant deposits in central Chile. Detailed studies of the igneous petrochemistry of such late barren porphyries will not provide a single clue to the presence of an associated orebody. In the case of the giant breccia deposits in central Chile, the magmatic-hydrothermal fluids that generated the mineralized breccias were derived from as yet unexposed plutons, so no samples are yet available from these so-called “productive” plutons to determine if they have unique chemical characteristics (Skewes and Stern, 1996).

Understanding the fundamental causes of what focused so much magmatic activity and copper mineralization in the specific area where El Teniente formed would be the ultimate exploration tool, but this understanding remains too speculative to be predictive. More significantly, patterns of intersecting regional Andean structures, segmentation of the subducted slab, and evolution of magmatic activity as this segmentation evolved, vary in different regions of the Andes. This is obvious, for example, from the differences in ages of copper deposits in central and northern Chile (Sillitoe, 1988). It appears clear that the timing of formation of El Teniente and other giant copper deposits in central Chile was related to the late Miocene changes in subduction geometry that accompanied subduction of the Juan Fernández Ridge. What is not yet clear are the crustal or subcrustal factors that focused magmatic activity and mineralization in the specific areas where the three known giant copper deposits formed. Until these parameters, and how they might vary between different Andean segments, are better understood, the best exploration tools for finding such deposits would appear to be the same ones that have been used to understand and unravel the nature and genesis of the giant El Teniente deposit. These tools are basic geology involving mapping and core logging, petrology, geochemistry, and geochronology. Even a lieutenant might recognize native copper and oxidized copper minerals at the surface above a giant deposit, but it took a great deal of basic geologic work to actually “discover” the size and complexity, in both time and space, of El Teniente.

Acknowledgments

We thank Rodrigo Morel, Alvaro Puig, Carlos Guzmán, Estanislao Godoy, Patricio Cuadra, Michael Dobbs, Andrés Brzovic, Arturo Morales, José Seguel, Omar Quezada, and Domingo Espiñeira for informative discussions in and around the mine. Reviews by Charles Cunningham, Greg Corbett, Richard Nielsen, and Richard Goldfarb significantly improved the final manuscript. Dan Mitchell, Darío Rubio, and Claudio Soto helped enormously with the figures. The Superintendencia Geología de Teniente, CODELCO-Chile, supported the preparation and publication of the manuscript.

REFERENCES

Cline, J., and Bodnar, R.J., 1984, Direct evolution of saline brine from a crystallizing silicic melt at the Questa, New Mexico, molybdenum deposit: Economic Geology, v. 89, p. 1,780–1,802.
igneous rocks of central Chile: III Simposio Sudamericano de Geología Isotópica, Pucón, Chile, Extended Abstracts, p. 348–351. (CD-ROM)

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, v. 23, p. 39–52.


