4.1. INTRODUCTION

Porphyry copper deposits globally have similar alteration and vein assemblages, which are typically developed within and around porphyry stocks. Early workers proposed models of concentric zoning of K-silicate, phyllic and propylitic assemblages around porphyry centres (e.g., Rose, 1970; Lowell and Guilbert, 1970). Gustafson and Hunt's (1975) comprehensive description of the El Salvador deposit highlighted alteration overprinting relationships and proposed a basic vein paragenesis (A, B and D veins) recognizable in many porphyry deposits. Sillitoe and Gappe's (1984) study of the Philippine porphyry copper-gold deposits documented associations with hypogene intermediate and advanced argillic alteration, diatremes, and intramineral intrusions. Dilles and Einaudi (1992) delineated regional-scale alteration patterns, including deep sodic-calcic alteration, around the Yerington Batholith and associated Ann-Mason porphyry copper deposit, in a district that has been fortuitously rotated to expose a vertical cross section from 1-6 km palaeodepth. More recent studies have highlighted variations in the composition and distribution of the hydrothermal assemblages from different deposits, due to a number of variables including depth of intrusion and fluid exsolution, magma chemistry, rate of uplift and erosion, and the local tectonic, structural, and geological setting (e.g., Lang et al., 1995; Corbett and Leach, 1998; Hedenquist et al., 1998; Fournier, 1999; Sillitoe, 2000; Tosdal and Richards, 2001; Camus, 2003; Richards, 2003). This detailed knowledge of the spatial and temporal evolution of porphyry copper systems has helped improve understanding of relationships between the intrusive bodies, veining, and alteration.

This chapter describes veins, breccias, and altered rocks from El Teniente. These are presented within a detailed paragenetic framework, the basic elements of which were developed by previous workers. This has been built upon considerably in the current study by logging of 20km of drill core and 230 thin sections. Drillholes were logged mostly from three cross sections, section-83, (1000N), section-124 (100N), and section-239 (oblique; Fig. 3.1). For each paragenetic stage, cross sections have been
constructed displaying vein and alteration intensity and mineralogy, to build up an understanding of the three dimensional distributions. The integrated, deposit-scale vein, alteration, and intrusion paragenesis presented in this chapter provides a temporal framework for structural, fluid inclusions, and isotope studies presented in later chapters.

**Terminology**

The following terms are used in this chapter to describe the characteristics of the veins and alteration styles (from Titley, 1982).

- Pervasive alteration – all minerals in the rock have been altered to a new assemblage, typically resulting in textural destruction.
- Selectively pervasive alteration – only specific minerals (e.g., mafic phenocrysts), or components of the rock (e.g., groundmass) have been altered.
- Weak, moderate, or intense – describes the relative intensity of the alteration based on subjective visual estimates.
- Vein – a fracture filled by hydrothermal minerals, >5mm wide.
- Veinlet – a fracture filled by hydrothermal minerals, <5mm wide.
- Microveinlet – a veinlet only visible with a microscope.
- Vein selvage – hydrothermal minerals that occur adjacent to the vein walls.
- Vein halo – extent of an alteration assemblage surrounding a vein.
- Fault – A fracture along which there has been shear displacement. Faults are independent of scale, or the presence or absence of hydrothermal infill.

**Previous work**

Alteration and mineralisation at El Teniente has been separated into four hypogene stages by previous authors, the Late Magmatic (LM), Principal Hydrothermal (PH), Late Hydrothermal (LH), and post-mineralisation \( (postuma) \) stages. This paragenetic framework was built up progressively by Howell and Molloy (1960), Camus (1975), Villalobos (1975), Ojeda et al (1980), Zúñiga (1982), and Cuadra (1986). These authors concluded that the LM stage was formed during the intrusion of the dacite porphyry and the Sewell Diorite, and the LH stage was associated with intrusion of the Braden Pipe and late dacite porphyries. Arevalo and Floody (1995) compiled
150,000m of logging data to produce sections and level plans through the whole de­posit of LM-, PH-, and LH-stage vein intensity, phyllic alteration intensity, and sulfide ratios.

4.2 COPPER AND MOLYBDENUM GRADE DISTRIBUTION AND SULFIDE ZONATION

Most of the copper and molybdenum mineralisation at Teniente is hosted in a vein stockwork (Fig. 4.1A) and localized hydrothermal breccia zones. A lesser proportion is disseminated in the altered Teniente host sequence and felsic intrusions. Approximately 80% of the mineralisation is estimated to occur in the Teniente host sequence, and the remainder in felsic-intermediate intrusions and Braden Pipe (e.g., Camus, 1975).

Bornite, chalcopyrite, and pyrite are the principal sulfide minerals. These minerals are zoned at the deposit scale, with a bornite-rich core located at the southern end of the dacite porphyry dyke (Fig. 4.2), which contains 1-4% bornite plus lesser chalcopyrite. Where they are intergrown, bornite consistently surrounds chalcopyrite, indicating a later timing (Fig. 4.1B). The bornite core passes outwards to an anular chalcopyrite-dominated zone, which contains most of the copper resource. Outboard from the chalcopyrite zone, a chalcopyrite + pyrite zone occurs, which passes to an outermost, extensive pyrite halo, containing 3-8% pyrite. Where they co-exist, chalcopyrite typically has surrounded and infilled fractures in pyrite (Fig. 4.1C). Isolated pyrite crystals in the peripheral domains typically contain rounded fine (<100um) inclusions of mixed pyrrhotite and chalcopyrite (Fig. 4.1D). Rutile inclusions also occur in the pyrite and chalcopyrite.

The 0.5% copper grade contour for the hypogene ore at Teniente defines a wedge-shaped zone approximately 2.5km long and up to 1.8km wide, only disrupted by the low grade Braden Pipe (Figs. 4.3A and 3.1). Immediately outside the 0.5% copper grade contour total sulfide abundances are similar to the ore zone, but the pyrite:chalcopyrite ratio increases markedly. Within the ore zone high-grade copper zones are locally associated with the contacts of the dacite porphyry, the dacite pipes, and the grey porphyry (Fig. 4.3A), where mineralised breccias occur and vein intensities are high.
Molybdenum has a near-continuous concentric distribution around the Braden Pipe, with the highest values at a distance of 100-250m from its contact (Fig. 4.3B). High grade molybdenum zones occur locally at the contacts of the felsic intrusions, correlating with high copper grades. The 0.01% molybdenum grade contour approximately coincides with the 0.5% copper contour at the deposit periphery and in the Braden Pipe (Fig. 4.3).

Figure 4.1. Photographs and microphotographs of El Teniente stockwork and sulfides.
A) Typically intense, multi-phase quartz-anhydrite-sulfide vein stockwork in the roof of an underground drive at El Teniente. Most of the veins are LM stage veins, occurring in sets with consistent orientations (Chapter 5). Vein abundances are up to 50 veins and veinlets/m core (Scale bar = 50cm).
B) Bornite surrounding chalcopyrite (yellow) in a Na-K-feldspar (cloudy) + quartz/anhydrite (clear) altered rock (ET313, DDH1512, 847’, PP and RL. Scale bar= 500µm).
C) Chalcopyrite has replaced rounded, anhedral pyrite in this vein, collected from the pyrite-chalcopyrite stable zone at the deposit periphery. The vein has a quartz-sericite-sulfide alteration halo. This timing relationship is typical of all veins in which pyrite and chalcopyrite co-exist at El Teniente, with early pyrite corroded and replaced by chalcopyrite. Molybdenite occurs on the right margin of the vein, probably due to later stage re-opening (ET741, DDH1314, 42’. Scale bar = 2cm).
D) Rounded pyrrhotite (grey-pink) and chalcopyrite (bright yellow) inclusions in disseminated pyrite (pale yellow) from the peripheral propylitic zone. Composite pyrrhotite-chalcopyrite inclusions comprise up to 5% of the pyrite crystals (ET149, DDH1698, 875’. RL. Scale bar = 500µm).

Abbreviations used in Chapter 4 figure captions: Act-tr = actinolite-tremolite, alt = alteration, anh = anhydrite, bt = biotite, carb = carbonate, chl = chlorite, cp = chalcopyrite, incs = inclusions, Ksp = K-feldspar, LM = Late Magmatic, mag = magnetite, mo = molybdenite, Po = pyrrhotite, PP = Plane polarized light, py = pyrite, qz = quartz, RL = reflected light, ser = sericite, sulf = sulfide, vn = vein, XP = crossed polarized light.
Chapter 4. Mineralised veins, breccias and altered rocks

Figure 4.2. A) Sulfide zonation at El Teniente, from the database of Arevalo and Floody (1995). The overall zonation is from bornite proximal to and within the dacite porphyry, passing outwards to chalcopyrite and to pyrite peripherally. Pyrite is the dominant sulfide mineral inside the Braden Pipe. Large zones of overlap exist between each field, and in most of the deposit two iron ± copper sulfide phases occur. The contacts of the dacite porphyry and Sewell Diorite are also shown.

B) Geology of the Teniente deposit through the Teniente-6 level, shown for reference. See Figure 3.1 for legend.

Grade (%Cu)

- <0.5
- 0.5-0.75
- 0.75-1.0
- 1.0-1.50
- 1.50-2.0
- >2.0

Figure 4.3. Plan of copper and molybdenum distribution across the Ten-5 level (from El Teniente database), showing the contacts of the Braden pipe, dacite porphyry and Sewell Diorite for geological reference.

A) Copper distribution. The 0.5% copper contour occurs close to the transition where pyrite becomes dominant over chalcopyrite at the periphery of the deposit, and in the Braden Pipe. Within the deposit, copper grades are mostly between 0.75% and 1.5%. Higher grade zones, consistently >1% copper occur close to the dacite pipes, and are focused in a NW trending corridor approximately 2km x 600m. Note that high grades immediately north of the Braden Pipe are partly due to secondary enrichment due to deepening of the supergene zone in this area.

B) Molybdenum distribution. A moderate- to high-grade zone (>0.03% Mo) occurs as a near-continuous ring around the Braden Pipe, focussed 100-250m from its contact. Localised high grade zones (>0.070% Mo) also occur around the felsic intrusions in the north and east of the deposit, and LH-stage anhydrite breccias in the far south of the deposit. The <0.01% molybdenum plots close to the <0.5% copper contour. Molybdenum grades, like copper grades, drop off abruptly in the Sewell Diorite.
High molybdenum and copper grades surround the dacite pipe on section-83 (Fig. 4.4A). The transition from bornite to chalcopyrite to outer pyrite has been disrupted by small bornite to chalcopyrite zones developed around the grey porphyry on section-124 (Fig. 4.4B) and the LH breccias on section-239 (Fig. 4.4C).

4.3 STAGE 1 - PREMINERALISATION STAGE

The existing paragenetic framework for El Teniente outlined in section 4.1 has been modified during the current study. Specifically, a premineralisation stage has been added and the postmineralisation (postuma) stage is incorporated into the LH stage. Within each paragenetic stage discrete vein stages have been identified. The spatial and temporal distribution of the alteration and vein stages relative to the intrusive stages is summarized in Figure 4.5 and Table 4.1, based on crosscutting and overprinting relationships.

Two stages of veining and associated alteration of the wall rocks occurred during the premineralisation stage; the early magnetite veins and alteration assemblage and the early phyllic - tourmaline veins and alteration assemblages.

Early magnetite alteration and veining

Early magnetite alteration

Early magnetite alteration has been described briefly in Skewes et al. (2002), and Cannell et al. (submitted). This alteration style is not associated with sulfides, and occurs exclusively in the Teniente host sequence. The early magnetite alteration assemblage can be subdivided into texturally preserving or texturally destructive assemblages. Texturally preserving early magnetite alteration occurs as a metallic-grey magnetite wash through the Teniente host sequence. The magnetite wash has been partly destroyed by biotite halos emanating from cross-cutting LM stage vein and veinlets (Fig. 4.6A). Microscopically, it is characterized by up to 25% fine subhedral to euhedral magnetite grains and variable actinolite-tremolite (0-25%; Fig. 4.6B). The magnetite has been partially hematised (up to 20%). Early magnetite alteration has resulted in a dusting of magnetite inclusions (< 0.05mm diameter) in primary plagioclase crystals. This texture has been preserved even when the groundmass has been biotite altered (Figs. 4.6C and D).
Chapter 4. Mineralised veins, breccias and altered rocks

Figure 4.4. Sulfide mineral zonation, copper-molybdenum grades, and basic geology for the three main logged sections. See Figures 3.1 and 4.2 for section locations.

A) Section-83, located approximately on 1000N, north of the Braden Pipe. This section was logged to investigate the relationship between the felsic intrusives and mineralisation and alteration. The generalised sulfide zonation is from chalcopyrite-bornite in the innermost zone proximal to the dacite porphyry, passing to chalcopyrite, and to pyrite distally, outside of the 0.5% copper (and 0.01% Mo) contour. Copper grades are highest (>1.5% Cu) in the secondary zone proximal to the dacite porphyry contacts. Internally in the dacite porphyry the grades are low. High hypogene copper and molybdenum grades also occur around the contacts of the thin, vertically continuous dacite pipes at 800E.

B) Section-124, located approximately on 100N, logged to determine the influence of the dacite porphyry, dacite pipes, grey porphyry, Sewell Diorite, and Braden Pipe on mineralisation and alteration. The generalised sulfide zonation is from bornite > chalcopyrite proximal to the Braden Pipe, passing to chalcopyrite, then to pyrite distally. This is interrupted by a zone of chalcopyrite-only stability proximal to the grey porphyry, which has intruded the Sewell Diorite. Copper grades are highest in the supergene zone proximal to the dacite pipes and Braden Pipe, and in the hypogene zone proximal to the grey porphyry. High hypogene molybdenum (>0.03%) grades are associated with the dacite pipes, the grey porphyry, and the Marginal Breccia. copper and molybdenum grades are low inside the post-mineralisation Braden Breccia, and the Sewell Diorite.

C) Section-239, located in the south of the deposit. LH alteration and mineralisation are strongly developed on this section. Two zones of high grade LH anhydrite-sulfide cemented breccia occur parallel to the Braden Pipe contact, associated with thin strongly altered late dacite dykes. DDH1423 intersected 30m @ 4.65% copper and 0.51% molybdenum from the distal breccia. The generalised sulfide zonation is from chalcopyrite-bornite to the north (proximal to the dacite porphyry), passing outwards to chalcopyrite and then to pyrite. This zonation has been complicated by the emplacement of the chalcopyrite- and bornite-rich distal LH breccia.
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Figure 4.5. Schematic space-time plot of the distribution of the veins and alteration assemblages around the intrusions at El Teniente. The vertical scale of each stage indicates its relative intensity. The stages are arranged in paragenetic order from bottom to top. Abbreviations: cpx = clinopyroxene, pl = plagioclase, sa = saussureite, qz = quartz, brec = breccia, sh = shale, m = magnetite, sp = sphalerite, bar = barite, sh = shale, act-trem = actinolite-tremolite, chal = chalcopyrite, pyr = pyrite, gal = galena. The stages are arranged in paragenetic order from bottom to top. The scales indicate the relative intensity of each stage.
<table>
<thead>
<tr>
<th>Vein Stage</th>
<th>Mineralogy</th>
<th>Features</th>
<th>Metal Content (0-3)</th>
<th>Vein Abundance (1-3)</th>
<th>Associated intrusions, alteration, sulfides</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Premineralisation stage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a (early magnetite) veins</td>
<td>mag, Ca-plag, qz, acl, anh</td>
<td>Thin, to several cm thick. Diffuse veins with early magnetite alteration halo</td>
<td>0 0 1</td>
<td></td>
<td>Early magnetite alteration. Related to Sewell Diorite?</td>
</tr>
<tr>
<td>1b veins</td>
<td>qz ± tour, ser, chl</td>
<td>Qz veins (&quot;dykes&quot;) up to 6m thick, NE trending</td>
<td>0 0 1</td>
<td></td>
<td>Early phyllic -tourmaline alteration (ser, chl, tour). Related to Sewell Diorite?</td>
</tr>
<tr>
<td><strong>Late Magmatic (LM) stage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anh - sulf - bt bxs and veins</td>
<td>anh bxs, veins (abl, tour, cp, fdl)</td>
<td>Similar to stage 2d anh bxs, includes bt or tour. Includes other bt-bearing vein types.</td>
<td>1 1 1 1</td>
<td></td>
<td>Associated with potassic alteration (bt, Na-K-plag), grading to distal propylitic alteration (chlorite, sericite, magnetite, epidote).</td>
</tr>
<tr>
<td>2a veins</td>
<td>qz ± cpy, bn, anh chl, sulf, anh, qz – bt – Na-K-plag, anh, qz halo</td>
<td>&quot;Waxy&quot;, wavy-edged, thin, rare veins in dacite intrusives ± anh, bn, cpy</td>
<td>½ 0 3 1</td>
<td></td>
<td>Main dacite porphyry dyke + pipes. Type 2-distal (ser-chl stable), and type 2f veins predominate in peripheral zones of deposit. Sulfis are bn, cpy, py, mo</td>
</tr>
<tr>
<td>2b (Na-K-feld) veins</td>
<td>qz, anh, sulf ± K-fld, chl, bt</td>
<td>Abundant, zoned veins, with Na-K-feld halo. Temporal overlap with stage 2c and 2d veins.</td>
<td>2 2 3 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2c (qz – anh) veins</td>
<td>qz, anh, sulf ± K-fld, chl, bt</td>
<td>Abundant, sub-mm to 4cm thick. ± bt halo.</td>
<td>1 1 0 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2d (anh) breccias</td>
<td>anh bxs (± sulf)</td>
<td>Crackly breccia. Associated with contacts of dacite intrusions ± Na-K-feld or bt halo</td>
<td>1 3 1 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2e veins</td>
<td>qz, sulf (zanah)</td>
<td>Thick (5mm to 3cm), continuous, straight-edged. Typical sulf (+Mo) seam and or selvage. ± bt or phyllic halo, typically sub-horizontal.</td>
<td>1 1 1 1</td>
<td></td>
<td>Late phyllic alteration. Related to intrusion of Braden Breccia and late dacite porphyry. Sulfis are cpy, bn, py, Mo (bn absent).</td>
</tr>
<tr>
<td>2f (clh) veinlets</td>
<td>sulf, chl (zanah, qz, ser, bt)</td>
<td>Thin (&lt;5mm), abundant in transitional and propylitic zones. ± chl, ser halo. Intermedate argilic veinlets? Commonly form central seam in reopened LM veins, especially stage 2b.</td>
<td>2 1 2 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Principal Hydrothermal (PH) stage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 veins</td>
<td>qz, anh, sulf</td>
<td>Thick up to 4cm cp-rich veins, mineral gangue qz and anh. Well developed phyllic (ser, chl, bt) halo.</td>
<td>3 2 2 1</td>
<td></td>
<td>Phyllic halo + pervasive phyllic (ser, chl, anh, qz) alteration. Sulfis are cpy, py, Mo (bn absent). Concentrated distally from dacite dyke.</td>
</tr>
<tr>
<td><strong>Late Hydrothermal (LH) stage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4a (tour) bxs</td>
<td>tour, anh, sulf (gyps, qz)</td>
<td>&quot;Crackly breccia&quot; and veins. Pale ser halo (± cl), tour smimming walls. Related to Marginal Breccia?</td>
<td>½ 0 1 1</td>
<td></td>
<td>Second phyllic (± fibby) alteration stage, related to intrusion of Braden Breccia and late dacite porphyry. Veins are concentrated close to these intrusions. Sulfis are cpy, bn, py, ten, tett, mo, soh (+ minor sphal, gal, en, stib). Gangue minerals are anh, qz, tour, gyps, carb, bar</td>
</tr>
<tr>
<td>4b veins</td>
<td>anh, cpy, bn (qz, tm, gyps)</td>
<td>&lt;2cm thick. Ser ± chl halo. Similar to PH veins, but they cut stage 4a, and can contain bn.</td>
<td>½ 1 1 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4c veins</td>
<td>carb (anh, qz, gyps, tour ± various sulf)</td>
<td>Ser, chl halo. Up to 10's cm thick, variable vein mineralogy. Include LH anh bxs.</td>
<td>1 3 1 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4d veinlets</td>
<td>gyps, chl (± various minerals)</td>
<td>Gyps ± chl dominated. Typically thin, chl, ser halo. Occur inside and outside the Braden Pipe.</td>
<td>0 0 1 1</td>
<td></td>
<td>Ex-postuma stage (Cuadra, 1986)</td>
</tr>
</tbody>
</table>

Table 4.1. El Teniente vein, alteration and intrusive paragenesis, including an estimation of the copper and molybdenum content and relative abundance of each vein stage. Abbreviations are defined in Figure 4.5.
Figure 4.6. Early magnetite alteration in the Teniente host sequence. Scale bar in core photographs = 5cm, and in microphotographs = 500µm. Refer to Fig. 4.1 for abbreviations.

A) Selectively pervasive texturally-preserving early magnetite alteration. The metallic grey colour of the early magnetite assemblage is due to finely disseminated magnetite. The early magnetite assemblage is altered to biotite around the LM-stage veinlets, visible as dark grey halos. Coherent andesitic facies of the Teniente host sequence (ET3, Ten-6 metallurgical drillcore).

B) Selectively pervasive texturally preserving early magnetite alteration has produced secondary actinolite-tremolite (possibly replacing an earlier amphibole), and fine opaque magnetite interstitial to plagioclase phenocrysts. The crystal-supported texture of the fine andesite porphyry has been preserved in this example (ET604, DDH1565, 117.5m. XP).

C and D) Microphotograph in PP and XP respectively of an LM vein with a biotite halo (left of red dashed line) cutting early magnetite altered Teniente host sequence (right of line). The groundmass actinolite-tremolite and magnetite on the right are altered to biotite ± rutile in the halo of the LM vein. Note the magnetite dusting in the feldspar phenocryst is preserved in the biotite altered domain, despite magnetite destruction in the groundmass (ET91, DDH1689, 775').

E) Texturally destructive early magnetite alteration halos (metallic grey) around early magnetite (stage 1a) veins, in coherent andesite facies of the Teniente host sequence. The early magnetite veins and alteration assemblage are cut by LM (stage 2) veins (Metallurgical drillcore, Esmerelda mine).

F) Texturally destructive pervasive early magnetite alteration has produced a secondary twinned actinolite crystal (Appendix 2D), which encloses coarse magnetite. This has been replaced by Ca-plagioclase and fine magnetite proximal to the early magnetite veinlets (composed of quartz, Ca-plagioclase and magnetite; ET232, DDH1530, 585'. XP).
Chapter 4. Mineralised veins, breccias and altered rocks

Texturally destructive early magnetite alteration has produced vein halos (Fig. 4.6E) and pervasive alteration zones up to 5m thick. In addition to magnetite and variable actinolite-tremolite, Ca-plagioclase (An_{40-93} predominantly An_{67-93}; Appendix 2; Skewes, 1997), quartz, and anhydrite are significant components of this assemblage. Epidote locally comprises up to 70% of the alteration assemblage in the propylitic zone. Primary and metamorphic hornblende crystals are partially to completely altered to tremolite-actinolite, anhydrite, and magnetite. Limited actinolite-tremolite microprobe analyses indicate an actinolitic composition (Si = 7.52-7.56 cations, magnesium number = 0.76-0.77; Leake, 1978; Appendix 2D). With increasing alteration intensity the mafic minerals are totally replaced by Ca-plagioclase and magnetite (Fig. 4.6F).

Stage 1a (early magnetite) veins

Stage 1a (early magnetite) veins and veinlets (Figs. 4.6E - F) are laterally discontinuous magnetite-plagioclase-quartz-filled fractures. They have early magnetite alteration halos which extend up to several centimeters from the vein.

Timing and distribution of stage 1a veins and early magnetite alteration assemblages

Stage 1a veins have been cut by all other vein and alteration stages. Magnetite altered clasts occur in biotite breccias (see below) and as irregular patches of remnant alteration or vesicle-fill (Fig 3.6C) in the wall rocks. Remnants of the early magnetite alteration assemblage are commonly preserved throughout the Teniente host sequence, indicating that this early alteration assemblage was widely developed at El Teniente prior to potassic alteration.

It is difficult to determine the original distribution of stage 1a veins and related early magnetite alteration assemblage, due to overprinting by biotite and phyllic alteration. The early magnetite alteration assemblage and stage 1a veins are best preserved in peripheral areas of the deposit, away from the intrusive bodies (Fig. 4.7). On section-239 (Fig. 4.7C) early magnetite alteration has an apparent lithological control, concentrated in subhorizontal zones parallel to the lithological layering in a volcanioclastic breccia-dominated sequence.
Chapter 4. Mineralised veins, breccias and altered rocks

Section-83, Early magnetite alteration intensity

A) Section-83. The strongest development of the early magnetite assemblage occurs in the peripheral regions of the section, in particular to the west. Early magnetite assemblage has been destroyed immediately adjacent to the dacite pipe at 800E, and in zones of strong phyllic alteration intensity.

Section-124, Early Magnetite alteration intensity

B) Section-124. Early magnetite alteration assemblage is concentrated distally from the Braden Pipe. Note the alteration zones proximal to the dacite pipes and the grey porphyry have destroyed the early magnetite alteration.

Section-239, Early Magnetite alteration intensity

C) Section-239. Early magnetite alteration intensity is higher peripherally to the Braden Pipe and is destroyed by phyllic alteration in the upper portion of the section, and around the late dacite porphyry and LH breccia zone. The alteration assemblage is focused in subhorizontal zones, parallel to the bedding, indicating a lithological control on the distribution of the alteration assemblage.

Figure 4.7. Distribution of early magnetite alteration on the sections. See Figures 3.1 and 4.2 for section locations, and Figure 4.4 for the geology of each cross section.

A) Section-83. The strongest development of the early magnetite assemblage occurs in the peripheral regions of the section, in particular to the west. Early magnetite assemblage has been destroyed immediately adjacent to the dacite pipe at 800E, and in zones of strong phyllic alteration intensity.

B) Section-124. Early magnetite alteration assemblage is concentrated distally from the Braden Pipe. Note the alteration zones proximal to the dacite pipes and the grey porphyry have destroyed the early magnetite alteration.

C) Section-239. Early magnetite alteration intensity is higher peripherally to the Braden Pipe and is destroyed by phyllic alteration in the upper portion of the section, and around the late dacite porphyry and LH breccia zone. The alteration assemblage is focused in subhorizontal zones, parallel to the bedding, indicating a lithological control on the distribution of the alteration assemblage.
Stage 1b veins and early phyllic-tourmaline alteration

Early phyllic-tourmaline alteration assemblage

The early phyllic-tourmaline alteration assemblage is composed of chlorite, sericite, quartz, tourmaline, ± magnetite. Pyrite is locally associated with this assemblage in the Teniente deposit. Tourmaline is characteristically coarse grained, forming rosettes up to 2cm in diameter.

Stage 1b veins

Stage 1b veins were termed by previous workers as the “tempranas” (Camus, 1975; Cuadra, 1986). Stage 1b veins are barren, irregular, or diffuse edged quartz veins, and include the "quartz dykes" of Camus (1975) which are up to 8m thick. These reportedly have been cut by the dacite porphyry in the north of the deposit (Floody, pers comm, 2000). Stage 1b veins are composed of a fine (<0.1mm) anhedral mosaic of quartz and accessory anhydrite. They are commonly associated with early phyllic-tourmaline alteration. Thick stage 1b veins are locally zoned from quartz - quartz/tourmaline - sericite/tourmaline halo - chlorite/sericite ± tourmaline outer halo. Stage 1b veins are cut by all other vein types. Crosscutting relationships between stage 1b veins and stage 1a veinlets have not been observed.

Distribution of stage 1b veins and early phyllic-tourmaline alteration

The early phyllic-tourmaline alteration assemblages and related stage 1b veins are focused in the south of the deposit, adjacent to the Sewell Diorite on section-239 (Fig. 4.8), and within the Sewell Diorite on section-124 (not shown). Stage 1b veins and early phyllic - tourmaline alteration assemblages were not observed on section-83 in the northern end of the deposit.

Tourmaline and quartz-cemented breccias associated with phyllic alteration (± Cu-Fe sulfides) are present in many of the prospects in the Teniente district, including La Huifa, Laguna Negra, parts of Agua Amarga, Los Puquios, and La Juanita, interpreted to be part of a regional hydrothermal event related to intrusion of the 9-7 Ma Teniente Plutonic Complex (Chapter 2). It is possible that the early phyllic-tourmaline alteration assemblage and stage 1b veins were related to the Teniente Plutonic Complex event.
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Section-239, Early Phyllic alteration intensity

Figure 4.8. Distribution of early phyllic -tourmaline alteration on section-239. Early phyllic -tourmaline alteration is mainly controlled by the location of stage 1b veins and breccias. Early phyllic alteration intensity increases peripherally from the Braden Pipe towards the Sewell Diorite, located south of the section. Quartz-only type 1b veins occur near the Braden Pipe, passing to quartz-tourmaline veins to the south.

4.4 STAGE 2 – LATE MAGMATIC STAGE

The Late Magmatic (LM) stage resulted in the emplacement of a stockwork of quartz - anhydrite - sulfide (± Na-K-feldspar - biotite - rutile - chlorite - sericite veins, Fig. 4.1A) which hosts most of the copper and molybdenum mineralization at El Teniente. These veins are subdivided based on their mineralogy, morphology, and timing. Potassic and propylitic alteration of the Teniente host sequence and Teniente intrusive complex occurred in association with LM vein formation.

Late Magmatic stage alteration

Potassic alteration assemblages at El Teniente are subdivided into K-feldspar and Na-K-feldspar alteration assemblages, which occur locally in and around the dacite porphyry and pipes, and a biotite alteration assemblage, which occurs in the Teniente
host sequence (Fig. 4.9). The biotite altered zone is subdivided into an inner potassic zone (corresponding to the "advanced biotitic zone" and "advanced potassic zone" of Villalobos, 1975) and an outer transitional potassic-propylitic zone (the "incipient biotitic zone" of Villalobos, 1975; Fig. 4.9). The potassic zone occurs within 100 - 400m of the dacite porphyry and locally around the dacite pipes (Fig. 4.9B) and grey porphyry (Fig 4.9B). The transitional zone occurs at higher elevations (generally above 2,000m), outboard of the potassic zone and within the 0.5 % copper grade contour. The outermost propylitic zone extends beyond this grade contour and was intersected in the most distal holes logged on each section.

**K-feldspar alteration**

Within the dacite porphyry and to a lesser extent in the dacite pipes the potassic alteration assemblage is characterised by secondary perthitic feldspars, which are only detectable by thin section petrography or staining. There is a spatially restricted zone of intense K-feldspar alteration in the southern end of the dacite porphyry (the "microperthite-rich core" of Ossandón, 1974; Camus, 1975; Zúñiga, 1982) which is associated with high bornite:chalcopyrite ratios. Secondary K-feldspar in this zone occurs as microveinlets which have cut the plagioclase phenocrysts (Fig. 4.10A), as halos to quartz-anhydrite-sulfide veinlets (Fig. 4.10B), and as a groundmass component (Fig. 3.13F), analogous to the K-feldspar groundmass flooding described by Titley (1982). Primary biotite books (albeit in some cases weakly chloritised) are preserved in the K-feldspar-altered rocks and primary plagioclase grains typically have a weak sericite-carbonate alteration overprint. K-feldspar alteration of the dacite pipe decreases in intensity to the north.

**Na-K-feldspar alteration**

The Na-K-feldspar alteration assemblage has not been previously described from El Teniente. It occurs as hard, light-coloured alteration halos around LM veins (Figs. 4.10F) and as irregularly-shaped, strongly developed pervasive replacement zones up to 200m wide around dacite pipes (Fig. 4.9B), associated with demagnetization and textural destruction of the wall rocks. The Na-K-feldspar assemblage is composed of granoblastic anhedral Na-plagioclase (labradorite to albite, Ab\(_{44-96}\), predominantly Ab\(_{61-96}\), Appendix 2), sodic alkali-feldspar (Or\(_{13-29}\), K-feldspar (Or\(_{55-91}\)), and quartz that comprises up to 90% of the rock (Figs. 4.10C and D). A brecciated texture is pre-
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Section-83, Late Magmatic alteration zones

A) Section-83. The potassic zone (where biotite and Na-K-feldspar assemblages occur with related LM veins) occurs close to the dacite porphyry, passing laterally and vertically to the transitional potassic-propylitic zone. The propylitic zone occurs further out, beyond the 0.5% Cu limit to the deposit.

B) Section-124. Pervasive Na-K-feldspar alteration occurs within and close to the dacite pipe at approximately 1100E - 1200E. Biotite alteration occurs on the west side of the section (proximal to the dacite porphyry) and at depth. Biotite alteration also occurs locally around the dacite pipe at 1300E, and around the grey porphyry. The transitional domain exists in the higher levels of the section, and the propylitic domain occurs in the Sewell Diorite at the outer.

Section-239. The biotite alteration assemblage occurs to the north (closest to the dacite porphyry), and at depth, passing to the transitional domain at higher levels and the propylitic zone distally.

Figure 4.9. Late Magmatic alteration zones. See Figures 3.1 and 4.2 for section locations.
Figure 4.10. K-feldspar alteration of the dacite intrusions (A and B) and pervasive Na-K-feldspar alteration of the Teniente host sequence (C - F). Na-K feldspar alteration is texturally destructive, and the precursor facies are unrecognisable.

A) Thin LM K-feldspar-quartz-sulfide veinlet, cutting plagioclase-phyric dacite porphyry dyke. Plagioclase phenocrysts have been altered to inclusion-free microperthite around the veinlet. The parts of the phenocryst that were not perthitised by the veinlet were susceptible to overprinting sericite alteration (ET25, DDH1738, 97'. XP. Scale bar = 1mm).

B) Irregular K-feldspar microveinlets (unsericitised) cutting plagioclase phenocrysts (sericitised) in a dacite pipe. The microveinlets are only visible where they cut plagioclase phenocrysts (ET701, DDH1889, 708'. XP. Scale bar= 200μm).

C) Photomicrograph of pervasive texturally destructive Na-K-feldspar alteration, composed of turbid Na-plagioclase (Ab89-94), quartz (clear), anhydrite (high interference colours), and minor remnant biotite (brown, Ti = 0.23-0.26 cation; Appendix 2C). Sericite associated with Na-K-feldspar alteration is very finely disseminated through the plagioclase crystals, and is easily distinguishable texturally from the coarse sericite from the PH stage (ET344, DDH1486, 1358'. XP. Scale bar = 1mm).

D) Photomicrograph of Na-K-feldspar alteration assemblage (anhedral mosaic of Na-K-feldspar, quartz and minor anhydrite and sulfide), focused around an LM veinlet (left). Relict clasts are a darker colour due to pervasive sericite-carbonate alteration (ET324, DDH1512, 1250'. XP. Scale bar = 1mm).

E) Stained pervasive Na-K-feldspar altered core block. Most of the yellow-stained K-feldspar occurs in veinlets which cut the Na-feldspar bearing assemblage. The K-feldspar in the veinlet running down the long axis of the sample has a composition of Or15-87 (Appendix 2A; ET313, DDH1512, 847'. XP. Scale bar = 1cm).

F) Pervasive Na-K-feldspar alteration assemblage (pale coloured) overprinting biotite altered breccia. Veins with Na-K-feldspar alteration halos have cut the biotite altered breccia (lower right; Metallurgical drillcore, Sub-6 mine area. Scale bar = 10cm).
Anhydrite, rutile, biotite, and bornite, chalcopyrite, molybdenite, and chlorite are also present, and fine grained sericite-calcite wash has selectively altered plagioclase (Fig. 4.10C). Staining indicates complicated paragenetic relationships between K-feldspar and Na-feldspar (Fig. 4.10E). At least some of the K-feldspar formed after the Na-feldspar. Without staining it is not possible to distinguish Na-feldspar from the K-feldspar in these rocks macroscopically.

Based on cross-cutting and overprinting relationships Na-K-feldspar alteration post-dates biotite alteration. However, some biotite-bearing veins have Na-K-feldspar outer halos, suggesting either a second generation of biotite alteration or synchronous zoned biotite – K-feldspar – Na-feldspar alteration. Timing relationships between K-feldspar alteration in the dacite intrusions and Na-K-feldspar alteration are not clear. The spatial relationship of both alteration assemblages with the dacite porphyries suggest they are time-equivalent assemblages, and reflect variations in the a\textsubscript{Na+}/a\textsubscript{K+} ratio of the hydrothermal fluids.

**Biotite alteration – potassic zone**

Potassic alteration of the Teniente host sequence has produced abundant secondary biotite with accessory rutile, anhydrite, quartz, chlorite, and sulfides (Fig. 4.11A). Selectively pervasive biotite alteration has preferentially affected the groundmass of the andesites, in many cases leaving plagioclase phenocrysts unaltered, resulting in partial preservation of the primary igneous texture (Figs. 4.11A and B). Textural destruction has occurred where the biotite alteration was more intensely developed. In such cases the plagioclase phenocrysts have corroded edges. Locally biotite has been concentrated in halos to LM stage veins (Fig. 4.11B), or along a network of fine microveinlets (Fig. 4.11C).

The Teniente host sequence in the potassic zone is dark grey coloured. Primary textures have been destroyed in the most intensely biotite-altered intervals. Mafic minerals are preserved rarely. Dark brown groundmass biotite occurs as fine (typically 0.05-0.1mm), shreddy masses comprising up to 50% of the rock (Figs. 4.11A and D). Ubiquitous rutile, between 1-3%, is intergrown with the biotite, occurring as anhedral semi-opaque to brown masses, or as fine "grapeshot" aggregates. Anhydrite (up to 5%) and sulfides (bornite, chalcopyrite, pyrite, up to 4%) are also present. Biotite and sulfides have straight contacts (Fig. 4.11D), indicative of an equilibrium assemblage. A varia-
Figure 4.11. Biotite alteration of the Teniente host sequence at El Teniente. Scale bar in core photograph is 2cm, and in microphotographs is 200μm. Abbreviations are listed in Fig. 4.1.

A) Pervasive biotite alteration of the Teniente host sequence has produced brown Ti-rich biotite, anhydrite (high birefringence), and disseminated sulphides (opales). This assemblage has selectively altered the groundmass, leaving the plagioclases intact. Macroscopic and microscopic textural destruction occurred where biotite has corroded the edges of the plagioclase phenocrysts (ET19, DDH1738, 15°, XP).

B) Texturally destructive biotite alteration halo around a LM veinlet. The biotite halo grades outwards to less intensely developed biotite alteration that has preserved the porphyritic andesite texture (ET473, DDH1413, 1300°).

C) Biotite alteration halos associated with thin brown biotite veinlets (+ minor anhydrite). Biotite alteration in this sample has overprinted the plagioclase phenocrysts as well as the groundmass, resulting in textural destruction of the precursor lithology. The biotite veinlets are cut by a LM vein (integrown quartz, feldspar, anhydrite and chalcopyrite) with a thin biotite halo. (ET664, DDH1306, 353°, PP).

D) Aggregate of secondary chalcopyrite, biotite, anhydrite and minor rutile, possibly after replacement of a mafic mineral. Note the straight commumal contacts between biotite, sulfides and anhydrite. The brown colour of the biotite, and scarcity of magnetite, sericite and chlorite are features of the proximal biotite assemblage. (ET671, FOV=1mm, PP).

E) Ex-mafic phenocryst (outlined) altered to a potassic assemblage of biotite, anhydrite, sulfide and rutile, adjacent to a LM vein (left of photograph). The altered phenocryst is surrounded by early magnetite altered groundmass (ET450, DDH855, 1117°, PP).

F) Primary ferromagnesian mineral has been altered to a biotite - sulfide - anhydrite assemblage (right), a biotite - anhydrite assemblage (upper centre), and a biotite - rutile assemblage (lower left; ET241, DDH1530, 706m, PP).

G) Primary magnetite partially replaced by shreddy biotite + rutile (ET704, DDH1463, 117°, PP).
bly-developed sericite-carbonate wash has selectively altered the plagioclase phenocrysts. Ex-mafic phenocrysts and secondary tremolite-actinolite crystals are altered to biotite, ± anhydrite, rutile, chlorite, sulfides, Fe-oxides (mainly magnetite, and rare hematite), and feldspars (Figs. 4.11E, and F). Primary Fe-Ti-oxides are altered to aggregates of biotite, rutile, and sulfides (Fig. 4.9G). In intensely biotite-altered intervals, sulfides and rutile are the only opaque minerals (Figs. 4.11C and F).

Biotite alteration intensity in the Teniente host sequence has been estimated visually on the basis of degree of textural destruction (Fig. 4.12). Biotite alteration is most intensely developed in the potassic zones proximal to the dacite porphyry, dacite pipes, and grey porphyry (Figs. 4.12A and B), and decreases in intensity in the transitional potassic-propylitic domain.

**Transitional potassic-propylitic alteration**

The transitional potassic-propylitic zone occurs further out from the dacite porphyry, and extends beyond the 0.5% copper grade contour. In general the degree of textural preservation is greater in the transitional zone than in the potassic zone. The alteration assemblage in this domain is characterized by a greenish-brown biotite (in contrast to the dark brown biotite in the potassic zone) and an increase of chlorite and sericite in the groundmass (Fig. 4.13A - B). Pyrite ± secondary magnetite abundances are locally elevated in the transitional potassic-propylitic zone, with a concordant decrease in chalcopyrite and bornite contents. The pyrite:chalcopyrite ratio increases outboard from the centre of the deposit, and the chalcopyrite locally has pyrrhotite and chalcopyrite inclusions (Fig. 4.1D). Relict magnetite, locally with irregular to cross-hatched ilmenite exsolution lamellae (Fig. 4.13C), has been replaced by biotite, chlorite, sericite, anhydrite, and rutile. Sulfides and anhydrite are consistently rimmed by, or intergrown with chlorite and/or sericite (Figs. 4.13A and B). The plagioclases crystals have been weakly to moderately pervasively altered to sericite and calcite.

**Propylitic alteration**

The propylitic alteration zone in the Teniente host sequence occurs outboard of the transitional potassic-propylitic alteration zone, and outboard of the 0.5% Cu grade contour. The propylitic assemblage is composed of chlorite (5-20%), sericite, pyrite and is biotite absent. The pyrite typically contains and is rimmed by chlorite. Accessory magnetite, ilmenite, rutile, anhydrite, quartz, sporadically developed epidote, and rare
sericite (phengitic muscovite, from PIMA analyses) also occur in the assemblage. Mafic phenocrysts have been altered to chlorite, anhydrite, rutile, pyrite, ± magnetite (Fig. 4.13C). Relict vesicles are filled with quartz, pyrite, and chlorite (Fig. 4.13E). Alteration intensity and vein abundances are notably lower in the propylitic zone than in the potassic alteration zone.

Propylitic alteration from the Sewell Diorite and the northern end of the dacite porphyry is characterised by chlorite and epidote alteration of the ferromagnesian minerals, and the presence of magnetite, hematite, pyrite, sericite, and calcite (Ossandón, 1974).
Figure 4.13. Transitional potassic-propylitic (A-C) and propylitic (D-E) alteration assemblage in the Teniente host sequence. Scale bar = 500μm.

A) Transitional potassic-propylitic alteration assemblage, characterized by green-brown (low Ti) biotite, and intergrown clots of chlorite (light green), sulfide (opaque, pyrite and chalcopyrite) and anhydrite (clear). Sericite needles and chlorite fans are intergrown with disseminated sulfides (ET62, DDH1738, 1404').

B) Light brown to green biotite, opaques (magnetite and chalcopyrite) and chlorite (light green) has replaced a mafic crystal (outlined), in a gabbroic facies of the Teniente host sequence. On the left is a skeletal ilmenite crystal, intergrown with rutile, biotite and minor chlorite and anhydrite (possibly after magnetite; ET232, DDH1530, 585m).

C) Skeletal ilmenite crystal (confirmed by electron microprobe), surrounded by green biotite, anhydrite and minor rutile and chlorite in gabbro. This crystal is interpreted to have been a primary magnetite with cross-hatched ilmenite exsolution lamellae. Selective alteration of the magnetite without replacement of the ilmenite has resulted in the skeletal ilmenite shapes surrounded by biotite, anhydrite and rutile (ET232, DDH1530, 585m).

D) Propylitic alteration of a porphyritic andesite lava. Relict mafic phenocryst (outlined) altered to anhydrite (clear), chlorite (light green), and magnetite (opaque) at the rim. Pervasive propylitic assemblage in groundmass consists of chlorite, magnetite and a weak sericite alteration of plagioclase (ET777, DDH1981, 725'. XP. Scale bar = 200μm).

E) Propylitically altered fine-grained andesite porphyry. Rounded clots of quartz, pyrite and chlorite (± sericite), rimmed by minor biotite are interpreted to be amygdales. A patch of epidote + magnetite alteration occurs in the right of the photograph. The sample is cut by stage 2-distal veins with chloritic and sericitic halos (ET147, DDH1698, 834'. Scale bar = 1cm).
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The propylitic assemblage was only encountered in the Teniente host sequence in the outermost drillholes up to 1000m from the dacite porphyry and Braden Pipe on section-83 (Fig. 4.9). This propylitic assemblage is believed to grade into the district-scale propylitic alteration assemblage, characterized by selective alteration of primary mafic minerals and amygdales to chlorite, magnetite, epidote, and hematite, accompanied by weak sericitisation and albitisation of the plagioclase phenocrysts (Villalobos, 1975, Floody, 1998).

Late Magmatic stage veins and breccias

The LM vein and breccia stages are zoned spatially with respect to the dacite intrusions (Fig. 4.14).

Biotite breccias

The Teniente host sequence has been cut by biotite-cemented breccias. The fine grained breccias are difficult to distinguish from the pervasively biotite-altered fine grained Teniente host sequence units. They have only been recognised underground and in drill core by recent workers (Skewes, 1999; Skewes et. al., 2002; Cannell et al., submitted). Biotite breccias are composed of abundant, intensely biotite-altered clasts of the Teniente host sequence and in some cases clasts of felsic intrusions, which are variably biotite, early magnetite, or chlorite altered (Figs. 4.15A and B). Rare exotic clasts, including silicified clasts and crystal fragments also occur. The breccia cement is composed of abundant, fine-grained, brown shreiddy biotite and lesser anhydrite, Cu-Fe-sulfides, molybdenite, plagioclase, and quartz. Altered rock flour has not been identified in the breccia cement.

The biotite breccia bodies observed in the current study were rarely more than five metres wide. However, on section-83 a 35m interval of clast- to matrix-supported biotite breccia was intercepted (Fig. 3.3, in DDH1889). The breccia is composed of sub-rounded clasts up to 30cm wide of fine coherent andesite, andesite porphyry, diorite porphyry, dacite porphyry, and variably altered unidentifiable clasts. Equant to subhedral feldspar crystal fragments up to 3mm wide are present. High grade copper (1 - 3 % Cu) and molybdenum (0.03 - 0.06 % Mo) mineralisation occurs disseminated in the cement, and also in an anhydrite-sulfide breccia that has overprinted the biotite breccia.
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Section 83, Late Magmatic vein styles

A) Section 83. Stage 2c veins are predominant proximal to the dacite porphyry and at higher elevations. At depth stage 2b veins are the main vein stage present, associated with vein controlled Na-K-feldspar alteration assemblages. Thin zones of stage 2b and stage 2d anhydrite breccias are localised around the contacts of the dacite pipes, and rarely the dacite porphyry. The thin vertical zone of anhydrite breccia at 1000E is associated with a dacite pipe off section to the south. Type 2-distal and stage 2-chlorite veins are abundant on the periphery of the section.

B) Section 124. An irregular zone of strong pervasive Na-K-feldspar alteration is localised around the dacite pipe close to the Braden Pipe. Up and down dip from this zone are intervals of stage 2d anhydrite breccias, and stage 2b veins with vein controlled Na-K-feldspar alteration. Stage 2 distal and stage 2-chlorite veins predominate in the transitional and propylitic zones, and at higher levels. Proximal to the grey porphyry a richly copper and molybdenum mineralised LM stage biotite-anhydrite-sulfide breccia is biotite stable below 2100m, and tourmaline and sericite stable at higher levels.

Figure 4.14. Distribution of Late Magmatic vein stages on section.
A) Section 83. Stage 2c veins are predominant proximal to the dacite porphyry and at higher elevations. At depth stage 2b veins are the main vein stage present, associated with vein controlled Na-K-feldspar alteration assemblages. Thin zones of stage 2b and stage 2d anhydrite breccias are localised around the contacts of the dacite pipes, and rarely the dacite porphyry. The thin vertical zone of anhydrite breccia at 1000E is associated with a dacite pipe off section to the south. Type 2-distal and stage 2-chlorite veins are abundant on the periphery of the section.
B) Section 124. An irregular zone of strong pervasive Na-K-feldspar alteration is localised around the dacite pipe close to the Braden Pipe. Up and down dip from this zone are intervals of stage 2d anhydrite breccias, and stage 2b veins with vein controlled Na-K-feldspar alteration. Stage 2 distal and stage 2-chlorite veins predominate in the transitional and propylitic zones, and at higher levels. Proximal to the grey porphyry a richly copper and molybdenum mineralised LM stage biotite-anhydrite-sulfide breccia is biotite stable below 2100m, and tourmaline and sericite stable at higher levels.
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The biotite breccias are interpreted to have a vertical or subvertical orientation, based on correlation between drillholes, and occur in the Teniente host sequence close to contacts with the felsic porphyries, in particular the dacite pipes (Figs. 3.2 and 3.3). Almost all of the Teniente vein stages (excluding stage 1) have cut the biotite breccias. Terminated quartz veins at clast contacts and quartz vein fragments were rarely observed in the breccia (Fig. 4.15B). Coupled with the presence of early magnetite altered clasts, the biotite breccia is inferred to have intruded after the early magnetite alteration event and before, and partially overlapping with, the LM stage stockwork-forming event.

Stage 2a veins

Stage 2a veins are the earliest formed vein stage recognised in the dacite porphyry and dacite pipes (Fig. 4.15C). These veins do not occur in the Teniente host sequence. These quartz ± bornite - chalcopyrite - anhydrite veins have wispy, convolute margins and are analogus to the A veins of Gustafson and Hunt (1975). These veins are interpreted to be high temperature veins formed in a semi-ductile rock (e.g., Gustafson and Hunt, 1975). They are similar mineralogically to the unidirectional solidification textures (USTs) in the dacite pipes (Fig. 3.13F).

Stage 2 anhydrite-sulfide-biotite breccias and veins

Anhydrite - sulfide - biotite - (± K-feldspar, quartz, tourmaline) filled veinlets, veins and breccias occur proximal to the grey porphyry (Fig. 4.14B), associated with potassic alteration of the Teniente host sequence and Sewell Diorite. A well mineralised stage 2 anhydrite - chalcopyrite breccia (4.15D) spatially localised around the grey porphyry is associated with high copper grades (Fig. 4.4B). Below 2,100m biotite is intergrown with the chalcopyrite and the wall rocks are biotite altered (Fig. 4.15D). At higher elevations, acicular tourmaline is intergrown with chalcopyrite cement, biotite is absent, copper assays are consistently > 2%, and the wall rocks are phyllic-altered. A similar vertical zonation, grading from biotite-stable at depth to tourmaline and sericite-stable at higher elevations, has been described from the Sur - Sur breccia complex at the Río Blanco deposit, 100km north of El Teniente (Frikken 2004; Frikken et al., submitted).
Figure 4.15. LM vein and breccia styles. Scale bars in core photographs = 2cm, and in microphotographs = 1mm. Refer to Fig. 4.1 for abbreviations.

A) Biotite breccia containing subrounded felsic and mafic clasts in a matrix composed of biotite, anhydrite, feldspar, quartz and sulfides (ET69, DDH1689, 139').

B) Contact between andesite porphyry (right) and biotite breccia (left). The breccia contains variably biotite and early magnetite altered local wall rock clasts in a hydrothermal biotite-rich cement containing variable copper-Mo-sulfides. Minor quartz vein fragments are visible at the far left of the photograph (ET112B, DDH1698, 55').

C) Stage 2a quartz veins + minor bornite-chalcopyrite in a dacite pipe. Many stage 2a veins are "wispy". Other have irregular margins (top) or are composed of unconnected chains of euhedral quartz crystals (bottom). Both samples contain greenish aggregates of partially chloritised biotite, and minor disseminated bornite and chalcopyrite (top - ET665, DDH1306, 392', bottom - ET700, DDH1889, 648').

D) Stage 2 biotite-anhydrite-sulfide breccia, composed of anhydrite (white), and intergrown biotite (dark brown) and chalcopyrite (bright yellow) cement infilling between biotite-altered Sewell Diorite clasts (ET825, DDH1680, 1424').

E) Thick stage 2b vein, characteristically zoned with an inner anhydrite, quartz, sulfide, chlorite, sericite seam (A), a biotite-rich selvage (dark grey, B), and a pale grey to white Na-K-feldspar halo (C). A weakly developed outermost biotite halo is also present in this sample. Chalcopyrite is present in all the zones of the vein. The vein cuts a variably-biotite-altered andesite porphyry (ET265, DDH1529, 766').

F) Stage 2b veins with a visible Na-K-feldspar halo, cut by straighter, more continuous stage 2c veins without a halo. Stage 2b and 2c veins are the main stockwork-forming veins (Sub-6 mine metallurgical core).

G) Characteristically zoned stage 2b veins with a pale Na-K-feldspar halo, cut by straighter stage 2c quartz veins which lack halos (ET102, DDH1689, 1030').

H) Microphotograph of a stage 2b vein, composed of an inner seam of sericite and carbonate altered feldspar, and remnant chalcopyrite intergrown with biotite. The halo is composed of Na-K-feldspar, quartz, anhydrite, and chalcopyrite, overprinting biotite alteration. The sericitic seam is interpreted to be due to re-opening of the vein and influx of sericite-stable fluids, causing biotite and sulphide dissolution, and sericitisation of the feldspars (ET77, DDH1689, 364'. PP).

I) Stage 2b vein, formed in two stages. An early vein assemblage of Na-K-feldspar-quartz-anhydrite-chalcopyrite (poikilitically enclosing quartz and feldspar) has cut biotite-altered Teniente hist sequence. The vein was subsequently reopened, and a sericite-chalcopyrite assemblage precipitated. Note the dissolution of early chalcopyrite by later stage sericite (ET705, DDH1463, 201'. XP).
Chapter 4. Mineralised veins, breccias and altered rocks
Stage 2b (Na-K-feldspar) veins

Stage 2b veins are 3mm - 3cm wide, and are characteristically zoned from a central seam of quartz, anhydrite, chlorite, sulfides, ± green sericite, with a thin biotite selvage (Fig. 4.15E). Stage 2b veins are distinguished from other LM vein types by their diffuse outermost pale grey Na-K-feldspar halo, composed of fine anhedral granoblastic labradorite to albite (Ab$_{44-96}$; Appendix 2), sodic alkali-feldspar (Or$_{13-29}$), K-feldspar (Or$_{85-91}$), quartz, ± anhydrite, rutile, sulfides, sericite, and carbonate. (Figs. 4.15F and G). Some stage 2b veins have a biotite or chlorite-carbonate altered outer-most halo.

A large proportion of these veins formed in two stages (Figs. 4.15H and I). The first stage involved deposition of quartz, anhydrite, Na-K-feldspar, biotite (locally as a selvage), sulfides, and minor chlorite in a vein with a Na-K-feldspar halo. Sulfides were coprecipitated with biotite (Fig. 4.15H) and/or Na-K-feldspar (Fig. 4.15I). Electron microprobe analyses indicate that the vein biotite has a different composition to the biotite in the selectively pervasive biotite alteration assemblage (Appendix 2C). The second stage involved re-opening of stage 2b veins, and overprinting of the original vein mineralogy by a central sericite-chlorite-sulfide stable assemblage (stage 2 chlorite veins - see below). Early stage plagioclase, biotite and sulfides (bornite and chalcopyrite) were altered to a later stage assemblage of sericite, chlorite, and sulfides (bornite, chalcopyrite; Fig. 4.15I).

On all of the cross sections logged during this study stage 2b veins were found to be abundant at depth, where they are thicker (up to 3cm), have wider Na-K-feldspar halos (Fig 4.14). Pervasive Na-K-feldspar alteration (e.g., proximal to the dacite pipe on section-124, Fig 4.14B) is interpreted to have formed concurrently with stage 2b veins.

Stage 2c (quartz-anhydrite-sulfide) veins

Stage 2c quartz - anhydrite - sulfide (± K-feldspar, plagioclase, rare biotite) veins and veinlets are generally 1mm - 3cm thick (Fig. 4.16A), and locally have biotite alteration halos. These abundant veins are straighter than and lack the internal zonation and Na-K-feldspar alteration halos of stage 2b veins (Figs. 4.15F and G).

Stage 2b and 2c veins are the main components of the Teniente vein stockwork in the deposit, which consists of up to 50 veins + veinlets per metre of core and 30 vol. % of the rock (Fig. 4.1A). The vein stockwork is most intensely developed near the dacite
contacts (e.g., Fig. 4.16B). Stage 2c veins predominate over stage 2b veins at higher elevations on all sections (Fig. 4.14). The stage 2b and 2c veins may be end-members of a spectrum of veins, with some veins appearing to change along strike from one vein stage to the other.

**Stage 2d (anhydrite) breccias**

Stage 2d hydrothermal breccias are cemented by anhydrite ± quartz – sulfides – Na-K-feldspar. The breccias contain clasts of Teniente host sequence and felsic intrusive clasts, and are spatially associated with a pervasive Na-K-feldspar alteration assemblage locally (Fig. 4.16C). Stage 2d breccias typically have high copper grades and occur within the Teniente host sequence adjacent to (and locally within) the dacite pipes, and the dacite porphyry (e.g., Figs. 4.14 and 3.1). Dacite occurs as clasts within the anhydrite breccia, or in some cases as a crystalline igneous groundmass enclosing andesitic wall rock clasts, forming a heterogeneous breccia with an igneous + hydrothermal cement.

**Stage 2e veins**

Stage 2e veins are straight-edged, continuous, 8-60mm thick quartz veins, typically with sulfide seams or selvages (Fig. 4.16D). They are composed of a fine grained anhedral quartz selvage, overgrown by a generation of coarse, subhedral quartz, locally with central voids infilled with chalcopyrite. Molybdenite commonly occurs either within a central suture or as a selvage (Fig. 4.16D). Most stage 2e veins do not have an alteration halo. Others have biotite, Na-K-feldspar, or phyllic halos. Shallow dipping stage 2e veins have been described underground (Russo, pers. comm., 1999). Stage 2e veins are similar to the B veins described by Gustafsson and Hunt (1975) from El Salvador.

**Stage 2f (chlorite) veinlets**

Stage 2f veinlets are thin (<3mm), sulfide-rich veinlets composed of chlorite - chalcopyrite – pyrite ± sericite – anhydrite – quartz, with a chlorite ± sericite alteration halo (Fig. 4.16E). The veinlets occur mainly on the periphery of the deposit (Figs. 4.5 and 4.14), inside and outside of the 0.5 % copper contour. They have also been observed in drillcore under the Agua Amarga prospect (5km SW of Teniente, Fig. 2.5). In the central regions of the deposit, stage 2f vein assemblages have formed central seams in earlier formed LM veins, particularly stage 2b veins. Stage 2-distal veins.
Figure 4.16. LM and PH vein and breccia styles. Scale bar in core photographs = 2cm, and in microphotographs = 2mm.

A) Stage 2c veinlets, composed of a mosaic of anhedral quartz, anhydrite, sulfide and minor Na-K-feldspar, cutting biotite-altered Teniente host sequence (ET19, DDH1738, 13'. XP).

B) Contact between a dacite pipe (left) and the Teniente host sequence (right). A biotite-cemented breccia at the contact contains angular clasts of both Teniente host sequence and dacitic clasts. Strongly developed stage 2b and 2c veins and stage 2d breccias, and pervasive Na-K-feldspar alteration also occur in the Teniente host sequence close to the dacite contacts. The veins display overlapping timing relationships with respect to the dacite and the breccia (Ten-6 metallurgical core).

C) Stage 2d anhydrite-cemented (± quartz-sulfide) breccia. Note the jigsaw-fit texture of most of the clasts. Some of the clasts have been altered to a pale brown Na-K-feldspar (+ minor biotite) assemblage (Sub-6 mine area metallurgical core).

D) Characteristically thick and straight edged Stage 2e quartz vein, with subhedral quartz crystals and a central chalcopyrite and molybdenite seam. Molybdenite occurs mainly as central seams or symmetrical selvages in stage 2e veins (ET598, DDH1525, 231m).

E) Chalcopyrite-bearing stage 2-chlorite veinlets, which are abundant in the transitional and propylitic domains of the deposit, and have opened and infilled stage 2b veins in the proximal biotite domain (ET145, DDH1698, 819').

F) Stage 2-distal veinlet, with an inner assemblage of sericite, chlorite, sulfides, quartz, anhydrite, and a quartz, Na-K-feldspar halo, which is partly sericitised. The feldspar phenocrysts in the Teniente host sequence are partly sericitised near the vein. Sericite needles (± chlorite fans) are intergrown with the sulfides, suggesting equilibrium precipitation. Stage 2-distal veins are abundant in the transitional and propylitic domains and are interpreted to be temporally equivalent to the stage 2b and 2c LM vein stages that occur in the proximal biotite domain of the deposit (ET388, DDH1423, 822').

G) Thick stage 3 vein, with a characteristic chalcopyrite-rich (+ minor pyrite) central seam with minor anhydrite-quartz-chlorite gangue, and a sericite halo containing minor sulfides, chlorite (green) and tourmaline (black) (ET484, DDH1413, 1118').
These veins occur distal to the dacite porphyry, associated with the transitional and the propylitic alteration assemblages on the deposit periphery (Fig. 4.14). They are diffuse-edged veins between 2mm and 4cm thick, composed of quartz, anhydrite, chalcopyrite, pyrite, and ubiquitous sericite and chlorite (Fig. 4.16F). Phyllic and sericitised Na-K-feldspar alteration halos (Fig. 4.16F) occur around stage 2-distal veins. Stage 2-distal veins are interpreted to be the distal equivalents of the proximal stage 2 veins that define the mineralised El Teniente stockwork.
Paragenesis of Late Magmatic veins

The earliest Late Magmatic veins in the Teniente host sequence are stage 2b and 2c veins and veinlets. Stage 2b veins have typically been cut by stage 2c veins (Figs. 4.15F and G, 4.17A); however, the reverse relationship also occurs (Fig. 4.17A). Stage 2b veins are mostly cut by the dacite contacts (Fig. 3.8D). They are less abundant in the dacite porphyry and dacite pipes than the Teniente host sequence. Some stage 2c veins are terminated at the contacts of the dacite porphyry and dacite pipes (Figs. 4.16B and 4.17B); however, most stage 2c veins cross cut these contacts (Fig. 4.17C). Stage 2d breccias cut and are cut by stage 2b and 2c veins (Fig. 4.17D). The stage 2b veins, 2c veins and 2d breccias are interpreted to have a broadly contemporaneous age of formation, overlapping with the timing of dacite intrusion. The inconsistent cross-cutting relationships between stage 2b and 2c veins, 2d breccias and dacite contacts indicates that multiple (and possibly cyclical) stages of vein formation, and/or dacite intrusion occurred.

Stage 2e veins crosscut stage 2b, 2c, and 2d veins. Stage 2f veinlets post date all LM stage veins, except some stage 2e veins, based on cross cutting relationships.

Rare LM veins have cross-cut the LM anhydrite - chalcopyrite - biotite breccia, indicating it has an early LM timing. However, the temporal relationship between the breccia and stage 2a, 2b, 2c, and 2d veins could not be confidently assessed due to the location of the breccia near the deposit periphery.

Zonation of Late Magmatic veins

Vein assemblages, like the alteration assemblages (Fig. 4.14), are zoned laterally in the deposit (Table 4.2). Biotite and Na-K-feldspar stable vein assemblages (stage 2a, 2b, 2c, 2d, 2e veins and breccias) occur in the potassic zone in the deposit centre, whereas sericite – chlorite stable vein assemblages (stage 2-distal, stage 2f-chlorite) occur at the deposit periphery, in the transitional potassic-propylitic and the propylitic zones.

LM vein abundance is highest in the potassic zone, where vein densities are up to 50 veins + veinlets/m core, comprising up to 30% of the rock volume (Fig. 4.18). The abundance decreases away from the dacite porphyry, to a typical value of around 20-30 veins + veinlets/m core in the transitional zone down to <20 veins + veinlets/m in
Figure 4.17. Vein and intrusive paragenetic relationships.

A) Stage 2b vein (anhydrite, quartz, sulfide, chlorite, biotite vein with Na-K-feldspar halo), cutting a stage 2c quartz-anhydrite-sulfide veinlet, and cut by a stage 2c quartz-anhydrite-chalcopyrite-molybdenite vein. This illustrates the overlapping timing relationships between stage 2b and 2c veins (ET449, DDH1429, 1820').

B) Contact between dacite porphyry and biotite breccia. Stage 2c (quartz, anhydrite, sulfide) veinlets crosscut by dacite porphyry contact. Note wallrock clast with stage 2c veinlet cut at clast margin (ET21, DDH1738, 59').

C) Stage 2c (quartz-anhydrite-chalcopyrite-bornite-molybdenite) veinlets crosscutting a biotite breccia containing dacite porphyry clasts. The veinlets cut the dacite clast contacts. Na-K-feldspar alteration haloes are sporadically developed around the veinlets (ET14, Underground specimen, 850N, 620E, 2354m elevation).

D) Stage 2d anhydrite breccia, cut by stage 2c quartz-bornite veinlets. A stage 3 chalcopyrite-quartz vein with a sericite-chlorite halo cuts all the vein types. (ET670, DDH1689, 178')

E) Stage 2c vein network cross cut by a stage 3 anhydrite-chalcopyrite vein with sericite-chlorite halo (ET36, DDH1738, 541')

F) Stage 2-distal veins (quartz-anhydrite-chlorite-sulfide veins with sericite-chlorite halos), cut by Late Hydrothermal stage 4c breccia (chlorite-chalcopyrite-anhydrite cemented breccia with a sericite-chlorite halo). This photograph illustrates the multiple nature of sericite-chlorite alteration events at El Teniente (ET628, DDH1565, 233.5m).

the propylitic zone (<10% of the rock volume). Localised zones of abundant LM veins occur around the dacite pipes (Fig. 4.18A and B) and proximal to the grey porphyry (Fig. 4.18B).

4.5 STAGE 3 - PRINCIPAL HYDROTHERMAL STAGE

The Principle Hydrothermal (PH) stage is characterised by chalcopyrite-rich veins
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Figure 4.18. LM vein + veinlet abundance for the three main logged sections. Note that a degree of ambiguity exists in distinguishing the LM veins from the PH veins in the transitional and propylitic domains, due to the similarity in vein mineralogy, and re-opening of LM veins by PH veins.

A) Section-83. High LM vein densities (up to 50 veins + veinlets/m core) occur close to the dacite porphyry, and locally around the dacite apophyses. LM veins decrease in intensity away from the dacite porphyry, down to <20 veins + veinlets/m core in the propylitic domain.

B) Section-124. High vein densities occur close to the dacite porphyry (west of the section), and locally around and down dip from the dacite pipes. To the east, LM vein intensity gradually decreases. Moderate vein intensities occur around the grey porphyry due to LM biotite-anhydrite-sulfide breccias and veins developed around this body.

C) Section-239. High vein densities occur in the proximal biotite zone close to the Braden Pipe and decrease to the south. DDH1981, located in the south of the section, intersected the lowest LM vein densities encountered in the deposit, <5 veins + veinlets/m core, representing the outermost limit of LM vein penetration. Biotite alteration is con-
Potassic zone | Transitional potassic - propylitic zone | Propylitic zone
--- | --- | ---
Location | Proximal to dacite porphyry and locally around dacite pipes | Distal from dacite porphyry, and >2200m elevation | Deposit periphery, near and extends beyond the 0.5% Cu limit.
Dominant pervasive alteration assemblage | Biotite alteration assemblage | Transitional potassic - propylitic assemblage | Propylitic assemblage
Other alteration types | Pervasive Na-K-feldspar alteration | Pervasive phyllic alteration, vein controlled Na-K-feldspar alteration | Rare phyllic (phengitic sericite), early magnetite ± epidote
Dominant vein / breccia type | Stage 2a-2e, biotite - anhydrite - sulfide type 2 breccias, biotite breccias | Stage 2-distal, stage 2f-chlorite, type 3 | Stage 2f-chlorite, stage 2-distal
Vein intensity | High | Medium-high | Low
Sulfides | Chalcopyrite and bornite | Chalcopyrite and pyrite | Pyrite ± chalcopyrite pyrrhotite inclusions
Phyllosilicate mineral intergrown with sulfides | Biotite | Sericite and chlorite | Chlorite ± sercite
Cu and Mo grades | High Cu (>1%) and Mo (>0.01%) | High-moderate Cu (mostly >1%), moderate Mo (mostly 0.01 - 0.03%) | Low Cu (< 0.5%), and Mo (<0.01%)

Table 4.2. Summary of the vein and alteration assemblages for each of the alteration zones at Teniente.

Associated with vein-controlled and pervasive phyllic alteration. These veins and alteration assemblages have cross cut all the LM stage veins and alteration assemblages (Fig. 4.17E). Chalcopyrite is the dominant sulfide mineral precipitated during the PH stage, with accessory pyrite and molybdenite. Bornite is notably absent from PH-stage veins.

**Principal Hydrothermal stage phyllic alteration**

The phyllic alteration assemblage occurs as bleached halos to PH and LH veins in both the Teniente host sequence (Fig. 4.19A) and in the felsic intrusions (Fig. 4.19B) and also as pervasive alteration zones in the peripheral zones of the deposit. PIMA analyses indicate that the sericite has AlOH peak wavelengths characteristic of slightly paragonitic to slightly phengitic muscovite. Secondary anhydrite, sulfides (up to 5%, typically enclosing sericite needles), rutile, K-feldspar, zircon, sphene, tourmaline (dravite), and apatite are accessory phases. Phyllic vein halos are typically zoned from inner sericite to outer chlorite (Figs. 4.17E and 4.19C). Weak phyllic alteration is manifested as selective sericitic alteration of plagioclase, typically accompanied by carbonate. Moderate phyllic alteration is marked by breakdown of secondary biotite and relict mafic minerals to sericite ± chlorite-quartz-sulfides. Strongly phyllic-altered intervals (e.g., adjacent to the PH vein in Fig. 4.19C) are composed of sericite (up to 90%), quartz (5-20%), chlorite (0-10%), and sulfides up to 5%. 99
Selectively pervasive phyllic alteration is weakly developed through the most of the dacite porphyry and dacite pipes, and is moderately developed in most of the Sewell Diorite. Biotite phenocrysts are altered to sericite, chlorite, and carbonate, focused along the cleavage planes. Sericite has preferentially altered calcic plagioclase, and to a lesser degree Na-feldspar, whereas K-feldspar is typically unaltered.

PH-stage phyllic alteration is focused in the transitional zone (Fig. 4.20). Pervasive phyllic alteration (>20% of rock volume) occurs at elevations above 2,100m in the transitional zone and strong pervasive alteration (>60%) only occurs higher than ~2,200m elevation. There is only significant pervasive phyllic alteration below 2,200m on the western side of section-83 (Fig. 4.20A). In most of the deposit phyllic alteration has been confined to centimetre-scale halos around stage 3 veins. Phyllic alteration
Section-83, Principal Hydrothermal phyllic alteration intensity

A) On the western side of the dacite porphyry there is a good correlation between stage vein intensity (Section 4.8A), and phyllic alteration intensity, which increases in the transitional zone to form a planar zone of near massive phyllic alteration at the western edge of the deposit. On the eastern side the phyllic alteration intensity increases peripherally from the dacite porphyry, and also increases vertically. Zones of pervasive alteration (solid colours) are restricted to elevations above ~2,100m elevation. Below this level the phyllic alteration occurs as vein halos (lines and dashes). Richly Cu-mineralised stage 3 veins persist to the deepest levels, however these veins have phyllic halos that are thin to entirely absent.

B) Section-124. Pervasive phyllic alteration (solid colours) is restricted to elevations above 2,200m, focused in the transitional domain. In the proximal biotite domain and the propylitic domain, phyllic alteration is confined to vein halos (lines and dashes). Phyllic alteration is very weakly developed at depth to the west, despite the presence of richly mineralised stage 3 veins.

C) Section-239. Pervasive phyllic alteration (solid colours) is restricted to levels above 2,100m, focused in the transitional domain. In the potassic zone, PH stage phyllic alteration occurs as vein halos (lines and dashes).

Figure 4.20. PH-stage phyllic alteration intensity. Pervasive phyllic alteration (comprising 20 - 100% of the rock volume) is indicated by solid colours. Lines and dashes indicate phyllic alteration occurs as vein halos.
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Section 83, Principal Hydrothermal vein intensity

Figure 4.21. PH vein + veinlet abundances, based on vein counting from during core logging. As for Fig. 4.19, it is somewhat ambiguous distinguishing the LM veins from the PH veins in the peripheral potassic zone and the propylitic zone, due to the similarity in vein mineralogy, and the common re-opening and altering of LM veins by later PH veins. A) Section-83. PH veins are only weakly developed near the dacite porphyry, especially at depth. PH vein abundance increases away from the dacite porphyry, and vertically upwards, reaching a maximum (>20 veins + veinlets/m core) in the transitional domain. Distally, in the propylitic domain, phyllic vein abundances decrease abruptly. B) Section-124. PH veins are concentrated in the transitional domain, where these can be up to 30 veins + veinlets/m core. At depth to the west of the section, proximal to the Braden Pipe, phyllic veins are absent. C) Section-239. PH veins are focused in the transitional domain, and decrease in intensity at depth, towards the dacite porphyry (to the east of the section), and distally towards the propylitic domain.
intensity decreases with depth, to the extent that chalcopyrite-rich stage 3 veins adjacent to the dacite porphyry deep in the deposit do not have phyllic halos (Figs. 4.20A and B).

**Principal Hydrothermal stage veins**

*Stage 3 veins*

Stage 3 veins are similar to the classic D veins of Gustafson and Hunt (1975). They are planar, continuous veins of chalcopyrite (± pyrite) with accessory quartz and anhydrite gangue and are between 2mm and 3cm thick (Figs. 4.16G, 4.17E, and 4.19A). Pyrite predominates over chalcopyrite in stage 3 veins at the deposit periphery. Stage 3 veins have phyllic alteration halos (sericite ± chlorite, quartz, sulfides, ± minor tourmaline, rutile, anhydrite, carbonate) up to 10cm wide, typically zoned from inner sericite to outer chlorite (Figs. 4.19A and C).

Stage 3 veins occur at lower abundances (generally <3 veins/m core, and <20 veinlets/m core; Fig. 4.21) than the LM veins. However, due to the chalcopyrite-rich nature stage 3 veins host a significant proportion of copper in the deposit (approximately 30% visual estimate; see below). The stage 3 veins are only weakly developed within 200m of the dacite porphyry contact and show a progressive increase in abundance towards the transitional zone, before decreasing in the propylitic zone. PH vein abundances generally increase with increasing elevation (Fig. 4.21).

### 4.6 STAGE 4 – LATE HYDROTHERMAL STAGE

The PH stage has been overprinted by the Late Hydrothermal (LH) stage, a second phyllic stage that is associated with the Braden Pipe and late dacite intrusions. LH veins are less abundant than, and consistently post-date LM and PH veins (Fig. 4.17F). LH veins have a diverse sulfide mineral assemblage, including bornite, chalcopyrite, pyrite, and minor stibnite, galena, sphalerite, and enargite. Tenantite-tetrahedrite are also present, which vary compositionally from the arsenic-rich end member (Tet 0.0) to the antimony-rich end member (Tet 95.0), with most of analyses near one of the two end-member compositions (Araya et. al., 1977). Gangue minerals include quartz, anhydrite, tourmaline, gypsum, barite, and carbonates (calcite, dolomite, siderite, ankerite).
Late Hydrothermal stage phyllic alteration

LH veins and breccias have phyllic alteration halo and are in some cases associated with pervasive phyllic alteration. The LH- and PH-stage phyllic assemblages are macroscopically similar and were distinguished during logging mainly by their associated vein types. In general, the LH-stage phyllic assemblage contains less chlorite and quartz and more accessory tourmaline than the PH-stage phyllic assemblage. PIMA analyses (this study) indicate that LH sericite is more illitic (based on a deeper OH\textsuperscript{−} trough) and more phengitic (based on AlOH peak wavelength) than the PH stage sericite, which contains more muscovite. Kaolinite was identified in a single LH vein halo and in clasts within the Braden Pipe. Pyrophyllite was reported by Camus (1975), although it was not detected in the current study.

LH veins and alteration assemblages are more strongly developed in the south than in the north and central portions of the deposit. Of the three logged sections, LH stage veins and related phyllic alteration assemblages are best developed on section-239 (Fig. 4.22). LH veins and alteration assemblages are almost absent on section-83 and most of section-124. LH alteration intensity (Fig. 4.22B) is greatest within 100m of the Braden Pipe on section-239 and decreases distally and with depth. Pervasive phyllic alteration) occurs locally around LH stage breccias and extends up and down dip from them (Fig. 4.22B). Strong pervasive LH phyllic alteration occurs at shallow depths.

Late Hydrothermal stage veins and breccias

Stage 4a (tourmaline) veins and breccias

Stage 4a veins and breccias are filled with tourmaline, anhydrite, chalcopyrite, and minor accessory quartz, and gypsum, with a pale sericitic halo (Fig. 4.23A). The acicular tourmaline has grown from the walls into open space, which was subsequently filled by anhydrite and chalcopyrite. The veins are planar, mostly 2mm to 2cm, locally occurring as crackle breccia zones (Fig. 4.23A). Stage 4a veins are similar mineralogically and texturally to the Marginal Breccia facies of the Braden Pipe and also to an irregularly shaped tourmaline - anhydrite - sulfide-cemented breccia body approximately 100m wide in the Ten-4 sur mine area. Stage 4a breccias occur as rare clasts within the Braden Breccia (Camus, 1975; Floody, 2000).
Section-239, Late Hydrothermal
vein intensity

- Strong, semi-massive
- Weak (3-6 veins/m core)
- Trace (<3 veins/m core)

U1llll blac!Qidela1!on zones

Section-239, Late Hydrothermal
alteration intensity

- >60%
- 40-60%
- 10-20%
- 5-10%
- 2-5%

Figure 4.22. LH stage veins and related phyllic alteration assemblages are best developed on Section-239, and therefore only this section is used to illustrate the spatial distribution of this stage.

A) LH vein abundance, which is highest (up to 15 veins + veinlets/m core) within about 100m of the Braden Pipe, and decreases distally and with depth. Vein abundance is also high in the zones of stage 4c breccia associated with the late dacite dykes.

B) LH phyllic alteration intensity. Pervasive phyllic alteration (20-100% of the rock volume; solid colours) is associated with the stage 4c anhydrite breccias, and also occurs at high elevations (above 2,300m) on the section. Vein-controlled phyllic alteration (lines and dashes) decreases in intensity away from the Braden Pipe, and decreases with depth.

C) LH vein styles. Stage 4a tourmaline-bearing veins occur through the section, but are relatively weak close to the Braden Pipe, possibly due to overprinting and re-opening by later LH veins. Stage 4b veins occur proximal to the Braden Pipe, extending up to 300m away from it. Bornite is stable in these veins proximal to the pipe, and molybdenite is the predominant sulfide mineral further out. Note that the edge of significant molybdenum mineralisation (>0.01% Mo) coincides with the outer limit of the stage 4b veins. High grade (>1.5 % Cu) stage 4c anhydrite breccias are developed in two steeply dipping zones associated with late dacite dykes. Stage 4c and stage 4d veins are weakly distributed across the whole section, including the Braden Pipe.
A) Stage 4a tourmaline breccia, cemented with tourmaline needles that have grown from the walls and clasts, intergrown with chalcopyrite. Anhydrite and gypsum have filled the remaining open spaces. The breccia clasts and wall rock have been phyllically altered (ET520, DDH1418, 1089').

B) Stage 4c breccia, with a hydrothermal quartz-bornite cement (left), and anhydrite-molybdenite cement (right), and phyllic (sericite-chlorite) alteration of the angular wall rock clasts. These samples are from the distal stage 4c breccia zone on section-239 (Fig. 4.4C) that assayed 30m @ 4.65% Cu and 0.51% Mo (left - ET404, DDH1423, 1518', right - ET405, DDH1423, 1530').

C) Stage 4c vein, composed of chalcopyrite and pyrite rimmed by tennantite-tetrahedrite (grey), surrounded by carbonate - quartz gangue (white), with a thin tourmaline vein selvage, and a sericite (+ minor tourmaline) halo (andesite porphyry, ET459, DDH1413, 179').

D) Gypsum mega-crystals, some of which are up to 6m long, from a crystal cavern in the Braden Pipe on the Ten-8 level. Lining the walls of these caverns are aggregates of euhedral barite, siderite, quartz, apatite, pyrite, sphalerite, chalcopyrite, tennantite and galena. These minerals were precipitated from LH-stage fluids circulating through the Braden Pipe, remnants of which are trapped in the gypsum mega-crystals as fluid inclusions tens of centimetres long.

Stage 4b veins

Stage 4b veins are thin quartz-anhydrite-sulfide (± chalcopyrite-bornite-molybdenite) veins and veinlets with a phyllic halo. Stage 4b veins are similar to stage 3 veins, but they have cut stage 4a veins and commonly contain bornite in addition to chalcopyrite. Stage 4b molybdenum-dominated veinlets occur both inside and outside the Braden Pipe.

Stage 4c veins

Stage 4c veins and breccias are mineralogically variable, containing anhydrite, quartz, gypsum, tourmaline, barite, chalcopyrite, bornite, pyrite, tennantite-tetrahedrite, molybdenite, and rare sphalerite, galena and enargite (Figs. 4.23B and C). They are mostly between 5mm and 5cm thick and have sericite-chlorite alteration halos. Richly mineralised stage 4c anhydrite - bornite - chalcopyrite (± molybdenite) breccias (e.g., Fig. 4.23B) occur on section-239 (Fig. 4.4C). Most of the faults that can be mapped underground (Chapter 5) contain this infill assemblage. Stage 4c veins oc-
Chapter 4. Mineralised veins, breccias and altered rocks

cur in the Braden Pipe at a lower intensity than outside the pipe.

Spectacular mega-crystal-filled caverns which occur in the Braden Pipe (Fig. 4.23D) are attributable to stage 4c hydrothermal activity. They contain subhedral and euhedral crystals of various sulphates, carbonates, quartz, apatite, tennantite-tetrahedrite, sphalerite, chalcopyrite, galena, and pyrite (Camus, 1975; Floody, 2000). Euhedral gypsum crystals up to 6m long have grown into open spaces, and the cavern walls are lined with crystalline gangue and sulphide minerals (Fig. 4.23D). The caverns are up to 300 cubic metres in volume, and some of them were filled with water when first intercepted during mining development.

Stage 4d (gypsum-chlorite) veinlets

Stage 4d veins are the final vein stage recognized at Teniente. They cut all rock types at Teniente. Stage 4d veinlets are thin gypsum-chlorite dominated veinlets and fracture coatings, commonly with slickenslides. Geotechnically these fractures are important, as the presence of these two soft gangue minerals in fractures has the potential to decrease the bulk strength of the rock.

Spatial zonation of Late Hydrothermal veins

LH vein abundance (Fig. 4.22A) correlates with LH alteration intensity (Fig. 4.22B), decreasing away from the Braden Pipe and with depth on section-239. Stage 4a (tourmaline) veins occur across the entire section (Fig. 4.22C), with a lower abundance close to the Braden Pipe, possibly due to overprinting and reopening by later LH vein generations. Stage 4b veins are spatially restricted to within 300m of the Braden Pipe (Fig. 4.22C). Sulfides in these veins are zoned from bornite, chalcopyrite, and molybdenite close to the pipe, to molybdenum and accessory chalcopyrite further out. Stage 4c and 4d veins are weakly distributed across most of the section, including within the Braden Pipe. The distal richly-copper mineralised stage 4c breccia zone is associated with a late dacite dyke and a pebble dyke, and is surrounded by stage 4c molybdenite-chalcopyrite-bearing veinlets.

Late Hydrothermal sulfide zonation

The zonation of sulfides and sulfosalts in LH veins and breccias is bornite (± tennantite, molybdenite, base metals) closest to the Braden Pipe, passing to chalcopy-
rite (± molybdenite), and to outermost pyrite (Fig. 4.24). Bornite and tennantite-tetrahedrite occur in LH veins up to 200m from the Braden Pipe, whereas molybdenite extends out to 300m from the pipe. This zonation pattern is disrupted by the distal stage 4c anhydrite/sulfide breccia zone, which contains abundant bornite, chalcopyrite, molybdenite and minor tennantite. Throughout the deposit there is a strong association between pyrite and tennantite in LH veins (e.g., Fig. 4.23C).

Distance from Braden Pipe

<table>
<thead>
<tr>
<th>Distance from Braden Pipe</th>
<th>0m</th>
<th>100m</th>
<th>200m</th>
<th>300m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfide zonation</td>
<td>Bn&gt;cp&gt;tenn/mo (+base metals)</td>
<td>Cp&gt;bn&gt;</td>
<td>Cp&gt;py&gt;</td>
<td>Cp&gt;py/imo</td>
</tr>
<tr>
<td>Summary</td>
<td>Bn/tenn/mo</td>
<td>tenn/mo</td>
<td>tenn/mo</td>
<td>Py/tenn/mo</td>
</tr>
</tbody>
</table>

Figure 4.24. Sulfide zonation in LH stage veins relative to the Braden Pipe, based on section-239.

Mineralisation in the Braden Pipe

The Braden Breccia has historically been regarded as sterile (e.g., Camus, 1975). Due to the highly competent and low grade nature of the Braden Breccia, most of the underground developments such as offices and the decline are located in the breccia unit. However, a resource calculation for the Braden Breccia (not including the Marginal Breccia) indicates a total resource of 5.3 Gt @ 0.46 % copper, including 96.6 Mt @ 1.16 % copper with a cutoff grade of 0.7 % copper (Floody, 2000). Floody (2000) reports that high copper grades are related to tourmalinisation (± chalcopyrite, quartz) in the Braden Breccia. The alteration and mineralisation occurs within and around internal concentric (Fig. 3.10) and planar structures within the pipe. These zones of tourmalinisation are interpreted to be due fracture networks that focused late stage fluids. Tourmaline alteration along the margin of the pipe is responsible for the apparent gradational contacts between the Braden Breccia and the Marginal Breccia (Floody, 2000). Minor mineralised stage 4b and stage 4c veins and veinlets occur in the Braden Breccia and Marginal Breccia, where they are concentrated at the margins of the pipe.

4.7 Supergene Stage

A supergene zone is developed between 100m and 600m depth below the pre-mining surface at El Teniente (e.g., Cuadra, 1986). It is composed of an uppermost leached zone, and a lower enriched zone. A variety of copper minerals occur in the high-grade upper portion of the enriched zone, including chrysocolla, malachite, azurite, cuprite, brochantite, antlerite, and calcophyllite (Cuadra, 1986). Chalcocite and
covellite are the main secondary copper minerals at depth. The supergene argillic alteration assemblage is composed of kaolinite, and lesser montmorillonite, alunite, and relict sericite (Camus, 1975). It coincides with the zone of supergene hydration of anhydrite to gypsum. Supergene argillic alteration and secondary chalcocite enrichment is concentrated in the south end of the deposit (Ojeda et al, 1980), and penetrates to greatest depths along the margins of the felsic intrusive bodies and the Braden Pipe.

4.8 Metal Contents of the Main Paragenetic Stages

Copper

During core-logging the relative proportion of copper (in % of total) contained in LM, PH, and LH stage vein and alteration assemblages was visually estimated over 15m intervals. These data has been contoured to illustrate the relative proportion of copper in the different paragenetic stages (Fig. 4.25). In the potassic zone on each section, stage 3 PH-stage veins host between 5 and 40% of the copper. LM stage veins and alteration assemblages host the remainder of the copper in the potassic zone on section-83 (Fig. 4.25A). LH veins are rare on section-83, and contribute little to the total metal budget. For sections-124 and -239 (Figs. 4.25B and C), LM and LH vein, breccia, and alteration assemblages host the remainder of the copper in the potassic zone.

Many LM and PH veins in the transitional domain are difficult to differentiate, and have experienced a complicated history of reopening and overprinting. Therefore, identifying vein generations and relative proportion of copper contribution is difficult both in the transitional domain and to a lesser extent in the propylitic domain. In the transitional potassic-propylitic zone, it is tentatively estimated that up to 80% of the copper is hosted by strongly developed PH-stage stage 3 veins, veinlets and phyllic alteration assemblages. In the propylitic domains of each section stage 2f-chlorite and stage 2-distal veins predominate over stage 3 PH veins, and host more than 50% of the Cu.

For the whole deposit, approximately 60% of the copper is estimated to be hosted in LM vein, breccia, and alteration assemblages, 30% in PH-stage vein and alteration assemblages, and approximately 10% is associated with LH vein, breccia, and alteration assemblages (Table 4.3).
Chapter 4. Mineralised veins, breccias and altered rocks

Section-83, % Cu hosted in Principal Hydrothermal vein - alteration assemblages

A) Section-83. In the central portions of the section, proximal to the dacite porphyry, phyllic veins are uncommon and contain a relatively small percentage of the copper-sulphides (10-40%). In this zone the LM veins host most of the copper. In the transitional zone the stage 3 veins become more abundant, and host a larger proportion of the copper. In the outermost propylitic zone, stage 3 veins are relatively rare, and most of the copper is hosted by LM stage 2-chlorite veins. As there are only trace LH veins on section-83, then the remainder is hosted primarily in LM veins and alteration assemblages.

B) Section-124. On the western (left) side of the section, PH veins are uncommon, and the LM and LH veins contain most of the copper. In the transitional domain the stage 3 veins are abundant, and host a large percentage of the copper. Zones of >60% PH copper only occur in the zones of intense pervasive phyllic alteration, possibly due to stripping of earlier formed copper during the PH stage. Proximal to the grey porphyry close to and within the Sewell Diorite, stage 3 veins are still strong and contribute approximately 50% of the copper in these intervals. Distally, at the eastern edge of the section, stage 3 veins are rare and host a lesser proportion of the copper.

C) Section-239. On the west side of the section phyllic veins are uncommon and contain a relatively small percentage of the copper-sulphides (<40%). In this zone the LM veins and the LH veins contain most of the copper. To the east, stage 3 veins become more abundant, and host a larger proportion of the copper. Outside of the deposit limits, only minor copper is contained in PH vein and alteration assemblages.

Figure 4.25. Relative proportion of copper (in % of total) contained in PH-stage veins and alteration assemblages.

A) Section-83. In the central portions of the section, proximal to the dacite porphyry, phyllic veins are uncommon and contain a relatively small percentage of the copper-sulphides (10-40%). In this zone the LM veins host most of the copper. In the transitional zone the stage 3 veins become more abundant, and host a larger proportion of the copper. In the outermost propylitic zone, stage 3 veins are relatively rare, and most of the copper is hosted by LM stage 2-chlorite veins. As there are only trace LH veins on section-83, then the remainder is hosted primarily in LM veins and alteration assemblages.

B) Section-124. On the western (left) side of the section, PH veins are uncommon, and the LM and LH veins contain most of the copper. In the transitional domain the stage 3 veins are abundant, and host a large percentage of the copper. Zones of >60% PH copper only occur in the zones of intense pervasive phyllic alteration, possibly due to stripping of earlier formed copper during the PH stage. Proximal to the grey porphyry close to and within the Sewell Diorite, stage 3 veins are still strong and contribute approximately 50% of the copper in these intervals. Distally, at the eastern edge of the section, stage 3 veins are rare and host a lesser proportion of the copper.

C) Section-239. On the west side of the section phyllic veins are uncommon and contain a relatively small percentage of the copper-sulphides (<40%). In this zone the LM veins and the LH veins contain most of the copper. To the east, stage 3 veins become more abundant, and host a larger proportion of the copper. Outside of the deposit limits, only minor copper is contained in PH vein and alteration assemblages.
Chapter 4. Mineralised veins, breccias and altered rocks

Table 4.3. Visual estimates of the relative proportion of copper (in % of total) contained in LM, PH and LH vein and alteration assemblages, for the three main sections logged, with estimated error ranges.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Relative proportion of Cu hosted by each stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>section-83</td>
</tr>
<tr>
<td>Late Magmatic</td>
<td>65 ± 10%</td>
</tr>
<tr>
<td>Principal Hydrothermal</td>
<td>35 ± 10%</td>
</tr>
<tr>
<td>Late Hydrothermal</td>
<td>&lt;5%</td>
</tr>
</tbody>
</table>

Molybdenite

Molybdenite is the only molybdenum-bearing phase at El Teniente, and occurs in LM, PH, and LH veins. The proportions of molybdenite hosted by each stage was not estimated during logging. Instead, the presence and form of molybdenite in each vein stage was recorded from the ~1,000 core samples bought back from the field (Fig. 4.26) to qualitatively estimate the relative molybdenum abundance for each vein stage. Molybdenite in the Teniente deposit occurs in the following forms:

- Thin, mono-mineralic centre-line seams or selvages to veins (e.g., Fig. 4.1C, 4.16D)
- disseminations in quartz and anhydrite veins
- thin mono-mineralic veinlets (with or without a phyllic halo)
- semi-massive or irregular vein / breccia fill (Fig. 4.23B)
- rare disseminations in the wall rocks or biotite breccias

Molybdenite in LM and PH veins and breccias typically occurs in isolated crystals or veinlets, only rarely in contact with Cu-Fe sulfides. More stage 2b and 2e veins contained molybdenite than any other vein types sampled in the current study (Fig. 4.26). Many stage 2b veins contain disseminated molybdenite, while for stage 2e veins molybdenite-only selvages and seams are the most common morphology. The relative abundance of molybdenite in stage 2e veins is emphasized, as these veins are much less abundant than the stage 2b veins. Several stage 2e veins contain semi-massive molybdenite fill in veins up to 1cm wide. High molybdenum grades around the grey porphyry (Fig. 4.4B) indicate that the LM stage biotite-anhydrite-sulfide veins and breccias surrounding the grey porphyry contain significant molybdenum. Molybdenite-only veinlets, with or without a phyllic halo, also contain significant molybdenum. Stage 3 PH-stage veins contain moderate amounts of molybdenite, mainly as selvages and seams.

Significant molybdenum is hosted by LH stage structures, especially stage 4c veins and breccias (Fig. 4.26). A stage 4c breccia on section-239 (Fig. 4.4C) contains semi-
massive molybdenite (+ anhydrite, Cu-Fe sulfides, and sulfosalts) in the cement (Fig. 4.23B). In contrast to the LM and PH stages, LH-stage molybdenite is commonly intergrown with Cu-Fe sulfides. Stage 4b molybdenite-only veins occur in the Teniente host sequence, the Braden Pipe, and the late dacite body that forms the roots of the Braden Pipe. On section-239 the 0.01% molybdenum contour coincides with the outer limit of stage 4b veins (Fig. 4.22C). The concentric zone of molybdenum enrichment at 100-200 m distance from the Braden Pipe (Fig. 4.3B) may be the result of a concentration of stage 4b and 4c veins concentric to the Braden Pipe. Alternatively it may be a result of concentric LM-stage molybdenite-bearing veins focused around a deep magma chamber below the pipe (discussed further in Chapter 5).

### 4.9 MAGNETITE AND BIOTITE CHEMISTRY

Magnetites and biotites were analysed using a Cameca SX50 electron microprobe at the Central Science Laboratory, University of Tasmania, in order to investigate spatial and/or temporal compositional variations in mineral chemistry. Analytical data are contained in Appendix 2. Magnetites were classified as relict magnetite, premineralisation stage magnetite, and magnetite intergrown with pyrite and chalcopyrite. Although the relict magnetite crystals display disequilibrium textures within the potassic and propylitic altered rocks (e.g., Fig. 4.11G), they could not be identified as magmatic in origin unambiguously. \( \frac{V_2O_5}{TiO_2} \) and \( \frac{Al_2O_3}{TiO_2} \) ratios for analysed magnetites from
Teniente are shown in Figure 4.27. All of the magnetites have higher ratios than the range of magmatic values of Walshe et al. (2002), suggesting that all of the analysed magnetites were hydrothermal in origin. No consistent compositional differences were identified for the different magnetite generations.

Brown LM stage biotite from the potassic zone is notably more Ti-rich (Ti > 0.25 cation) than the characteristically greenish biotite from the transitional and propylitic domains (Ti cation < 0.25, Fig. 4.28A; Appendix 2C). Magmatic biotite from the dacite porphyry, and secondary biotite from the Sewell Diorite also have high Ti contents (Fig. 4.28B). Ti is inversely correlated to octahedral Al, most likely due to substitution of Ti into this site. A positive linear relationship exists between Ti and Cl, and to a lesser degree, Ti and F (not shown).

Pervasive and vein/breccia hosted biotites have relatively constant Mg numbers from 0.56 to 0.78 (Fig. 4.28C). The most phlogopitic biotites (Mg numbers 0.75-0.78) occur in the Na-K-feldspar assemblage. No consistent relationship exists between Mg number and Ti (Fig. 4.28C). Teniente biotites have variable $V_2O_3/Al_2O_3$ ratios (Fig. 4.28D).

4.10. DISCUSSION

Premineralisation stage

Early magnetite and early phyllic - tourmaline alteration events pre-date mineralization at El Teniente. Both alteration assemblages occur throughout the Teniente district (section 2.4). Veins, veinlets, and breccias with an early magnetite assemblage were observed during the current study at Codegua, La Huifa – Laguna Negra, and Agua Amarga prospects. Tourmaline – quartz - cemented breccias associated with sericite alteration and variable quantities of Cu-Fe-sulfides occur at La Huifa – Laguna Negra, near La Juanita, Agua Amarga, and Los Puquois (Floody and Huete, 1998). Most of these alteration zones are interpreted to be related to the intrusion of the 9-7 Ma Teniente Plutonic Complex (e.g., Floody and Huete, 1998; Section 2.5).

At El Teniente itself, both the early magnetite and early phyllic + tourmaline alteration assemblages appear to be spatially and temporally (?) associated with the Sewell Diorite. In the Sewell Diorite and the La Huifa porphyry, Reich (2000) detected variation in amphibole composition from magmatic magnesium-hornblende (Si < 7.25
Chapter 4. Mineralised veins, breccias and altered rocks

Figure 4.27. $V_2O_3/TiO_2$ vs $Al_2O_3/TiO_2$ ratios for disseminated magnetite at Teniente. The slopes for different $V_2O_3/Al_2O_3$ values are also indicated. High $V_2O_3/Al_2O_3$ values (1.0 - 10) infer oxidizing conditions and low values (0.01—0.001) reduced conditions (Walshe et al., 2003). Relict magnetite is out of equilibrium with the alteration assemblage, however magmatic magnetite was not unambiguously identified. Magmatic and hydrothermal magnetite fields from Walsh et al. (2003). Magnetites from the early magnetite assemblage plot at slightly higher $V_2O_3/Al_2O_3$ ratios than the relict magnetite in potassic-propylitic domains.

Relict
- Early magnetite assemblage
- Intergrown with chalcopyrite
+ Intergrown with pyrite

Figure 4.28. Biotite compositions from El Teniente.
A) Ti (number of cations) vs octahedral Al (Al VI site) for biotite from the potassic zone and transitional-propylitic zone. Brown biotites from the potassic zone have high Ti (Ti > 0.25 cations), and green biotite from the transitional and propylitic zones have low Ti (< 0.25 cation).

B) Ti (number of cations) vs octahedral Al (Al VI site) for primary biotite from the dacite porphyry and for secondary biotite from vein/breccia assemblages and other pervasive alteration assemblages. The igneous biotite from the dacite porphyry plots at highest Ti, and lowest Al VI concentrations.

C) Ti (number of cations) vs magnesium number for biotite.

cations) to secondary actinolite (Si > 7.5 cations). This compositional variation was interpreted to be due to a process of subsolidus deuteric alteration in the presence of an exsolved aqueous fluid (Agemar et al., 1999; Reich, 2000). The secondary actinolites analysed by Reich (2000) have a similar chemistry to the actinolites from the early magnetite assemblage in the Teniente host sequence (this study; Appendix 2). Based on similar timing relationships, similar secondary actinolite compositions from inside and outside the Sewell Diorite, and the broad district-scale spatial association, it is interpreted that early magnetite alteration coincided with intrusion of the regional scale Teniente plutonic complex units, including the Sewell Diorite. Early phyllic - tourmaline veins, breccias, and alteration assemblages are focused proximal to the Sewell Diorite (Figs. 4.5 and 4.8), implying that they were genetically associated with this intrusion and possibly other intrusions that comprise the 9-7 Ma Teniente Plutonic Complex in the Teniente district.

**Time-space evolution**

Most of the copper mineralisation at El Teniente was emplaced during the LM stage. Based on cross-cutting relationships, the LM stage overlapped temporally with felsic to intermediate intrusions dated at 5.7 – 4.8 Ma (Table 3.2). Abundant LM veins and strong biotite alteration intensity occur around the dacite porphyry, dacite pipes, and grey porphyry. Vein and alteration assemblages are zoned laterally around these intrusions, and are also zoned vertically. Biotite- and/or Na-K-feldspar-stable vein and alteration assemblages (bornite-chalcopyrite bearing) occur at depth and proximal to the dacite porphyry, passing laterally and vertically outwards to a chlorite-sericite-stable alteration assemblage, that contains chalcopyrite and pyrite. This mineralogical zonation is interpreted to reflect a thermal and/or chemical palaeo-gradient in outward-migrating magmatic-hydrothermal fluids, possibly due to cooling, interaction with the wall rock, or by mixing with external fluid. The vertical mineralogical zonation suggests thermal zonation upwards and outwards from an underlying magma chamber, from which mineralising fluids and heat were sourced. Sulfide textures indicate a prograding system, with distal pyrite overprinted and replaced by chalcopyrite, and with chalcopyrite replaced by bornite in the centre of the deposit, irrespective of the paragenetic stage.

The observed vein, alteration and sulfide zonations in the deposit are asymmetrically arranged around the dacite porphyry. For example the potassic zone occurs 100-
200m to the west and 400-500m to the east of the dacite contacts (Fig. 4.9), and the 0.5 % copper contour extends on plan view further to the east than to the west (Figs. 3.1 and 4.3). This assymetry may have been caused by:

- Superposition of mineralization and alteration from the dacite pipes into the dacite porphyry hydrothermal system. These pipes only occur east of the dacite porphyry

- Shape of the underlying magma chamber

- Hydrological constraints, such as a preferred fluid flow direction (due to structure, topography, or some other factor as yet unidentified), and/or increased fracture-induced permeability to the east of the dacite porphyry.

Although the mineralogical zonations at a broad scale are centred on the dacite porphyry, north of 1000N the 0.5 % Cu grade contour cuts the dacite porphyry (Figs. 4.3 and 3.1), and potassic alteration passes to propylitic alteration. The dacite porphyry as noted in Chapter 3 is barren where it is exposed on surface 1500m north of the Braden Pipe. These features indicate that the central and northern parts of the dacite dyke acted as no more than passive host rocks. The magmatic-hydrothermal fluids were focused through the southern margin of the dacite porphyry dyke, where it is truncated by the Braden Pipe. This is best explained by the dacite porphyry being a multi-phase intrusion (Chapter 3.3), and implies that the southern subhedral dacite phase of Ossandón (1974) and Rojas (2002) was more intimately involved with copper mineralisation than the northern euhedral phase.

Traditionally the Sewell Diorite has been ascribed an active role in the genesis of El Teniente (e.g., Howell and Molloy, 1960, Camus, 1975, Cuadra, 1986), as high grade LM-stage copper and molybdenum mineralisation and potassic alteration occur at the margins and internally (Figs. 4.4B and 4.9B). The mineralisation in the Sewell Diorite is reinterpreted here to be related to the intrusion of the grey porphyry and porphyritic dacite pipes along the stock margin. Away from these intrusions, the alteration and vein intensities drop markedly, as do the copper and molybdenum grades (Fig. 4.3). These features indicate that the Sewell Diorite was a passive host rock at the time of copper mineralization. It may have formed the pre-mineralisation stages as noted above.
A change in the physico-chemical conditions of the hydrothermal fluid is inferred from resulted in the formation of the sulfide-rich, gangue-poor PH veins associated with phyllic alteration. The main sulfide in PH veins is chalcopyrite, passing distally to pyrite. Bornite is absent. Chalcopyrite:pyrite ratios of LM and PH veins are similar, decreasing concordantly away from the dacite dyke, dacite pipes, and grey porphyry contacts. PH veins are concentrated in the transitional domain of the deposit, where they host a significant proportion of the mineralisation.

The intensity of PH stage phyllic (muscovite-quartz-chlorite) alteration in the deposit varies systematically with distance from the dacite porphyry and elevation (Fig. 4.20). This is in contrast to the traditional view that pervasive phyllic alteration at Teniente occurs when PH veins reach a certain abundance and their halos overlap (e.g., Camus, 1975; Ojeda et al., 1980; Arevalo and Floody, 1998). In the upper levels of the deposit (>2,100m elevation), large volumes of rock are pervasively altered to a phyllic assemblage, indicating that the acidic PH stage fluids were strongly out of equilibrium with the wall rocks. Below this elevation the PH phyllic alteration is localised around vein halos. In the potassic zone, below 1,900m elevation, PH veins have phyllic halos that are thin (<5mm) to absent (Fig. 4.9), suggesting that the hydrothermal fluid was close to equilibrium with the biotite-altered wall rocks. Despite the low PH vein abundance in this deep, proximal domain, these veins are chalcopyrite-rich and host 10-20% of the copper (Fig. 4.25). The presence of chalcopyrite-rich veins, formed from fluids that were close to equilibrium with the wall rocks, suggests that wall-rock interaction was not a significant factor in precipitating copper from the PH stage hydrothermal fluids.

Intrusion of the late dacite porphyries marked the start of the LH stage. Stage 4a tourmaline veins and breccias, and the tourmaline-rich Marginal Breccia were emplaced. These veins and breccias are typically cut by stage 4b veins, which are morphologically and mineralogically similar to stage 3 veins, except they contain bornite. As stage 3 veins are concentrated in the transitional zone and stage 4 veins are concentrated close to the Braden Pipe, only rare crosscutting relationships were observed, which indicate that most LH veins formed after PH veins. However, it is feasible that the PH and LH stages overlapped temporally and the stage 4b veins are correlatable to the more distal stage 3 veins. A change in the fluid composition and/or chemistry resulted in the precipitation of the characteristically diverse ore and gangue mineral as-
semblage of stage 4c veins. Stage 4c veins consistently cut all stage 3, 4a, and 4b vein types and formed synchronous with and after the formation of the Braden Pipe. They decrease in intensity outwards from this structure. Mainly barren stage 4d fractures filled with chlorite and gypsum were the final vein stage at El Teniente.

**Thermal and pH gradients inferred from observed mineral assemblages**

The mineral assemblages associated with each alteration event can be used to track temperature and pH gradients of the hydrothermal system (Fig. 4.29, Corbett and Leach, 1998). Outwards migration of LM-stage fluids from the proximal potassic domain (biotite, Na-K-feldspar, quartz assemblage) to the transitional potassic-propylitic domain (green biotite, chlorite, epidote, carbonate assemblage) and to the regional propylitic assemblage (chlorite, carbonate, epidote, zeolite) involved cooling at approximately constant pH (Fig. 4.29). The temporal evolution from the LM potassic assemblage to the PH phyllic assemblage (muscovite, quartz, chlorite, calcite) reflects cooling and an increase in acidity of the fluid (Fig. 4.29). LH alteration is characterized by illite, carbonates (including siderite), and less chlorite than the PH assemblage. Pyrophyllite was reported by Camus (1975), and rare kaolinite was detected by PIMA in the current study. This mixed phyllic / argillic assemblage is consistent with further cooling and acidity increase of the fluids from the PH stage to the LH stage (Fig. 4.29).

**Temperature – fO2 variation from biotite chemistry**

Colour variation in metamorphic and hydrothermal biotites is normally attributed to the temperature dependant variation of the Ti content of the biotites (e.g., Engel and Engel, 1960, Le Bel, 1979). Higher temperature biotites are orange-brown in colour and have higher Ti contents relative to the lower temperature greenish biotite. No geothermometer has been developed to quantify this Ti-content - temperature relationship.

Microprobe analyses of biotite from Teniente confirms that pervasive brown biotite from the domain proximal to the dacite porphyry is Ti-rich compared to the greenish pervasive biotite from the transitional domain (Fig. 4.28A), most likely reflecting decreasing temperatures from the dacite porphyry to the deposit periphery. High Ti contents in the magmatic biotite from the dacite porphyry and secondary biotite from the Sewell Diorite (Fig. 4.28B) are consistent with their formation in the thermal centres of the deposit. The Ti content has no relationship with Mg-number of the analysed biotites (Fig. 4.28C). The most phlogopitic biotites (Mg numbers 0.75-0.78) occur in the
Na-K-feldspar assemblage, implying this assemblage formed under conditions of higher oxygen fugacity. Overall, no consistent spatial variation in magnesium number was detected across the deposit.

A linear relationship between Ti and octahedral Al, independent of Mg number, was also identified in biotites at Cerro Verde-Santa Rosa porphyry copper deposit in Peru (Le Bel, 1979). This relationship was interpreted to reflect temperature variation at a constant, buffered oxygen fugacity (Le Bel, 1979).
4.11 **SUMMARY**

Veins, breccias, and alteration assemblages at El Teniente are divided into four paragenetic stages, the premineralisation (stage 1), Late Magmatic (LM, stage 2), Principal Hydrothermal (PH, stage 3), and Late Hydrothermal (LH, stage 4) stages.

- During the premineralisation stage, early magnetite veins were formed and pervasive magnetite (+ Ca-plagioclase, actinolite-tremolite, quartz, anhydrite) alteration of the Teniente host sequence occurred. Early phyllic (sercite-chlorite-tourmaline) alteration was accompanied by thick barren quartz veins.

- Most of the copper and molybdenum in the Teniente deposit is hosted by a vein stockwork which formed during the LM stage. Nine discrete vein and breccia stages are recognized which have a consistent temporal and spatial distribution in the deposit. The Teniente intrusive complex was emplaced during the LM stage.

- Mineralogically variable potassic alteration of the wall rocks accompanied LM vein formation. In the dacite intrusions pervasive to veinlet-controlled K-feldspar alteration occurred. Texturally destructive Na-K-feldspar alteration (+ quartz, anhydrite, sercite, bornite, chalcopyrite) has occurred around some of the dacite porphyry and pipe contacts. In the Teniente host sequence texturally destructive biotite (+ anhydrite, bornite, chalcopyrite, rutile) alteration occurred up to 1200m from the dacite contacts. Potassic alteration grades into a distal propylitic (chlorite, pyrite, magnetite) altered zone.

- Thick PH chalcopyrite-rich veins have cross cut all LM veins. These veins are associated with phyllic (sercite-quartz-chlorite) halos. In upper levels of the deposit periphery, texturally destructive pervasive phyllic alteration of the wall rocks has occurred.

- A concentric, albeit asymmetrical, zonation is present of the potassic, propylitic, and phyllic alteration assemblages, the LM and PH veins, and the vein-hosted and disseminated Fe-Cu sulfides. This deposit-scale zonation is broadly centred on the southern end of the dacite porphyry and locally around the dacite pipes.

- The LH stage is a second stage phyllic alteration stage spatially and temporally related to the intrusion of the Braden Pipe and the late dacite dykes. The LH vein assemblage includes a variety of base metal sulfides and sulfosalts, and a gangue assemblage suggestive of lower temperatures and more acidic conditions than the PH stage.