EL TENIENTE PORPHYRY COPPER-MOLYBDENUM DEPOSIT, CENTRAL CHILE

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Australia
Declaration

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James Cannell

Date: 11/11/2005
ABSTRACT

El Teniente occurs in the late Miocene-early Pliocene metallogenic belt of central Chile. It is the world’s largest known copper resource, containing 94.4Mt of fine copper, and 2.5Mt of fine molybdenum. The ore deposits formed during the final stages of a period of compression and crustal thickening initiated approximately 15 m.y. ago due to subduction of the Juan Fernandez Ridge.

El Teniente is hosted by the Miocene Farellones Formation and is located at the intersection of two major faults. The NNW trending Codegua Fault is interpreted to have formed from reactivation of a basement Triassic rift and has localised late Miocene volcanism. The NNE-trending Teniente Fault Zone controlled the emplacement of the 8.9 to 7 Ma Sewell Diorite complex. The Teniente host sequence is a strongly altered package of mafic to intermediate sills, stocks, extrusives and volcaniclastic rock. Early, widespread, barren magnetite-Ca-plagioclase alteration of the host sequence occurred, prior to emplacement of the late Miocene – early Pliocene calc-alkaline Teniente intrusive complex.

Copper-molybdenum ore at El Teniente is hosted in veins and subordinate breccias, and is associated with extensive zones of hydrothermal alteration. Sulfide minerals are zoned from bornite (core) through chalcopyrite to pyrite (deposit periphery). The 0.5 % copper contour defines a 2.6 km long and up to 2.0 km wide wedge shape, broadly centred on the Teniente intrusive complex. The timing of vein and breccia formation has been constrained temporally by nine new Re-Os dates (5.9 to 4.7 Ma) obtained from molybdenite. The grey porphyry (diorite), dacite pipes, and NNW-trending, multiphase dacite porphyry dyke intruded the host sequence during the Late Magmatic (LM) stage (5.9 to 4.95 Ma). Multiple generations of quartz-anhydrite-chalcopyrite-bornite veins and anhydrite-sulfide-biotite breccias formed at this time. These structures host approximately 60% of the copper at El Teniente. Na-K-feldspar alteration occurred within and around some of the dacite intrusions, grading out to intense, texturally destructive biotite alteration and distal chlorite-stable propylitic alteration assemblages.

Chalcopyrite-rich veins with phyllic (sericitic) alteration halos formed in the Principal Hydrothermal (PH) stage (4.95 to 4.85 Ma). Despite the short duration of this
stage and the low vein densities, these veins host approximately 30% of the total copper resource at El Teniente. No coeval intrusive phase has been identified.

The Late Hydrothermal (LH) stage (4.85 to 4.40 Ma) is a second stage of phyllic alteration and veining, which is related to intrusion of the 1200 m wide, funnel-shaped Braden pipe and also to the emplacement of late dacite dykes (4.8 Ma). The pipe is composed of an inner, unmineralised, rock flour matrix breccia facies, and an outer, tourmaline-chalcopyrite-anhydrite-cemented marginal facies. LH stage veins have a diverse ore and gangue mineralogy, including base metal sulfides, sulfosalts, tourmaline, and carbonates. Late post-mineralisation and alteration hornblende dykes (3.8 – 2.8 Ma) are the youngest rocks in the deposit.

LM and PH veins are orientated mostly concentrically and radially around a postulated deep-seated magma chamber, interpreted to have sourced the upper crustal intrusions, stresses, heat, metals, and fluids for the Teniente deposit. In contrast, the LH veins are orientated steeply-inward dipping, concentric to the magma chamber, implying that they formed during a stage of magma withdrawal. Other paragenetically late veins and faults are NE trending, which formed when far field stresses associated with the TFZ exceeded the stresses localised around the magma chamber.

Abundant liquid-rich (± opaque) low to moderate salinity fluid inclusions occur in LM veins, which are interpreted to have trapped a one-phase magmatic-hydrothermal fluid at 500°C ± 100°C. Sporadic decompression of this fluid resulted in generation of brine and vapour phases. The brine phase cooled and was diluted as it migrated laterally away from the dacites. Proton induced X-ray emission (PIXE) analyses detected several weight percent copper in both high and low salinity fluids in the centre of the deposit. One fluid inclusion analysed from the propylitic zone contains only 0.01 wt % copper. During the PH and LH stages the hydrothermal fluids were boiling at temperatures between 450 – 300°C. Hydrostatic pressure estimates indicate a depth below the palaeowater table of less than ~2,500m for the PH stage and less than ~1,700m for the LH stage. Salinity arrays provide support for fluid mixing as a potential depositional mechanism at El Teniente.

Oxygen and deuterium isotopic analysis indicates the predominance of magmatic-hydrothermal fluids (δ^{18}O_{fluid} = +5.7‰ to +8.2‰) in most stages at El Teniente, even at the deposit periphery. The exception is LH carbonates (δ^{18}O_{fluid} = +2.4‰ to +9.1‰)
which have a significant meteoric water component. $\delta D_{\text{fluid}}$ values for LM stage (-39‰ to -56‰) overlap with the felsic magmatic fluid values, whereas deuterium enrichment in PH and LH stage fluids (-38‰ to -6‰) imply the involvement of volcanic vapours. Sulfur isotope values for sulfides at El Teniente are between -5.9‰ and +2.4‰ and for sulfates are +10.0‰ to +13.4‰. These values are consistent with a bulk sulfur isotopic composition of 6‰. The most negative values from LM stage sulfides occur close to and within the dacites, grading out to values around zero on the deposit periphery. This zonation can be explained by an oxidized fluid ($\text{SO}_2/\text{H}_2\text{S} = 6$) being progressive reduced as it migrated outwards from the dacites. The vertical zonation of sulfur isotope values from the PH and LH stages can be modelled by cooling an oxidised fluid ($\text{SO}_2/\text{H}_2\text{S} = 2-3$) from approximately 475°C to 325°C over 1,000m elevation, indicating a vertical temperature gradient of 15°C/100m. This gradient is too large to be explained simply by conductive cooling or phase separation and requires either fluid mixing or thermal disequilibrium in the system.

Strontium and neodymium isotopes for anhydrite from all the vein stages are from 0.70396 to 0.70404 and 0.51276 to 0.51281, respectively. These values overlap with the local wall rock compositions from which they were most likely sourced. In contrast, lead isotopic values for the same anhydrites vary widely, for example $^{206}\text{Pb}/^{204}\text{Pb}$ values are between 17.490 and 18.559. These values are depleted compared to the sulfide ores, which have the same lead isotopic composition as the host rocks. Lead isotopic values in anhydrite are zoned, with most enriched values occurring in the centre of the deposit to most depleted values at the deposit periphery, which may have been derived from an unidentified exotic source of lead.

Ore deposition during the LM stage at El Teniente is believed to have occurred mainly due to sulfate reduction and cooling of lithostatically-pressured, magmatic-hydrothermal fluids. Secondary magnetite has been altered to biotite, implying that a very effective reductant interacted with both the mineralising fluid and the wallrock. The transition to the PH stage involved a change to brittle conditions and hydrostatic pressures, possibly due to rupturing of a lithostatic seal as the deposit was exhumed to depths shallower than 2,500m. High uplift rates (~2.4mm/yr) have been calculated for the short-lived PH and LH stages. Eventually magmatic and fluid pressures exceeded the confining lithostatic pressures (possibly facilitated by phreatomagmatic explosion),
Abstract

and explosive brecciation and fluidization of the rock mass occurred. This resulted in
the emplacement of the Braden Pipe. Ore deposition in the PH and LH stages was most
likely related to phase separation-induced cooling, coupled with meteoric fluid mixing,
at least during the LH stage.

Apart from its anomalous size, El Teniente is a typical porphyry copper-
molybdenum deposit, in terms of its alteration and sulfide assemblage, zonation,
association with felsic intrusions, and predominance of quartz vein-hosted copper
mineralization. Mineralogical, isotopic, and fluid inclusion datasets at El Teniente
indicate that a complex interplay of processes occurred during ore formation, including
fluid mixing, cooling, oxidation-reduction, phase separation, and water-rock
interaction. The combination of these processes resulted in the formation of this giant
porphyry copper deposit.
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Chapter 1

Introduction

1.1 Preamble

Chile is extraordinarily well endowed with porphyry-style copper deposits. In total, 455 million tonnes of fine copper has been identified from 54 deposits in Chile (Camus, 2003), including the three largest known porphyry ore deposits on Earth, El Teniente, Los Bronces – Rio Blanco, and Chuquicamata. These copper-molybdenum porphyry deposits are notable for their high hypogene grades and large tonnages, in contrast to the generally lower hypogene grades and supergene enrichment that characterizes the porphyry copper deposits of Arizona (e.g., Titley, 1993) and the southwest Pacific (e.g., Sillitoe and Gappe, 1984; Corbett and Leach, 1998).

El Teniente, containing 94.4 Mt of fine copper, is an ideal location to study the anatomy and fluid chemistry of an exceptionally large porphyry copper deposit. Little descriptive work has been published on the deposit since Cuadra (1986), although significant internal research has been conducted at the mine site during this period. Previous studies at El Teniente (e.g., Howell and Molloy, 1960; Camus, 1975; Villalobos, 1975; Ojeda, 1980; Cuadra, 1986) have documented features typical of porphyry copper deposits, including stockwork veins, potassic, phyllic and propylitic alteration assemblages, and multiphase calc-alkaline intrusions. These authors interpreted that copper mineralisation was intimately related to intrusive activity, consistent with prevailing porphyry copper deposit models at the time (e.g., Burnham, 1967, 1979; Lowell and Guilbert, 1970; Gustafson and Hunt, 1975; Henley and McNabb, 1978). In more recent times, Skewes et al. (2002) proposed that El Teniente should be reclassified as a breccia deposit and suggested that the felsic porphyries eliminated or redistributed earlier-formed mineralisation. In more recent times, Skewes et al. (2002) proposed that El Teniente should be reclassified as a breccia deposit and suggested that the felsic porphyries eliminated or redistributed earlier-formed mineralisation. One aim of the current study is to assess this controversy, by determining the genesis of the deposit through detailed documentation and analysis of the vein, breccia and alteration paragenesis, structure, geochronology, and geochemistry.
The currently accepted model for porphyry copper deposit formation is that they formed from magmatic fluids exsolved from a shallow crustal magma (e.g., Burnham, 1979). This model is being refined largely due to technological advances such as new micro-analytical technologies, which enable us to study in more detail the fluid chemistry associated with the ore-forming system (e.g., proton-induced X-ray emission analyses of fluid inclusions: PIXE). Moreover, with the advent of more precise chronometers, such as the Re-Os isotopic system for molybdenite (e.g., Stein et al., 2001), the longevity of magmatic-hydrothermal systems is being better defined with higher resolution. The current study applies new micro-analytical technologies where applicable to help constrain the conditions, processes, and longevity of the magmatic-hydrothermal system that formed the giant El Teniente ore deposit.

1.2 PROJECT AIMS AND OBJECTIVES

This study is part of the Australian Minerals Industry Research Association (AMIRA) funded project P511, entitled Giant Ore Deposit Systems (GODS). This collaborative research project involved workers from Commonwealth Scientific and Industrial Research Organisation (CSIRO) – Division of Exploration and Mining, Centre for Ore Deposit Research (CODES – University of Tasmania), and the Centre for Global Metallogeny (CGM – University of Western Australia). Three deposit classes were studied in the GODS project, giant porphyry copper-molybdenum deposits in Chile, copper-gold deposits in Papua New Guinea, and Archaean lode gold deposits in Western Australia. Corporacion Nacional del Cobre de Chile (CODELCO-Chile Central and Division El Teniente) provided access to El Teniente, and covered logistical expenses. P511 sponsors are listed below:

- Anglo American Exploration Australia Pty Ltd
- AngloGold Ltd
- AurionGold Ltd
- Barrick Gold of Australia
- BHP Billiton
- Centaur Mining and Exploration
- CODELCO-Chile
- Falconbridge Ltd
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- Gold Fields Ltd
- Newcrest Mining Ltd
- Newmont Exploration Pty Ltd
- Phelps Dodge Australasia Inc
- Placer Dome
- Sons of Gwalia Ltd
- Teck Cominco Ltd
- WMC Resources Ltd

The ultimate aim of the GODS project was to investigate "How and where does nature create giant, high grade mineral deposits". The following five key points were emphasized:

- What is the system?
- What is the pressure-temperature and geodynamic history?
- What is the nature of the fluid reservoirs in the system?
- What mechanisms advect/convect/focus fluids?
- What are the metal transport/depositional mechanisms for ore formation?

Within the framework of the GODS project, the objectives of this PhD study have been:

⇒ To investigate the regional and local geological setting of El Teniente porphyry deposit (Chapters 2 and 3, respectively). Chapter 2 is a literature review, whereas Chapter 3 combines previous work with new observations and interpretations.

⇒ To construct a new detailed vein, breccia, and alteration paragenesis for the deposit, and to map out the spatial distribution of the alteration assemblages, vein stages, and sulfide mineralisation (Chapter 4).

⇒ To compile a deposit-scale database of structural measurements taken by the mine geologists to re-interpret the structural evolution of the deposit (Chapter 5).

⇒ To use high precision, double-spike Re-Os isotopic age determinations on paragenetically-controlled molybdenite to date the absolute ages and duration of the paragenetic stages (Chapter 6). This was done in collaboration with Dr. Holly
Stein from Colorado State University.

To test for major and trace element immobility during hydrothermal alteration of the wall rocks, and then use the immobile elements to geochemically characterise the pre-, syn-, and post-mineral igneous rocks at El Teniente (Chapter 7).

To utilise fluid inclusion microthermometry plus stable and radiogenic isotopic analyses of the vein and alteration assemblages to investigate the nature of the ore-forming fluids, and to identify spatial and/or temporal variations in the physico-chemical conditions of ore formation (Chapters 8 and 9).

To provide an integrated genetic model for El Teniente deposit (Chapter 10).

1.3 METHODOLOGY

This PhD study included three fieldwork seasons for a combined total of 9 months at the Teniente mine site, most of which was spent logging diamond drill core. In total, nearly 20km of core was logged from 36 drillholes from three main sections and four subsidiary sections, to investigate the features of the deposit in three dimensions. Logged drillholes and a sample graphic drill log illustrating the features noted during logging are contained in Appendix 1. The core at Teniente is BQ size (35mm wide) and is hydraulically split, forming a rough broken surface that can be very difficult to log. High drillhole densities on selected sections allowed the construction of contoured sections detailing a variety of alteration, veining, and mineralisation features. Emphasis was placed on logging core from all regions of the hypogene portions of the deposit to gain a deposit-wide perspective. Approximately 850 core samples were collected from El Teniente. Due to logistical and safety issues only a few brief underground visits were made. This limited underground access, combined with poor lighting, shotcreteing of walls, and dirty exposed faces prevented any underground mapping being conducted in the current study.

Several reconnaissance field trips were made in the Teniente district, particularly to the regional exploration prospects to collect samples. Core samples were also collected from any prospects that had been drilled.

Laboratory analyses were mostly conducted at the Centre for Ore Deposit Research or the Central Science Laboratory, University of Tasmania, and include:
• PIMA (Portable Infrared Mineral Analyser) spectroscopy for identification of secondary hydrous phyllosilicates
• Electron microprobe analyses to ascertain feldspar, biotite, and magnetite compositions
• XRF (X-ray Fluorescence) major and trace element analyses of the host rocks
• Re-Os isotopic age determinations on molybdenite (conducted at the AIRIE laboratory, Colorado State University, by Dr. Holly Stein)
• Fluid inclusion microthermometry
• Proton induced X-ray emission (PIXE) analyses to provide quantitative data of the fluid inclusion compositions (conducted at CSIRO North Ryde in collaboration with Dr Chris Ryan and Dr Bin Fu)
• Conventional and laser ablation S isotopic analyses
• C-O isotopic analyses of carbonates
• O-D isotopic analyses of chlorite and tourmaline (conducted at Queens University by Dr. Kurt Kyser)
• Pb-Sr-Nd isotopic analyses of anhydrite (conducted at Adelaide University by Dr. John Foden)

1.4 El Teniente - Location, History and Mining

Location and Access

El Teniente is located in the VI region of central Chile on the western flank of the Andean Cordillera (Figs. 1.1 and 1.2). The mine is situated approximately 200 km south of Santiago, the capital of Chile. The nearest city is Rancagua. It is located 67 km west of the mine and is linked by the Carretera de Cobre ("Copper Highway"). The offices and most of the ore processing facilities are located in Colon Alto and Colon Bajo, at an elevation of approximately 2,000m. Smelting occurs nearby at Caletones, occasionally leading to air quality problems (Fig. 1.3A). The mine workings are between 2,000 and 3,200m elevation. The surrounding rugged peaks reach over 4,000m (Fig. 1.3B) and as a result access to the Teniente district is difficult, although it has
been facilitated in places by bulldozed exploration tracks. Thick snow falls further limit access to the district surrounding the deposit during winter (Fig. 1.3B). Vegetation is sparse on the surrounding mountains, due to the dry climate and a long history of sulfurous discharges from the smelting process.

**History**

According to Baros (1995), El Teniente (translation: The Lieutenant) was apparently discovered by a fugitive Spanish lieutenant in the 1700's, attempting to escape across the Andes, charged with disloyalty to the king. The story continues that he returned to Santiago with richly copper mineralised samples from the deposit, thus proving his loyalty, and he obtained a full pardon.

Teniente was historically mined by Jesuits dating back to the 16th Century. First official records of production are from the early 1800’s (Baros, 1995). In 1904 William Braden acquired capital to form the Braden Copper Company, the deposit was named the Braden mine, and a 250t/day concentrator was built (Baros, 1995). In 1909 Gug-
genheim interests took over the property. A railway was completed in 1911, and the concentrator’s capacity was raised to 5,000 t/day. In 1915, Kennecott Copper Corporation acquired a controlling interest in the site. They raised the daily production to 34,000 t/day by 1960. In 1967, CODELCO, a government corporation acquired the mine, changed the name to El Teniente, and have been increasing productivity and delineation of the deposit ever since.

Sewell, a remarkable town built on a steep ridgeline, is located near the mine entrance (Fig. 1.3B). Sewell housed up to 16,000 mine workers and their families in the 1960's. It was known as the "City of Staircases", due to the absence of roads, and was only connected to the outside world by a narrow gauge railway. Sewell was abandoned in the early 1970's when all the mine staff were relocated to Rancagua. Although now
Figure 1.3. A) View from Carretera de Cobre to Colon where the processing facilities are located, and Caletones, the site of the smelter.

B) Sewell, taken in winter around 1960 (reproduced from Hamre, 1999). Up to 16,000 people lived in the town at the time. The present day collapse cavity is located on the mountainside at the top of the photo.

C) View from the north of the collapse cavity produced by the underground block cave breaching the surface. The cavity forms a ring around the competent and mostly unmineralised Braden Pipe.
a ghost town, it has been recently nominated as a UNESCO "heritage site" (Hamre, 1999).

**Size and mining**

El Teniente is regarded as the world’s largest copper deposit, in terms of contained metal (Table 1.1). Indicated resources + production total 94.4 Mt of fine copper and 2.5 Mt of molybdenum. In addition approximately 437t of gold occurs, albeit at a low grade (approximately 0.04 g/t; Camus, 2003). The copper resource at El Teniente is similar to the total combined resources from Río Blanco-Los Bronces, Los Pelambres, Vizcachitas, and RosaRio de Rengo (Table 1.2). However, most of these ore deposits, including El Teniente, have not been thoroughly drilled, in particular at depth. Therefore, resource estimates are transient figures, and can change in response to new drilling information or economic variables, such as metal prices or cut-off grades.

El Teniente has been regarded as the largest underground mine in the world since at least the 1950’s (Howell and Molloy, 1960; Camus, 1975; Skewes et al., 2002). More than 2,400 km of underground galleries occur in the mine and more than 2,200 holes have been drilled, up to the year 2000. Economic mineralisation exists from surface, and is currently exploited down to 800m depth and has been intersected in the deepest drilling at 1,800m below surface. The 0.5 % copper contour in the deposit extends approximately 2,600m N-S by up to 2,000m E-W in plan view (chapter 3).

Mining occurs by underground block caving and panel caving, which forms a collapse crater >2km² on the surface above mining zones (Fig. 1.3C). Current extraction is approximately 100,000 t/day, at 1.21 % copper and 0.026 % molybdenum, with a yearly production of 360,000 tonnes of fine copper, 400 tonnes of molybdenum, and 800,000 tonnes H₂SO₄ (Camus, 2003). The ore, and underground personnel, are transported along an 8.5km long tunnel linking Colon Alto with the underground mine.

<table>
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<th>Reserves + production</th>
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<td>(tonnes of contained metal)</td>
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<td>Cu</td>
<td>1.17 Gt @ 1.59% Cu, = 15.71 Mt fine Cu</td>
<td>12.482 Gt @ 0.63 % Cu, = 78.84 Mt fine Cu</td>
<td>94.35 Mt</td>
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<tr>
<td>Mo</td>
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<td></td>
<td>2.5 Mt</td>
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<tr>
<td>Au</td>
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<td>437 t</td>
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*Table 1.1. El Teniente Cu, molybdenum and Au endowment (from Camus, 2003). Abbreviations: Gt = billion tonnes, Mt = million tonnes.*
Previous work

The geology of El Teniente was first described by Lindgren and Bastin (1922). They interpreted the deposit to have formed in association with a violent volcanic eruption that created the Braden Pipe. Gangue and ore minerals were precipitated in fractures generated by this explosive event in the surrounding andesite sill. Howell and Molloy (1960) established a district-scale geological framework for the deposit and described El Teniente as a classic example of a porphyry copper deposit hosted in altered andesite lavas, with alteration and veining concentrically zoned around a barren dacite porphyry core. Camus (1975) detailed the mineralogical and chemical zonation of wall rock alteration assemblages and sulfide minerals around the dacite porphyry (Teniente Porphyry). Villalobos (1975), Ojeda et al. (1980), and Cuadra (1986) established four paragenetic stages of alteration and mineralisation at El Teniente, the Tardimagmatica (Late Magmatic, LM) stage, the Hidrotermal Principal (Principal Hydrothermal, PH) stage, the Hidrotermal Tardia (Late Hydrothermal, LH) stage, and the Postuma stage.

Various internal studies and honours projects have focussed on specific mine areas or geological units in the deposit, for example Faunes (1981), Riveros (1989), and Guzman (1991). Zúñiga (1982) documented the zonation of alteration assemblages and intensity of development around the dacite porphyry in the NW of the deposit. Villalobos (1975) and Ossandón (1974) also studied the systematic variation of potassic alteration and vein intensity from the centre to the periphery of the deposit. Ossandón (1974) and Rojas (2002) subdivided the dacite porphyry into several texturally distinct units. Floody (2000) documented the geology and genesis of the Braden Pipe.
Limited fluid inclusion studies have been carried out previously by Ip (1987) and Skewes et al. (2002). Kusakabe et al. (1984, 1990) completed an O, H, and S isotopic study of the deposit. Pb isotopic analyses were performed by Puig (1988), Zentilli et al. (1988), and Tosdal et al. (1999). Sr-Nd isotopic analyses of breccia cements were published by Skewes (1992) and Skewes and Stern (1996). Clark (1983) and Cuadra (1986, 1992) performed K/Ar radiometric age determinations on sericite, biotite and whole rock samples. Maksaev et al. (2001, 2002, 2004) and Munizaga et al. (2002) have published results of a comprehensive, integrated geochronological study combining Ar-Ar dating, Re-Os dating on molybdenite and U-Pb SHRIMP dating on zircon from the felsic intrusions.

Several district-scale geological studies have been undertaken at Teniente. Rivera and Falcón (1998) produced a 1:25,000 map of the general geological and volcanological features of the Teniente district. Garrido (1994) studied the vein and fault orientations and kinematics of the Teniente mine and surrounding district. Floody and Huete (2000) described the geology, alteration characteristics, and exploration activities for all the prospects within the Teniente district. Kay and Kurtz (1995) performed a detailed geochemical study of the igneous rocks of the Teniente region and interpreted potential tectonic implications for ore deposit formation. Skewes and Stern (1996) linked crustal-scale processes of arc migration and crustal thickening with formation of the late Miocene – early Pliocene ore deposits.

Numerous internal studies have been performed by Skewes (e.g., 1997A, 1997B, 1998A, 1998B, 1999) These were all summarized in Skewes et al. (2002) who discussed the nature and geochemistry of the rock types and presented reconnaissance fluid inclusion and isotopic studies on several sections through the deposit. In contrast to the conventional porphyry models for the genesis of El Teniente, Skewes et al. (2002) proposed that copper mineralization at El Teniente is hosted predominantly in biotite breccias. These breccias are inferred to predate the dacite porphyry by up to several million years. Skewes et al. (2002) argue that the copper mineralization was subsequently remobilized, or eliminated, by the late-stage dacite porphyry. They argued that Teniente be classified as a breccia-hosted copper-molybdenum deposit, rather than a porphyry copper deposit. This is a point of contention addressed in the current thesis, as all other previous researchers of the deposit have advocated the classical porphyry copper deposit model for El Teniente.
2.1 TECTONIC SETTING

The present-day Andean Cordillera is related to subduction of the oceanic Nazca Plate beneath the South American Plate. El Teniente lies on the western flank of the Principal Cordillera (Figs. 1.2 and 2.1), composed of late Palaeozoic to Tertiary volcanic and volcaniclastic rocks that have been intruded by Tertiary plutons (Fig. 2.1). The Cordilleran rocks have experienced significant crustal shortening, facilitated by thrusting and folding. The Central Valley, a broad, N-trending, more than 1,000-km long depression filled with Quaternary sediments, separates the Principal Cordillera from the Coastal Cordillera to the west (Fig. 2.1). The Coastal Cordillera is composed of Late Palaeozoic sedimentary and volcanic rocks, intruded by batholiths, which have undergone a complex history of deformation.

El Teniente is located near the boundary between Southern Volcanic Zone (SVZ; Fig. 1.1; Stern, 1989; Stern and Skewes, 1995) and a low angle or ‘flat slab’ subduction zone, between 27°S and 33°S, above which no active volcanism occurs. In the SVZ the angle of the downgoing slab is approximately 30°, whereas the subduction angle in the flat slab segment is 5 – 10° (Cahill and Isaaks, 1992). The crust is 35-40 km thick in the SVZ compared to 55 - 65 km thick in the flat slab zone (Isaaks, 1988; Kay et al., 1991). The highest mountain in the Andes, Cerro Aconcagua, occurs above the flat subduction zone. Flattening of the subducted slab is believed to have been caused by subduction of the buoyant Juan Fernandez Ridge (Fig. 1.1; Gutscher et al., 2000; Yañez et al., 2002; Hollings et al., submitted).

Palaeozoic – Mesozoic tectonic evolution

The history of the western margin of the Gondwana supercontinent has been divided into three tectonic cycles by Mpodozis and Ramos (1990); the Famatiniano (early Palaeozoic), the Gondwanico (late Palaeozoic), and the Andino (Mesozoic – Cenozoic). The location of the cratonic margin is shown in Figure 2.2. Precambrian rocks are lo-
Chapter 2. Regional Geology

Argentina

Quaternary sediments
Quaternary volcanic rocks
Late Tertiary intrusions
Miocene Farellones Formation
Eocene-Miocene Coya-Machali Formation
Mesozoic sedimentary rocks
Active volcano
Fold Axis
Thrust

Figure 2.1. El Teniente regional geology. Modified from Charrier et al. (1994).
cally exposed in northern Chile and Argentina. During the Famatiniano cycle exotic terranes including the Arequipa and Chileania terranes were accreted onto the continental margin (Ramos, 1994). During the Gondwananico cycle, which began in the late Devonian, a continental magmatic arc formed due to subduction of the Pacific plate underneath the continental crust. Extensional basins were formed late in the cycle during the late Triassic – early Jurassic. These were filled with bimodal volcanic rocks, and continental and marine sediments (Camus, 2003). The rift basins formed sub-parallel to the NNW-trending cratonic continental margin (Ramos, 1994, Fig. 2.2). Some porphyry copper prospects formed during the Gondwanico cycle; however, none of them are large enough to be mined profitably (Camus, 2003).

The Andino tectonic cycle began in the early Jurassic with a change to Mariana-style subduction (according to the classification of Uyeda and Kanamori, 1979), characterized by steep angle of subduction (Camus, 2003). During this cycle a magmatic

![Figure 2.2. Location of the Precambrian continental margin, showing also the Triassic rift basins which formed sub-parallel to the continental margin, in and on the accreted Palaeozoic terranes (Ramos, 1994). This structural fabric is interpreted to have influenced the orientation of younger Mesozoic and Cenozoic structures that have been implicated in porphyry ore formation (e.g. Gow, 2000; Rivera and Cembrano, 2000; Gow and Walsh, submitted)](image-url)
arc was developed stretching from northern to southern Chile. The arc is composed of thick sequences of lavas, varying from rhyolite to basaltic andesite, with intercalated marine and continental sedimentary rocks, intruded by granitic to gabbroic plutons. Large back-arc extensional basins were formed behind the magmatic arc, in which several kilometres of marine and continental sediments accumulated. These back arc basins include the Tarapaca basin in northern Chile (18 – 28° S), the aborted marginal basin of central Chile (28 – 33° S), and the Neuquen Basin in Argentina (36 – 39° S; Camus, 2003).

During the late Cretaceous the Atlantic Ocean opened, causing Africa and South America to rift apart. Westwards movement of South America generated a compressive phase of deformation at its western continental margin. This affected the magmatic arc, the back arc basins, and the basement (Camus, 2003). Mariana-style subduction changed to Chilean-style subduction (Uyeda and Kanamori, 1979), characterized by a lower angle of subduction, and bulk crustal shortening (Camus, 2003). Structural inversion of the extensional basins shut down volcanism and resulted in uplift, crustal thickening, and erosion. All the economic porphyry copper (+molybdenum-gold) deposits of central and northern Chile formed in a compressional tectonic setting while Chilean-style subduction occurred in the Andino tectonic cycle (Camus, 2003).

During the late Mesozoic and Cenozoic continued subduction led to the formation of a series of continental magmatic arcs along the South American margin. Changes of velocity and convergence direction between the South American and the Nazca Plates led to episodic periods of compression, separated by intervals of tectonic relaxation, in some cases resulting in extensional conditions (Pardo-Casa and Molnar, 1987; Camus, 2003). An increase in convergence rate between the Nazca and South American plates (to more than 15cm/yr) caused the early Tertiary Incaic deformation event. Normal extensional faults were again reactivated in a reverse sense. The 1,000-km long Domeyko Fault Zone was generated in northern Chile during this time (Cornejo et al., 1997; McClay, 1998; Camus, 2003). In northern Chile the magmatic arcs migrated eastwards during Cretaceous – Tertiary compression, whereas in central and southern Chile the arc remained approximately stationary from its initial Jurassic location until the Pliocene (Stern and Skewes, 1995; Camus, 2003).
Chapter 2. Regional Geology

Tertiary tectonic evolution

The central Chilean magmatic arc in the early Tertiary arc was associated with a moderately-dipping (approximately 30°) subduction zone (Camus, 2003). A N-trending inter-arc volcano-sedimentary extensional basin was generated during the late Oligocene, bound by the Pocura and El Fierro normal faults between 33°S and 37°S. This basin was filled with the Coya-Machali and the Abanico Formations (Fig. 2.3A). The volcanic rocks have geochemical signatures that indicate a relatively thin crust (approximately 30-35 km thick; Kay and Kurtz, 1995; Camus, 2003).

Between approximately 20 and 15 Ma, a change to compressive tectonics led to reactivation of the Pocura and El Fierro Faults in a reverse sense and structural inversion of the volcano-sedimentary basin (Fig. 2.3B). Inversion caused crustal thickening, uplift, and deformation of the Coya-Machali and Abanico Formations. The change to compressive tectonics is believed to have occurred due to the onset of slab flattening in central Chile (e.g., Kay and Kurtz, 1995, Kay et al., 1999; Yanetz, 2002; Camus, 2003). The NE trend of the Juan Fernandez Ridge resulted in a southward migration of slab flattening during the Miocene (e.g., Hollings et al., submitted). Between approximately 15 – 8 Ma, volcanism was re-initiated in the volcano-sedimentary basin, and the Farellones Formation was deposited (Fig. 2.3B). It is estimated that crustal thicknesses were between 35-40 km during deposition of the Farellones Formation (Kay and Kurtz, 1995). Continued shallowing of the angle of subduction resulted in deformation, uplift of the fault-bound block, and thickening of the crust to approximately 50-60 km (Kay et al., 1999; Camus, 2003; Fig. 2.3C). Thin-skinned deformation occurred in the Aconcagua thrust and fold belt (27° to 33° S; Ramos, 1985) on the eastern side of the Principal Cordillera. Volcanism was shut down approximately 7 Ma, and plutons were trapped in the crust. During the Late Miocene-early Pliocene the volcanic front migrated approximately 40 km eastwards to its current position (Stern and Skewes, 1995). The central Chilean porphyry copper deposits formed during this last stage of arc evolution. The high rates of uplift and subsequent erosion are interpreted to have acted as a tectonic trigger for the formation of the porphyry copper deposits of central Chile (e.g., Skewes and Stern, 1995; Kay and Kurtz, 1995).
Chapter 2. Regional Geology

Extensional event (26 - 20 Ma)

A) Plan view of the N-trending extensional volcano-tectonic basin, bound by normal faults, which formed during the late Eocene.

B) Cross sectional view of the extensional basin, which was filled with the Coya-Machali Formation.

Tectonic inversion (19-8 Ma)

C) Plan view, showing the current locations of the central Chilean porphyry copper deposits. Tectonic inversion of the basin occurred from approximately 19 Ma, resulting in reactivation of the Pocura and El Fierro normal faults in a reverse sense.

D) Cross sectional view of the structurally inverted basin. The Farellones Formation was deposited in the basin above the deformed Coya-Machali Formation, in a progressively thickening crust.

Contractional event (7 Ma - recent)

E) Continued contraction led to extinction of the magmatic arc, and crustal thickening, uplift and erosion. Large intermediate to felsic plutons were emplaced along reactivated normal faults, some of which were accompanied by porphyry copper formation.

Figure 2.3. Schematic model of the tectonomagmatic evolution of the central Chilean porphyry copper belt (Castelli and Friarte, 1998; Castelli and Lara 1999; Carmus; 2003). The cross section was constructed for the Rio Blanco -Los Bronces deposit, and includes details specific to the deposit, for example the diorite, monzodiorite and granodiorite intrusions. However the fundamental aspects of the model also apply to El Teniente deposit. For scale, the width of the Farellones Formation is approximately 50km.

A) Plan view of the N-trending extensional volcano-tectonic basin, bound by normal faults, which formed during the late Eocene.

B) Cross sectional view of the extensional basin, which was filled with the Coya-Machali Formation.

C) Plan view, showing the current locations of the central Chilean porphyry copper deposits. Tectonic inversion of the basin occurred from approximately 19 Ma, resulting in reactivation of the Pocura and El Fierro normal faults in a reverse sense.

D) Cross sectional view of the structurally inverted basin. The Farellones Formation was deposited in the basin above the deformed Coya-Machali Formation, in a progressively thickening crust.

E) Continued contraction led to extinction of the magmatic arc, and crustal thickening, uplift and erosion. Large intermediate to felsic plutons were emplaced along reactivated normal faults, some of which were accompanied by porphyry copper formation.

Legend

- Farellones Formation (mid - late Miocene)
- Coya-Machali - Abanico Formation (Oligocene - early Miocene)
- Lo Valle, Las Chilcas Formations (late Cretaceous)
- Volcanic and sedimentary sequences of Jurassic - early Cretaceous
- Choiyoi Group (Permo-triassic basement)
- Diorite
- Monzodiorite
- Granodiorite
- Porphyry Cu deposit
- ET - El Teniente
- RB-LB - Rio Blanco - Los Bronces
- LP - Los Pelambres
- EP - El Pachon
- Faults
- normal faults
- reverse faults
- FF = El Fierro Fault
- PF = Pocura Fault
- ATFB = Aconcagua Thrust and Fold Belt
2.2 **GEOLOGICAL UNITS OF CENTRAL CHILE**

The Principal Cordillera is composed of volcanic and sedimentary rocks of the SVZ, which extends from 32° in the north to approximately 45° in the south of Chile. In central Chile the SVZ predominantly consists of the Coya Machali and Farellones Formations (Fig. 2.1), with a basement comprising volcanic and sedimentary rocks of the Late Cretaceous – Palaeocene Los Pelambres and Salamanca Formations in the north (Rivano and Sepulveda, 1991) and the Colimapu Formation to the south (Camus, 2003). Towards the east the Coya-Machali and Farellones Formations have discordant and/or faulted contacts with the Jurassic – Cretaceous marine and continental sedimentary sequences that form the Aconcagua thrust and fold belt (e.g. Wyss et al., 1996, Camus, 2003; Fig. 2.3).

**Coya Machali Formation**

The Coya-Machali Formation (also known as the Abanico Formation north of El Teniente; Klohn, 1960; Charrier et al., 2002) is the oldest unit that crops out in the Teniente district. The age of the formation is constrained from the late Eocene to early Miocene (Vergara and Drake, 1978; Charrier et al., 2002). Radiometric (K-Ar) age determinations have constrained the formation to 26 Ma and 16 Ma (Godoy, 1993; Charrier et al., 1994; Kay and Kurtz, 1995). The Coya-Machali Formation is composed of low to medium-K basalts, andesites, dacites, and related volcaniclastic rocks. Regionally this formation changes from a calc-alkaline composition in the north to a tholeiitic composition in the Teniente district (Hollings et al., submitted).

The Coya-Machali Formation is well exposed on the Carretera de Cobre, between El Teniente and Rancagua. Sequences of altered basic to intermediate volcanic flows, ignimbrites, reworked volcaniclastic rocks, and continental sedimentary units are cyclically repeated through the sequence. This sequence is interpreted to have been sourced from a series of volcanic centres close to lacustrine and fluvial systems (Rivera and Falcón, 2000). The sequences are folded and tilted, in marked contrast to the flat-lying Farellones Formation. The thickness of the Coya-Machali in the Teniente district is estimated to be 3,500m (Rivera and Falcón, 2000).
Radiometric (K-Ar) dating of the mid-late Miocene Farellones Formation has returned ages between ~15 and 6 Ma in the Teniente district (Klohn, 1960; Vergara et al., 1988; Rivano et al., 1990; Kay and Kurtz, 1995; Godoy et al., 1999). This formation has concordant, discordant and faulted contacts with the underlying Coya-Machali Formation (Godoy and Lara, 1994; Godoy et al., 1999; Rivera and Falcón, 2000; Charrier et al., 2002).

The Farellones Formation is a flat lying to gently dipping package of voluminous ash flows interbedded with lava flows, intruded by subvolcanic bodies. Geochemically the igneous units are medium-K to high-K, tholeiitic to calc-alkaline, arc-related rocks predominantly andesitic composition. Individual units can vary from dacites to olivine- and pyroxene-bearing basalts (Rivera and Falcón, 1998). Thickly bedded heterolithic volcaniclastic conglomerates and breccias are abundant in the Teniente district. Some andesites were observed in the current study with peperitic upper contacts, indicative of a locally sub-aqueous (lacustrine?) environment of deposition. The thickness of the Farellones Formation is estimated to be 2,500 m to >2,700 m (Table 2.1; Klohn, 1960; Thiele et al., 1991; Godoy et al., 1999).

### Farellones Formation

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<tr>
<td>Based on:</td>
<td>Field and underground mapping at the mine site</td>
<td>Field mapping</td>
<td>Identifying eruptive centres from field mapping and satellite images</td>
<td>Geochem criteria and age dating, Used field divisions of Koeppen and Godoy (1994)</td>
<td>Satellite images, aerial photos, field mapping, radiometric ages</td>
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<td>Stratigraphic subdivisions</td>
<td>Upper Farellones (~750 m) - varicoloured volcanic agglomerates and pyroclastic beds with intercalated andesitic and basaltic flows</td>
<td>Middle Farellones (~750 m) - Greenish epilithic andesite flows with well bedded lacustrine sediments</td>
<td>Lower Farellones (~1,200 m) - massive homogenous extrusive andesite with rare tectonic beds of agglomerate and amygdaloidal or vesicular andesite - El Teniente host?</td>
<td>Lower Member (~300 m) - Rhyolitic-dacitic tuffaceous ignimbrite related to caldera-type eruptions,</td>
<td>Upper Sewell Group (~0.7 Ma) - post-central volcanic chain and volcanic-sedimentary lithologies</td>
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<td>Upper Member (~1,500 m) - Basaltic andesite and volcaniclastics intruded by rhyodacite domes due to interfingering of basaltic flows and tephra from strato-volcanoes</td>
<td>- Cerro Castillo (near La Juanita mine) - Lower Malancilla centre - Lower Sewell Centre - Main Teniente host?</td>
<td>- Cerro Guanaco centre - Maqui Chico centre - Aravena centre</td>
<td>- Upper Sewell Group (~9.7 Ma) - Mainly S and E of Teniente, across Agua Amarga fault, and high elevations N of Agua Amarga fault</td>
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<td>- Lower Malancilla centre - Cerro Durazo - Quebrada Negra</td>
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<td>Comments</td>
<td>Approximate 2700 m thickness</td>
<td>Broad subdivision for area 32°-34°</td>
<td>Had difficulty integrating field observations with satellite image interpretations</td>
<td>Use the term TVC (Teniente Volcanic Complex) for Farellones Formation dated between 14.4-6 Ma.</td>
<td>Post-central volcanic chain and volcanic-sedimentary lithologies</td>
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Table 2.1, Stratigraphic subdivisions of the Farellones Formation in the vicinity of El Teniente deposit.
Several different stratigraphic subdivisions have been proposed for the Farellones Formation (Table 2.1). Early studies proposed a layer-cake stratigraphy for the Farellones Formation (e.g. Howell and Molloy, 1960). More recent studies have viewed the formation as a volcano-tectono-sedimentary basin composed of onlapping volcanic and volcaniclastic products derived from erupting and collapsing stratovolcanoes (e.g. Thiele et al., 1991; Godoy, 1993; Koeppen and Godoy, 1994; Rivera and Falcón, 1998; 2000). The eruptive products from multiple volcanic centres have intermingled to produce a complicated onlapping stratigraphy (Koeppen and Godoy, 1994). Godoy (1993) and Kay and Kurtz (1995) used the term Teniente Volcanic Complex (TVC) to describe rocks of the Farellones Formation that were deposited between 14.4 - 6.0 Ma in the Teniente district.

Rivera and Falcón (1998) provided the most comprehensive stratigraphic study to date of the Farellones Formation in the Teniente district (Table 2.1, Fig. 2.4). They proposed that the Farellones Formation lithologies formed within extensional volcancotectonic basins that were controlled by NW- to W-trending transverse faults, despite the overall N-S trend of the Farellones Formation belt. An intra-formational sub-basin approximately 25km wide opened during the late Miocene, bound by the La Juanita and El Azufre faults. Syn-extensional basaltic units were extruded at 11-10 Ma, and were overlain by a thick succession of detrital flows during basin subsidence (Fig. 2.4, Rivera and Falcón, 1998).

Volcanic activity was re-initiated in the sub-basin around 11-9 Ma with the formation of four discrete volcanic centres (Fig. 2.4) in a NW trending lineament cutting obliquely across the basin. This lineament has been termed the Codegua-Río Blanco Fault (Rivera and Falcón, 1998, referred to herein as the Codegua Fault). Aeromagnetic interpretation (P. Gow, pers. comm., 2001) suggests that N side up movement on the Codegua Fault led to the formation of a depression to the south of the fault. Relict stratovolcano features are preserved around the volcanic centres, such as inclined flank facies, subvolcanic andesitic feeder pipes, stocks and dykes, and peripheral hydrothermal alteration (Rivera and Falcón, 1998). Volcaniclastic products from the volcanic centres overlie the detrital flows and traveled up to 15km south to the edge of the basin-bounding La Juanita fault. Rivera and Falcón (1998) estimate the stratovolcanoes have been eroded between 1,000-2,000m. El Teniente occurs close to one of the relict volcanic centres on the Codegua Fault (Fig. 2.4).
Figure 2.4. Geology of the Teniente district. An intra-formation extensional basin is bound by the La Juanita and El Azufre faults. Within the basin a NW trending lineament of relict eruptive centres occurs, underlain by sub-volcanic andesitic intrusions, along the postulated Codegua Fault. Teniente occurs near the intersection of the Codegua Fault with the NE trending Teniente Fault Zone. Adapted from Rivera and Falcon (1998).
Chapter 2. Regional Geology

**Felsic and Intermediate Intrusions**

The Coya-Machali and the Farellones Formations in the Teniente district have been intruded by a series of calc-alkaline felsic to intermediate granitoids in the Teniente region (Fig. 2.1). These plutons, stocks, and dykes have ages between 12-7 Ma, and are collectively termed the Teniente Plutonic Complex (TPC; Kay and Kurtz, 1995). Individual phases of the Teniente Plutonic Complex include diorites, andesite porphyries, tonalites, monzonites, granodiorites, and granites. Hydrothermal biotite and tourmaline occur locally in and around these plutons. Intrusion emplacement appears to have been facilitated by NW to W trending fault zones that bound the late Miocene volcanotectonic extensional basin (Rivera and Falcon, 1998). Kay and Kurtz (1995) argued that, based on REE patterns, the Teniente Plutonic Complex plutons have geochemical affinities with the Farellones Formation units. The early Miocene La Obra pluton in the western Coya-Machali belt is postulated to be the intrusive equivalent for the Coya-Machali Formation (Kay and Kurtz, 1995).

The ENE trending Sewell Diorite intrusive complex, dated between 8.9 and 7.0 Ma, (K-Ar; Cuadra, 1986; Morel and Spröhnle, 1992; Kay and Kurtz, 1995; Figs. 2.3, 2.5) occurs adjacent to the Teniente deposit. This intrusive complex consists of porphyritic to equigranular plagioclase - (± hornblende - pyroxene) phryic diorite, monzonite, to granodiorite. The Sewell Diorite intrusive complex is associated with the TFZ, and has been overprinted by argillic alteration in the Agua Amarga prospect. Reich (2000) suggests the Sewell Diorite and the La Huifa dacitic porphyry share many of the petrographical and geochemical features of adakites.

The Teniente intrusive complex is described in detail in Chapter 3. It consists of a series of dacite porphyries (5.7 and 4.8 Ma; Maksaeve et al., 2002) and post mineralisation lamprophyre dykes (3.8 - 2.9 Ma; Cuadra, 1986; Maksaeve et al., 2002) that occur within the Teniente deposit, and which are intimately associated with copper and molybdenum mineralisation.

The Young plutonic complex, dated between 6.2 and 5.0 Ma, includes the Cerro Cathedral, Jeria, Paso Las Lenas, and Cruz de Peidra plutons (Kay and Kurtz, 1995). These plutons are all located eastwards of the longitude of the Teniente deposit and are spatially interspersed with older Teniente Plutonic Complex plutons. The young plutonic complex and the Teniente intrusive complex have overlapping age ranges and similar major element, trace element and REE characteristics (Kay and Kurtz, 1995).
Colon-Coya Formation

The Pliocene Colon-Coya Formation overlies the Farellones and the Coya-Machalí Formations (Fig. 2.6) and obscures their contact in the Teniente district. This formation is a mass debris flow (or avalanche detritus flow; using the terminology of McPhie et al., 1993) up to several hundred metres thick, postulated to be caused by the gravitational collapse of the Cerro Montura volcanic edifice to the east of El Teniente (Godoy et al., 1994; Koeppen and Godoy, 1994). The mass debris flow was transported as a dry flow, with fluvial reworking only evident in the final stages (Godoy et al., 1994). Blocks up to several hundred metres wide have been reported by Charrier and Muni­zaga (1979).

Glacial Talus

Valleys in the Teniente district are partly filled with glacio-fluvial debris and scree deposited by a period of Quaternary glaciation. No glaciers currently exist in the vicinity of El Teniente.

2.3 District-Scale Structural Geology

Previous studies of the structural geology of the Teniente district include Godoy and Lara (1994), Garrido (1995), Rivera and Falcón (1998), and Godoy et al. (1999). Kilometre scale open to moderately tight wavelength folds with NNW to NNE trending axes occur in the Coya-Machalí Formation. This contrasts with the consistently gently dipping (typically <15°) beds of the Farellones Formation. Based on radiometric dating, there is very little detectable hiatus between the Coya Machali and Farellones Formations in the Teniente district (Table 2.1). Deformation of the Coya-Machalí Formation is interpreted to have occurred during late-Miocene basin inversion (Godoy and Lara, 1994; Godoy et al., 1999; Charrier et al., 2002; Camus, 2003). The Farellones Formation was not subject to ductile deformation as it acted as a rigid block thrust over the Mesozoic sequences along reactivated normal faults (Fig. 2.3). A detachment possibly corresponding to a thrust has been identified at a depth of 2.3-2.5 km below the surface at El Teniente by gravimetric modelling and seismic profiles (Godoy et al., 1999). Consequently, in the middle of the basin, the contact between the Farellones and Coya-Machalí Formations is marked only by a gradual increase in deformation intensity (e.g. Charrier et al., 2002).
Brittle deformation is predominant in the Farellones Formation, and resulted in numerous fault zones and veins. Two of the most significant structures in the Teniente district are the Teniente Fault Zone (TFZ) and the Codegua fault (Fig. 2.4). El Teniente occurs close to the intersection of the two structures.

**Teniente Fault Zone**

The TFZ (also locally known as the Agua Amarga fault) is a zone of anastomosing faults trending NE-ENE. The fault zone has known dimensions of 14km long and 3km wide (Fig. 2.5; Garrido, 1995). The Teniente deposit occurs within the eastern end of the TFZ. The eastern extent of the TFZ is poorly known, but it may terminate against the Codegua Fault. Similarly the western termination of the TFZ is not known. A predominant dextral sense of movement has been reported, producing a kilometre or more of displacement (Garrido, 1995). In contrast, Howell and Molloy (1960) and Koeppen and Godoy (1994) recorded predominantly normal fault movement which uplifted the SE block and formed a volcano-tectonic depression to the NW. The TFZ appears to...
have controlled the emplacement of the Sewell Diorite intrusive complex, and the Agua Amarga alteration zone (Garrido, 1995, Fig. 2.5). Garrido (1995) postulated that this structure was active between 11 and 4 Ma and was important in the genesis of the Teniente deposit.

Kinematic analysis of faults from outside the TFZ by Garrido (1995) indicated a maximum shortening of N94° ± 9°E, consistent with the direction of convergence of the Nazca plate underneath the South American plate (estimated at 82° ± 4 by Pardo-Casas and Molnar, 1987; and at 78.8° by Tamaki, 1999). This maximum shortening direction was noted in rocks of all ages from the Teniente region to the Chilean coast. A similar compressional E-W direction of maximum stress has been reported from central and southern Chile by Lavenu and Cembrano (1999), dated between 4.7 Ma to 2.8 Ma.

Inside the TFZ, and inside the mine, kinematic indicators from the strike slip faults suggest a maximum shortening of N48°W ± 11° (Garrido, 1995; Fig. 2.5). Garrido (1995) interpreted that the TFZ was active during the E-W directed compression and acted as a zone of low resistance resulting in a rotation of the principal compressive stress ($\sigma_1$) to a NW direction (Garrido, 1995).

Overprinting the NW trending shortening event was a second episode of deformation that formed strike-slip and reverse faults in the Teniente district and reactivated faults from the earlier tectonic episode (Garrido, 1995). The $\sigma_1$ direction was oriented towards the N during this period of deformation. The 2.8 Ma lamprophyre dyke at El Teniente has been affected by this episode of deformation (Levanu and Cembrano, 1999), as have Pleistocene mass flow deposits (post 1.6 Ma) in the Teniente district. This deformational event appears to be consistent throughout the Quaternary in the forearc of central and southern Chile, and Garrido (1995) suggested that it is still the principal stress direction today. N-directed maximum stress can be explained by plateslip-vector partitioning, due to slightly oblique convergence of the subducting Nazca plate and a N-directed partitioning of the movement direction (McNutty et al., 1998; Levanu and Cembrano, 1999).

**Codegua Fault**

As noted above, the Codegua Fault (Fig. 2.4) appears to have focussed late Miocene
volcanic activity, subvolcanic intrusions, and hydrothermal alteration (Rivera and Falcon, 1998). Aeromagnetic interpretation suggests that the Codegua Fault was a basin-bounding structure, with significant vertical movement and accumulation of volcanic debris to the south of it (P. Gow, pers. comm., 2000).

The Codegua Fault is an obvious lineament in local to regional scale aeromagnetics images (P. Gow, pers. comm., 2000); however, surface expressions of this fault are difficult to find. Garrido (1995) identified the Codegua Fault from regional aeromagnetics data and traced it to the coast and eastwards into Argentina. Its position approximately coincides with ductile faults in the extreme north of the Carboniferous Coastal Batholith and the northern limit of the Central Depression (Garrido, 1995). Recent seismic movements along this fault indicate that it is still active (Garrido, 1995).

WNW to NNW arc-transverse structures, such as the Codegua Fault, have influenced the formation of volcano-tectonic basins from the Oligocene to the Recent throughout central Chile (Garrido, 1995; Rivera and Falcon, 2000; Rivera and Cembrano, 2000). These structures are believed to have been inherited from the WNW-NNW trending pre-Andean basement fabric. Reactivation of the Triassic-Jurassic rifts (Fig. 2.2) occurred in a reverse sense during compressional episodes in the Andean Cordillera (Gow, 2000; Rivera and Falcon, 2000; Rivera and Cembrano, 2000).

Rivera and Falcon (1998) postulated that the district scale faults, including the Agua Amarga fault, are Riedel structures that formed in response to sinistral transcurrent movement on the NW-trending Codegua Fault, with an E-directed maximum stress field. The main problem with this model is that both the predominant structural fabrics at El Teniente (Chapter 5) and also the TFZ are NE-trending. Although no evidence for the involvement of a NW trending fault in the mineralising process exists at the deposit scale, the Codegua Fault may have played a fundamental role in tapping a deep magma source and focussing the various intrusions, veins, and alteration assemblages at El Teniente.

**Other faults**

According to Rivera and Falcon (1998), the southern margin of the La Juanita-El Azufre sub-basin is defined to the south by the E-trending La Juanita Fault, and the northern margin by the WNW-trending El Azufre Fault (Fig. 2.4). The La Juanita Fault is a steeply N-dipping normal fault. Thick deposits of detritus accumulated on its
northern side, indicating that it was active as a growth fault during sedimentation and volcanism (Rivera and Falcón, 1998). The fault forms a prominent lineament traceable on satellite images and aeromagnetics images and hosts mineralisation at La Juanita mine. The poorly exposed sub-vertical El Azufre Fault is less prominent on the aeromagnetic and satellite images than the La Juanita Fault.

The Extravio-Los Mosquitos Fault is a NW trending structure that occurs in the north of the Teniente district (Fig. 2.4). It is poorly exposed at the surface (Garrido, 1995), but is an obvious lineament on aeromagnetics images. Also visible on the aeromagnetics image is a steep N30°E trending wrench fault interpreted to have undergone dextral, east-side up movement (P. Gow, pers. comm., 2000). This lineament passes close to El Teniente. No field evidence for this structure has been reported.

Although it is covered by the Colon-Coya Formation in the Teniente district, the western contact between the Farellones and Coya-Machalí Formations forms a notable regional N trending lineament. Godoy et al. (1999) interpreted that a thrust separates the two formations in the Teniente district.

2.4 **DISTRICT-SCALE HYDROTHERMAL ALTERATION**

Widespread hydrothermal alteration assemblages and minor copper mineral occurrences are present in El Teniente district (Fig. 2.6).

**Exploration prospects**

Most of the prospects (summarized in Table 2.2) form distinctive Landsat colour anomalies, and are associated with either argillic-siliceous breccia zones or tourmaline-quartz-phylllic breccias and related alteration zones. Small (<50m wide) unmineralised tourmaline breccia pipes, with attendant phyllic alteration of the clasts and wall rocks, occur between El Teniente and La Huifa - La Negra and also around La Juanita (Floody and Huete, 1998). The only known occurrences of potassic (K-feldspar) alteration outside of the Teniente deposit are associated with the weakly mineralised Extravio stock at La Huifa - La Negra and the small dioritic stock from Los Puquios prospect, south of Agua Amarga Fault.
Chapter 2. Regional Geology

Figure 2.6. Distribution of mapped pervasive phyllic, argillic, and propylitic alteration zones, major structures and location of the exploration prospects in El Teniente district. Compiled from Cuadra (1982); Wettké and Toro (1993); Floody (1996); Floody and Huesa (1998). The Pliocene Colon-Coya Formation obscures the contact between the Farellones and Coya-Machali Formations. The approximate positions of large Landsat colour anomalies are shaded in grey. Intense phyllic/argillic alteration and hydrothermal breccia zones are depicted in solid colours, whereas moderate pervasive alteration is indicated by hatching. Approximate elevations of prospects: Agua Amarga (including El Teniente) – 2000 to 3200m, La Hulfa - 3000 to 3500m, Olla Blanca - 2750 to 3200m, Codegua - 2000 to 3000m.
Amarga Blanca of (Charrier and Munizaga, 1979) intruding propylitically La Huifa- 4km NE Quartz diorite to dacitic porphyries (Reich, Codegua 15-20km Large Quebrada 5km N of Quartz diorite porphyry intruding Farellones Formation. Rock-flour Rock chip Oil Puquois Los La Juanita 15km Mineralisation associated with thin halos) are common. These are up to 30cm thick and occur in sheeted and en echelon.

Prospect | Location | Description | Results
--- | --- | --- | ---
La Huifa - La Negra | 4km NE of Teniente crater | Quartz diorite to dacitic porphyres (Reich, 2000), dated at ~8Ma (Charrier and Munizaga, 1979) intruding propylitically altered Farellones Formation. Minor stockwork quartz veins associated with potassic and phyllic alteration (dated at 7.0 Ma and 6.8 Ma Cuadra, 1992). Also tourmaline breccia bodies + Cu-sulphides + quartz + anhydrite associated with sericitic alteration, dated at 5.0 ± 0.3 Ma (Cuadra, 1986). Also rock flour and magnetite-matrix breccias. | Defined resource 11.1 Mt @ 1 % Cu and 0.039 % Mo from Extravio tourmaline breccia pipe (Floody and Huete, 1998)
Agua Amarga | Immediately SWW of Teniente crater | ~10km x 4km colour anomaly that encompasses the Teniente collapse crater, caused by zones of pervasive supergene argillic alteration. Includes hypogene argillic, silicic, rock-flour, and tourmaline cemented breccias. Associated with and controlled by the TFZ. Thick quartz veins and faults trend ENE. Main host rock is the Sewell Diorite intrusive complex. Alteration dated at 7.9 - 8.9 Ma (Cuadra, 1992). Drillholes have not identified hypogene structural target or source. | Deep drillholes and surface sampling has all returned negative results (Floody and Huete 1998; Quiroga and Morel, 1986)
Olla Blanca | 5km NW of Teniente crater | Strong phyllic (quartz-sericite) alteration and fracture controlled zones of intense silicification. Supergene argillic alteration (Morel, 1984). K/Ar ages of 8.0 ± 1.6 Ma and 9.0 ± 0.3 Ma (Cuadra, 1986). | No anomalous values recorded from surface samples or drillholes (Morel, 1984; Floody and Huete, 1998)
Quebrada Coya | 5km N of Teniente crater | Quartz diorite porphyry intruding Farellones Formation. Rock-flour breccias associated with sericitic ± kaolinitic alteration in NE trending zones. Quartz-sericite veins with miliitic pyrite and chalcopyrite | Rock chip samples and one drillhole did not return anomalous mineralisation (Floody and Huete, 1998)
Los Puquios | Directly SE of Teniente crater | Small potassically (biotite and K-feldspar) altered diorite porphyry intrusion into the Farellones Formation, associated with biotite, chlorite, sericite, quartz alteration in andesites. Tourmaline breccia bodies. Thin quartz veins with chalcopyrite and Cu-oxides, ± bainite and calcite, NE and NW trending fractures. | Significant rock chip assays and geophysical target, but negative drilling results (Floody and Huete, 1998)
Codegua | 15-20km NW of Teniente crater | Large colour anomaly 14x10km. Within this zone two N trending zones of intense argillic alteration and chalcocodine veins (ledges) occur. Silicic breccia zones are composed of central vuggy quartz passing outwards to quartz-alunite and quartz-kaolinite zones. At depth pyrophyllite and sericite occur together with the quartz (Lopez, pers comm., 2001) | No geochemical anomalies have been identified (Floody and Huete, 1998; Toro and Wettke, 1998), but it has never been drilled
La Juanita | 15km directly S of Teniente crater | Mineralisation associated with thin felsic porphyry dykes that have intruded the E-W trending La Juanita Fault. Bionite and chalcolite occur disseminated in the dykes and in the amygdaloids of the adjacent andesite flows. Proximal tourmaline-sericite alteration and distal chlorite, epidote and calcite alteration is mainly confined to the amygdaloids. Newly pluron dated at 9.3Ma (Kay and Kurtz, 1995) | Mineral Pangan extracted 0.279 Mt @ 3% Cu up to 2001.

Table 2.2. Summary of prospects in the Teniente district. Refer to Figure 2.6 for prospect locations.

The largest mineralised system in the Teniente district (excluding the Teniente deposit) is the Extravio tourmaline-breccia pipe at the La Huifa - La Negra prospect to the NE of Teniente. Drilling has defined a resource of 11 Mt at 1% Cu and 0.039% Mo (Floody and Huete, 1998). A total of 0.279 Mt @ 3% Cu was mined from the abandoned La Juanita adits by Mineral Pangal before 1973. No evidence of epithermal-style precious or base metal mineralisation has been found in the district.

Propylitic alteration assemblage

Propylitic alteration assemblages are widespread in the Teniente district (Fig. 2.6). North of the Agua Amarga Fault, pervasive propylitic alteration assemblages occur in the Coya-Machali Formation and, to a lesser degree, the Farellones Formation.

The regional propylitic alteration assemblage is characterised by pervasive chlorite – epidote – calcite ± hematite. Low angle (<40° dip) carbonate veins (± hematite-epidote halos) are common. These are up to 30cm thick and occur in sheeted and en echelon...
vein arrays well exposed in the cuttings along the Carretera de Cobre (Figs 2.7A, B, C). Thin carbonate veins were observed 10-15km NW of the mine, near the Codegua prospect, and to the NE of Teniente, near La Huifa – La Negra.

Propylitic alteration intensity increases close to the Olla Blanca and Quebrada Coya prospects (Fig. 2.6). Albite alteration and saussuritisation have been reported from these prospects by Floody and Huete (1998). Morel (1984) described the propylitic assemblage as a “background” alteration around the Olla Blanca prospect, and notes its similarity with the regional lower greenschist metamorphic assemblage that occurs in Mesozoic and Cenozoic rocks (Levi, 1970).

![Figure 2.7. Regional alteration assemblages from the Teniente district. A - C are examples of the regional propylitic assemblage from the Coya-Machali Formation exposed along the Carretera del Cobre.](image)

A) Thick epidote - carbonate - filled low angle shear zone associated with chlorite-hematite alteration of the andesitic wall rock. Note geological hammer in centre of the photograph for scale.

B) Sheeted low angle carbonate-chlorite vein array in andesite, with chlorite + epidote alteration halos around the veins.

C) Thick carbonate vein surrounded by strong hematite-carbonate alteration of the wall rock, cutting pervasively chlorite-altered volcanic wall rock away from the veins.

D) Argillic alteration of the subhorizontal intrusives and extrusives of the Farellones Formation at the Agua Amarga prospect, 5km SW of El Teniente, looking to the W. Argillic alteration forms the orange-yellow colour anomalies obvious on aerial photographs and satellite images. A vertical NE-trending ferruginous fault zone is visible at the top and bottom of the photograph. The white resistant material on top of the hill to the right of the fault is vuggy quartz. Despite the presence of siliceous breccias, continuous faults, felsic intrusions and extensive hypogene + supergene advanced argillic alteration, and the proximity of the prospect to El Teniente, no anomalous assays have been returned from the sampling and drilling performed to date at Agua Amarga (Fioody and Huete, 1998).
South of the TFZ and the Codegua Fault, the intensity of propylitic alteration of the Farellones Formation decreases dramatically (Fig. 2.6). Only weak chlorite – carbonate alteration is reported from this area, largely restricted to amygdales in the volcanic units. The only significant hydrothermal alteration south of the Agua Amarga fault occurs at La Juanita, localised by the La Juanita fault, and in unmineralised tourmaline breccia pipes and argillic alteration zones south of the La Juanita Fault (Floody and Huete, 1998).

**Early magnetite alteration**

Early magnetite alteration is an alteration assemblage only recently described from the Teniente deposit (Cannell et al, 2002; Skewes et al, 2002; Chapter 4). This alteration style has also been observed during the current study near Los Condores prospect, underneath Agua Amarga in drill core, and at La Huifa-La Negra (Fig. 2.6). Floody and Huete (1998) reported a similar regional magnetite – actinolite alteration assemblage associated with the regionally-developed propylitic assemblage. The hydrothermal early magnetite assemblage appears to have formed throughout the Teniente district, and has a much greater areal extent than the potassic and phyllic alteration assemblages that are localised at El Teniente.

A breccia occurs at La Negra which has a cement of magnetite - actinolite - tourmaline ± quartz - apatite - perthite, and associated with quartz-feldspar-chlorite-magnetite alteration of the clasts and wall rocks (Cuadra, 1982; Fig 2.6) This breccia is associated with a dioritic porphyry dated at 8 Ma (Cuadra, 1992).

**Phyllic and argillic alteration**

Laterally extensive phyllic and argillic alteration zones are present in the Teniente district, identified from field mapping and from Landsat colour anomalies (Fig. 2.6). The strongest of these correspond to the Agua Amarga prospect, to the SW of Teniente, that forms a colour anomaly approximately 8 x 4 km, and the Codegua prospect, that forms an anomaly approximately 14 x 10 km wide.

The Agua Amarga system is orientated NE, parallel to the Agua Amarga Fault, and is composed of argillic and phyllic alteration assemblages (Fig. 2.7D). The Codegua system contains a series of N-S trending intense argillic-siliceous alteration and breccia zones, reported to be at least partly hypogene (Lopez, pers comm., 2001). The N
trending contact between the Coya-Machali and the Farellones Formation around the Codegua prospect appears to have been a focus for argillic alteration (Fig. 2.6). At Olla Blanca, Morel (1984) interprets phyllic (quartz-sericite) hypogene alteration to be overprinted by supergene argillic alteration. Phyllic alteration assemblages and associated breccia zones (± tourmaline, ± supergene argillic alteration) also occur at Quebrada Coya, La Huifa - La Negra, Los Puquios, and El Teniente.

**Alteration geochronology**

The tourmaline – phyllic alteration assemblage reported from La Huifa-La Negra, Agua Amarga, and Los Puquios is mineralogically similar to the pre-mineralisation early phyllic + tourmaline alteration at El Teniente (Chapter 4), which is tentatively interpreted to be related to the ~ 7 Ma Sewell Diorite.

The K/Ar ages of the regional phyllic and argillic alteration assemblages (~ 9 to 7 Ma; Table 2.4) overlap with the ages of the Teniente Plutonic Complex intrusions (12 to 7 Ma; Kay and Kurtz, 1995). It is therefore interpreted that regional alteration, tourmaline brecciation, and minor mineralisation in the Teniente district are related to intrusion of dioritic to dacitic plagioclase porphyries of the Teniente Plutonic Complex. The exception is the mineralised Extravio tourmaline breccia at La Huifa (5 Ma; Floody and Huete, 1998; Chapter 6).

<table>
<thead>
<tr>
<th>Prospect</th>
<th>Age</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agua Amarga</td>
<td>8.9 - 7.9</td>
<td>K/Ar on sericite</td>
<td>Cuadra (1992)</td>
</tr>
</tbody>
</table>
| La Huifa  | 8.0 - 6.8 | K/Ar on biotite and sericite from diorite and associated breccias | Charrier and Munizaga (1979)  
          |          |                                     | Cuadra (1986)                       |
|           | 5.0       | K/Ar on sericite from the mineralised tourmaline breccias  | Cuadra (1992)                       |
| Olla Blanca | 9.0 – 8.9 | K/Ar on sericite                    | Cuadra (1992)                       |
| La Juanita | 9.3       | K/Ar on biotite from adjacent pluton - interpreted to be associated with La Juanita | Kay and Kurtz (1995). |

Table 2.34. Alteration geochronology from the Teniente district.

**Discussion**

A broad structural control on the distribution of district-scale phyllic and argillic alteration zones can be seen in Figure 2.6. The alteration zones are confined to the block bound by the TFZ and the faulted (?) Coya-Machali/Farellones Formation contact. Phyllic and argillic alteration zones occur parallel to and adjacent to the Codegua Fault and the TFZ (Figs. 2.5, 2.6). There is an apparent partitioning in alteration styles
across the Teniente district. Phyllic alteration is best developed in the east, in association with tourmaline breccia pipes. Argillic alteration systems occur to the west and the north. K/Ar dating suggests that the alteration types formed broadly contemporaneously, and the prospects all occur at a similar elevation (between 2,000 and 3,500m, Fig. 2.6). Both phyllic and argillic alteration assemblages occur at Agua Amarga and Olla Blanca. The spatial variability of alteration assemblages may have been caused by greater erosion and hence deeper exposure in the east, and higher level assemblages exposed in the western part of the district.

The abrupt change in intensity of the propylitic alteration assemblage across the TFZ (Fig. 2.6) may be explained two ways. Firstly, the hydrothermal system may have been compartmentalised in the northern fault bound block, and the TFZ would have acted as an aquaclude. No alteration occurs in the block bound by the Agua Amarga Fault and the La Juanita Fault. Alternatively, significant vertical movement could have occurred on the Agua Amarga Fault, to juxtapose blocks of variable propylitic alteration intensity.

2.5 SUMMARY

- The western margin of the Gondwana supercontinent has had a protracted history of subduction, accretion, volcanism, plutonism, deformation, and sedimentation, dating back to the early Palaeozoic.

- The central Chilean magmatic-volcanic arc was initiated in the Jurassic, associated with large extensional back arc basins. Due to opening of the Atlantic Ocean in the late Cretaceous, structural inversion of the basins occurred, generating crustal thickening and uplift. All of the economic Chilean porphyry copper deposits formed during the Cretaceous to recent period of arc compression.

- The early-mid Miocene Coya-Machali Formation accumulated in a N trending extensional inter-arc basin above thin crust (~30 - 40km). Slab flattening, possibly caused by subduction of the Juan Fernandez Ridge, resulted in structural inversion of the basin, deformation of the Coya Machali Formation, crustal thickening, and uplift. Lavas of the overlying Farellones Formation have REE patterns consistent with formation in thickened continental crust.
• Continued compression appears to have shut down volcanism in the late Miocene - Pliocene. This allowed for development of shallow crustal magma chambers, which appear to have been related to the formation of porphyry copper deposits in the central Chilean metallogenic belt. The latest Miocene - early Pliocene Teniente intrusive complex are the most evolved magmas that formed from a high pressure garnet-bearing residuum when the arc was at its thickest (~ 55 to 65 km; Kay and Kurtz, 1995).

• At the district scale, El Teniente is located at the intersection of the crustal scale Codegua Fault and the TFZ. The NNW-trending Codegua Fault appears to have exerted a fundamental control on the localisation of volcano-sedimentary facies in the Teniente district. NNW-trending structures, which form a persistent fabric in the Andes, are believed to be caused by reactivation of Triassic rifts in the basement.

• The TFZ is a broad NE-trending fault zone which has controlled argillic and phyllic alteration and intrusion of the Sewell Diorite intrusive complex to the southwest of the Teniente deposit.

• Kinetic analysis of the faults outside of the TFZ indicate that during mineralisation the regional compressive stress direction was aligned E-W due to arc-normal convergence (Garrido, 1995). Inside the TFZ and the Teniente deposit, \( \sigma_1 \) was aligned NW, probably due to diffraction of the stress regime within the TFZ (Garrido, 1995).

• El Teniente occurs at the southern edge of a structurally controlled and compartmentalized alteration system covering an area approximately 20km by 20km. Extensive supergene – hypogene advanced argillic alteration zones and smaller phyllic (sericitic) alteration zones are associated with tourmaline and/or quartz breccias. These assemblages overprint the background regional propylitic (chlorite, epidote, calcite, hematite) assemblage, and early magnetite (magnetite – feldspar – actinolite) veins, breccias, and alteration zones.

• Subsequent to the formation of El Teniente, volcanism recommenced with an eastwards migration of the magmatic arc (Fig. 2.1).