CHAPTER 3

EL TENIENTE DEPOSIT GEOLOGY

3.1 INTRODUCTION

This chapter describes the host rocks to El Teniente. Mineralisation is hosted in a strongly altered sequence of rocks within the Farellones Formation, whose nature and origin remains disputed. These rocks have been intruded by, in order of emplacement, the Sewell Diorite, the grey porphyry, a series of dacitic intrusions (dacite pipes, a dacite porphyry dyke, and late dacite dykes), and the enormous Braden breccia complex (Fig. 3.1). Post-mineralisation late hornblende dykes were the last intrusive phases in the deposit. The terms used in the current study for the igneous units are shown in Table 3.1, with reference to the previously used terminology. The geochronology and geochemistry of the host rocks are discussed in chapters 6 and 7 respectively.

Terms used in current study	*Previously used terms*	*Reference*
Teniente host sequence	Mine andesites	Camus, 1975; Ojeda et al., 1980; Cuadra, 1986
	Teniente mafic intrusive complex	Skewes et al., 2002
Teniente intrusive complex		
Sewell Diorite	Sewell Diorite, Sewell Tonalite, quartz diorite, tonalite	Howell and Molloy, 1960; Camus, 1975; Faunes, 1981; Guzman, 1991
Dacite pipes	Quartz-diorite apophyses, diorite apophyses, tonalilte apophyses	Villalobos, 1975; Guzman, 1991
Dacite porphyry dyke	Teniente dacite porphyry	Camus, 1975; Villalobos, 1975; Skewes et al., 2002; Rojas, 2003
Grey porphyry	A porphyry	Cuadra, 1992; Skewes et al., 2002
Late dacite dykes	Latite porphyry	Camus, 1975; Ojeda, 1980; Riveros, 1989
Late hornblende dykes	Lamprophyre dykes	Ojeda, 1980; Cuadra, 1986

Table 3.1. Names for igneous rock units used in the current study compared to terms used by previous authors. Different terminology has been used in the current study because of geochemical re-classification of the Teniente intrusive complex (detailed in chapter 7), and to avoid using interpretative terms (e.g., Teniente host sequence, instead of Teniente mafic intrusive complex, or mine andesites).

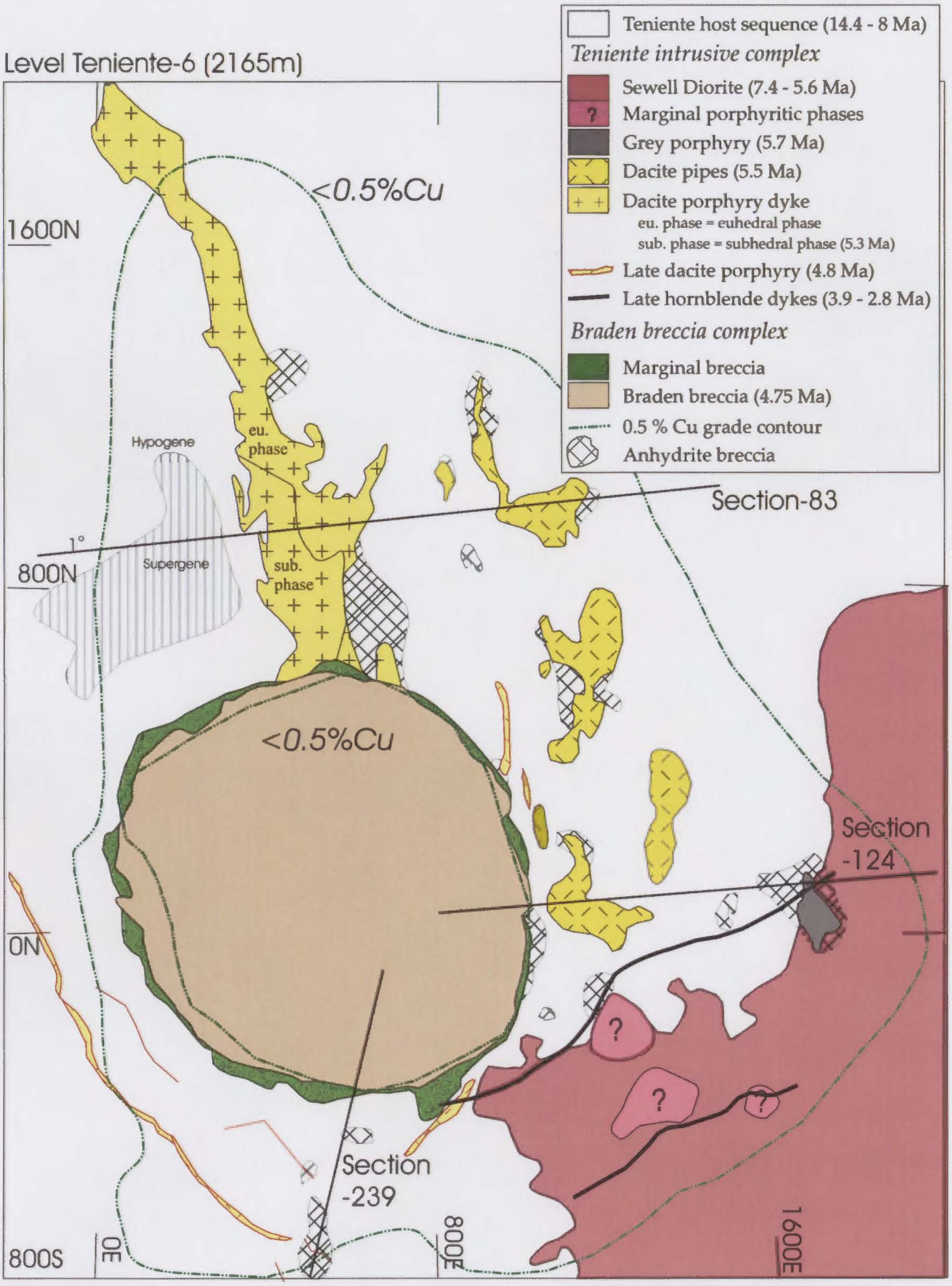


Figure 3.1. Geology of the Teniente deposit through the Teniente-6 level. Modified from the mine database. The deposit limits are indicated by the 0.5 % Cu limit. The approximate boundary between the euhedral (eu. phase) and subhedral (sub. phase) phases of the dacite porphyry are from Rojas (2003).

3.2 TENIENTE HOST SEQUENCE

Over 80% of the copper-molybdenum ore at El Teniente is hosted in dark grey, massive, plagioclase-phyric, biotite altered units of uncertain origin (Camus, 1975; Ojeda, 1980). Historically these have been termed the "mine andesites" (Table 3.1). Based on their mafic composition and the observation of interlocking plagioclase phenocrysts, Skewes et al. (2002) proposed the term "El Teniente mafic intrusive complex". To minimize ambiguity, in this thesis these rocks will be termed the Teniente host sequence.

The textural features of Teniente host sequence are obscured by widespread, pervasive, texturally destructive biotite and sericite alteration (Chapter 4). Consequently, previous workers have provided a variety of interpretations for the sequence. Lindgren and Bastin (1922) described the host rocks as intrusive andesites sills, whereas Howell and Molloy (1960) considered them to be thick, massive andesite flows of the Farellones Formation, with rare intercalated breccia lenses. Skewes (1998a, 1999) and Skewes et al. (2002) described the host sequence as crystal-supported gabbroic intrusions, intruded by biotite-matrix hydrothermal breccias.

Detailed lithological core-logging of the Teniente host sequence has not been attempted previously at El Teniente, due to the lack of textural or colour contrast between lithological units, poor quality of the hydraulically split BQ (36 mm diameter) core, and the time-consuming nature of the task. The intense biotite alteration that has texturally modified the precursor lithological sequence precludes a detailed volcanological – sedimentalogical study taking place, as subtle volcanic and volcaniclastic textures (e.g., McPhie et al., 1993) and contact relations have generally been destroyed. The textural features which are best preserved are breccia clasts, and plagioclase phenocrysts. For this project a logging scheme has been formulated for the Teniente host sequence, based mainly on these two characteristics. The logging scheme is summarised in Appendix 1B.

The Teniente host sequence units are ubiquitously plagioclase-phyric. Individual units contain as little as 5% and as much as 60% plagioclase phenocrysts (visual estimates), that range in size from 0.8 mm up to 6 mm in diameter. Hornblende crystals are rarely preserved. Opaques are dominated by magnetite, with minor ilmenite, sulfides, and rutile. The groundmass has been strongly biotite altered, with accessory anhydrite, plagioclase, sulfides, tremolite-actinolite, and quartz. The plagioclase phenocrysts are typically preserved, and are variably sericite and carbonate altered. Electron microprobe analyses of plagioclase phenocrysts have revealed strongly calcic compositions, varying from An_{46} to An_{92}, with the majority of analyses between An_{60} and An_{85} (Skewes, 1997; Appendix 1a).

Based on observed macroscopic and petrographic textural features, rarely-preserved contacts, and distributions and orientations on section, the Teniente host sequence has been subdivided into several lithofacies:

- **Volcano-sedimentary lithofacies**
    - Coherent andesite
    - Volcaniclastic siltstones and breccias
- **Intrusive lithofacies**
    - Fine and coarse grained andesite porphyry
    - Diorite porphyry
    - Gabbro
    - Andesite dykes
- **Hydrothermal biotite breccias** (described in chapter 4)

The distribution of these facies was interpreted for section-83 (Fig. 3.2), section-124 (Fig. 3.3), and section-239 (Fig. 3.4). Locations of the three cross sections are provided on Figure 3.1.

Volcano-sedimentary lithofacies

Volcaniclastic and volcanic facies are predominant on the west side of the dacite porphyry on section 83 (Fig. 3.2). They also occur above 2200 m elevation on the east side of the dacite porphyry on sections 83 (Fig. 3.2) and 124 (Fig. 3.3), and south of the Braden pipe on section 239 (Fig. 3.4). As a group, volcano-sedimentary lithologies are relatively crystal-poor, containing less than 30% feldspar phenocrysts.

Figure 3.2. Interpreted distribution of the Teniente host sequence on section-83 (~1000N). The section trace is shown in plan view on Figure 3.1. This section is based on detailed logging of core from the 14 diamond drillholes indicated by dashed lines. Drillholes have been projected from as much as 100m off section. A 450+m thick andesite porphyry sill complex, composed of fine-grained and coarse-grained variants, has intruded sub-horizontal volcano-sedimentary facies.

To the east of the dacite porphyry, andesite porphyry is the predominant host rock below the 2200m level. Enclaves of volcaniclastic siltstone occur within the fine andesite porphyry facies. The volcaniclastic breccia zone at approximately 2200mRL contains clasts of the underlying andesite porphyry, implying the andesite porphyry is either partly extrusive, or was uplifted and eroded after emplacement.

To the west of the dacite porphyry, the fine-grained andesite porphyry has crosscut a sequence of volcaniclastic siltstones and coherent andesite lava units. A significant stratigraphic break exists between the two sides of the dacite porphyry, which must have intruded either along a pre-existing fault, or a lithological boundary.

Coarse-grained, sub-equigranular igneous stocks have intruded on the eastern-most and western-most sides of the section (gabbro on the west and diorite porphyry on the east). The gabbro and diorite have subvertical orientations. Late-stage subvertical andesite porphyry dykes, coarse-grained and fine-grained andesite dykes, and biotite breccias have also cut the Teniente host sequence. The abundance of biotite breccias identified on this section is less than 5% of the total sequence.

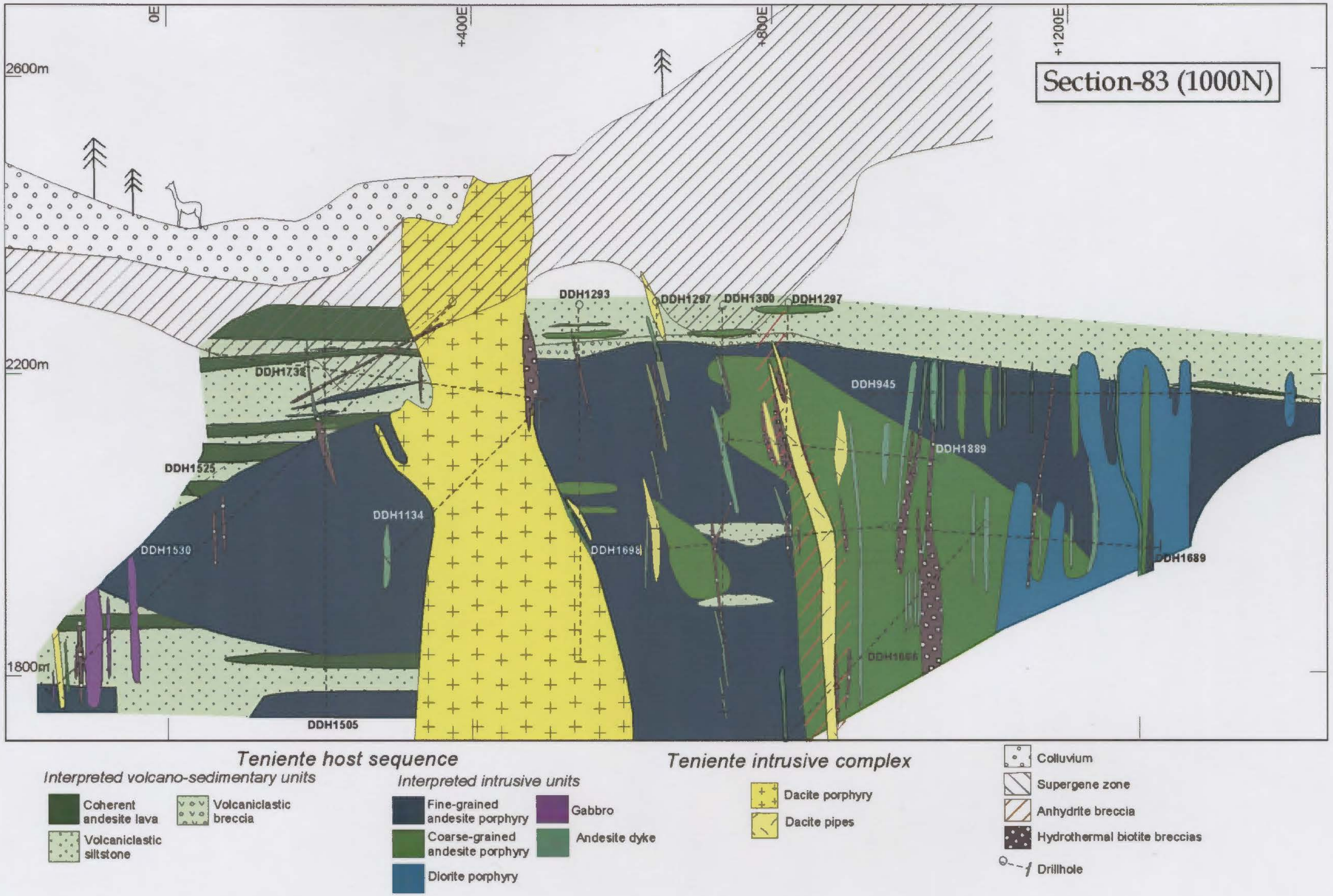

Section-83 (1000N)
0E
+400E
+800E
+1200E
2600m
2200m
1800m
DDH1293
DDH1297
DDH1300
DDH1297
DDH1738
DDH945
DDH1889
DDH1525
DDH1134
DDH1530
DDH1698
DDH1689
DDH1505
Teniente host sequence
Interpreted volcano-sedimentary units
Coherent andesite lava
Volcaniclastic breccia
Volcaniclastic siltstone
Interpreted intrusive units
Fine-grained andesite porphyry
Gabbro
Coarse-grained andesite porphyry
Andesite dyke
Diorite porphyry
Teniente intrusive complex
Dacite porphyry
Dacite pipes
Colluvium
Supergene zone
Anhydrite breccia
Hydrothermal biotite breccias
Drillhole

Figure 3.3. Interpreted distribution of the Teniente host sequence on section-124 (~100N). The section trace is shown in plan view on Figure 3.1. This section is based on the detailed logging of core from 10 diamond drillholes indicated by dashed lines. Although there is a high drillhole density on section-124, intense hydrothermal alteration, possible faulting, and complicated lithological relationships mean that alternative geological interpretations could readily be made in addition to the one shown here.

The volcano-sedimentary sequences are dominated by fine-grained volcaniclastic facies, with minor coherent andesite facies, black biotite-altered siltstones, and volcaniclastic breccia units. Weak subhorizontal bedding was observed in DDH1319 (vertical drillhole, bedding planes cutting the drillhole at right angles) and DDH885 (horizontal drillhole, bedding parallel to the drillhole). Correlation between units intercepted in drillholes DDH1319, DDH855, DDH1317 and DDH1314 indicate the units dip shallow to the west.

Below 2300m RL the predominant facies is andesite porphyry. Coarse-grained andesite porphyry only occurs below 1900m elevation. At higher elevations, individual fine-grained andesite porphyry units are up to 120m thick, apparently gently west-dipping and concordant to bedding. These units have chilled upper margins, and are either sills or thick, extrusive flows. Immediately overlying the fine-grained andesite porphyry units are thin volcaniclastic breccia units.

The host sequence has been offset by a high-angle reverse fault at 1300E, where the dacite pipe has intruded. The sequence is cut by a series of subvertical fine-grained and coarse-grained andesite dykes, and texturally variable diorite porphyry dykes. Biotite breccias are focussed close to the dacite pipe at 1300E, and close to the contact with the Sewell Diorite and grey porphyry in the east of the section. The abundance of biotite breccias positively identified on this section is less than 10 % of the total sequence. Zones of intense hydrothermal alteration (chapter 4) have destroyed the primary textures and facies interpretations are highly ambiguous.

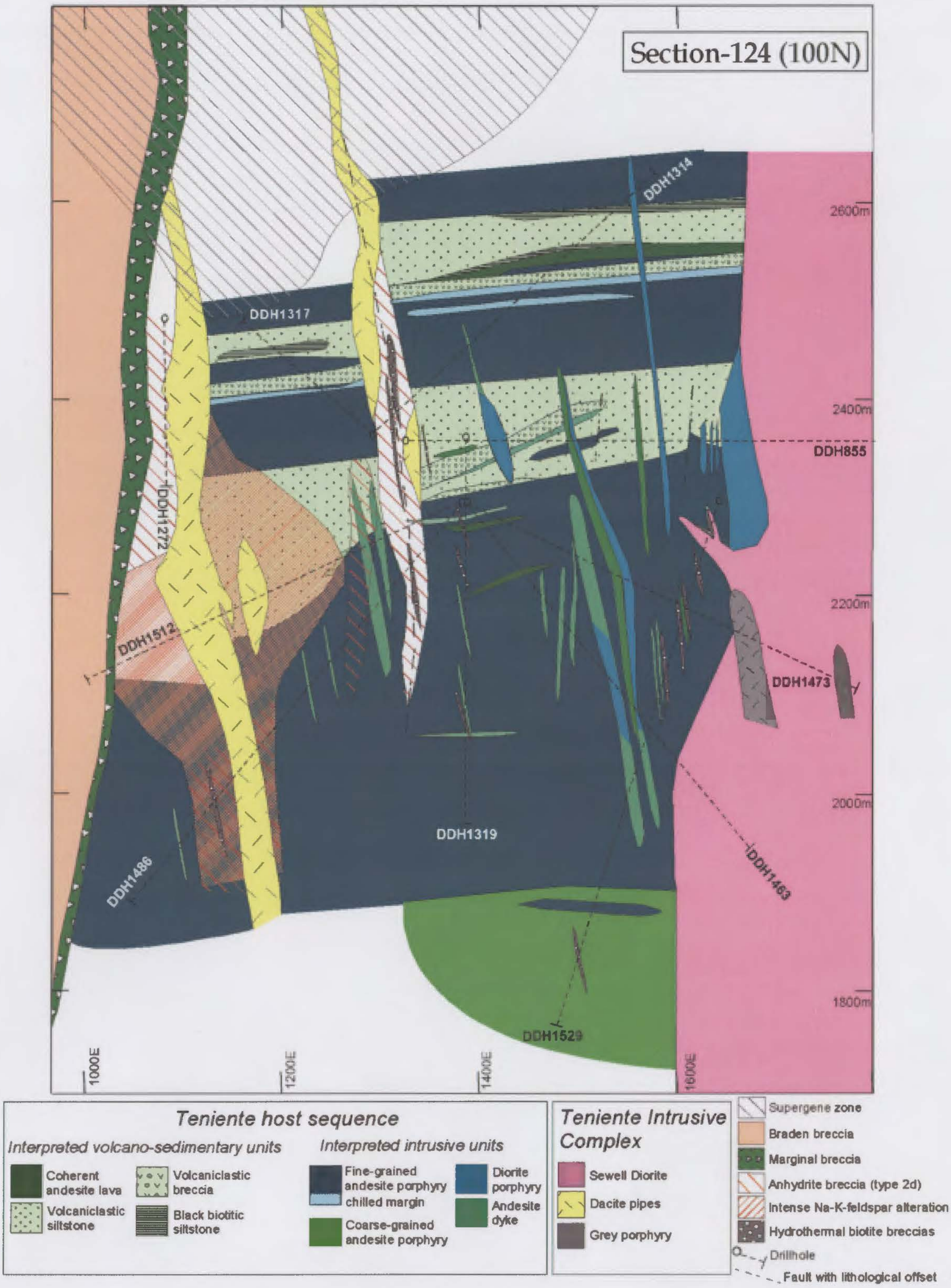
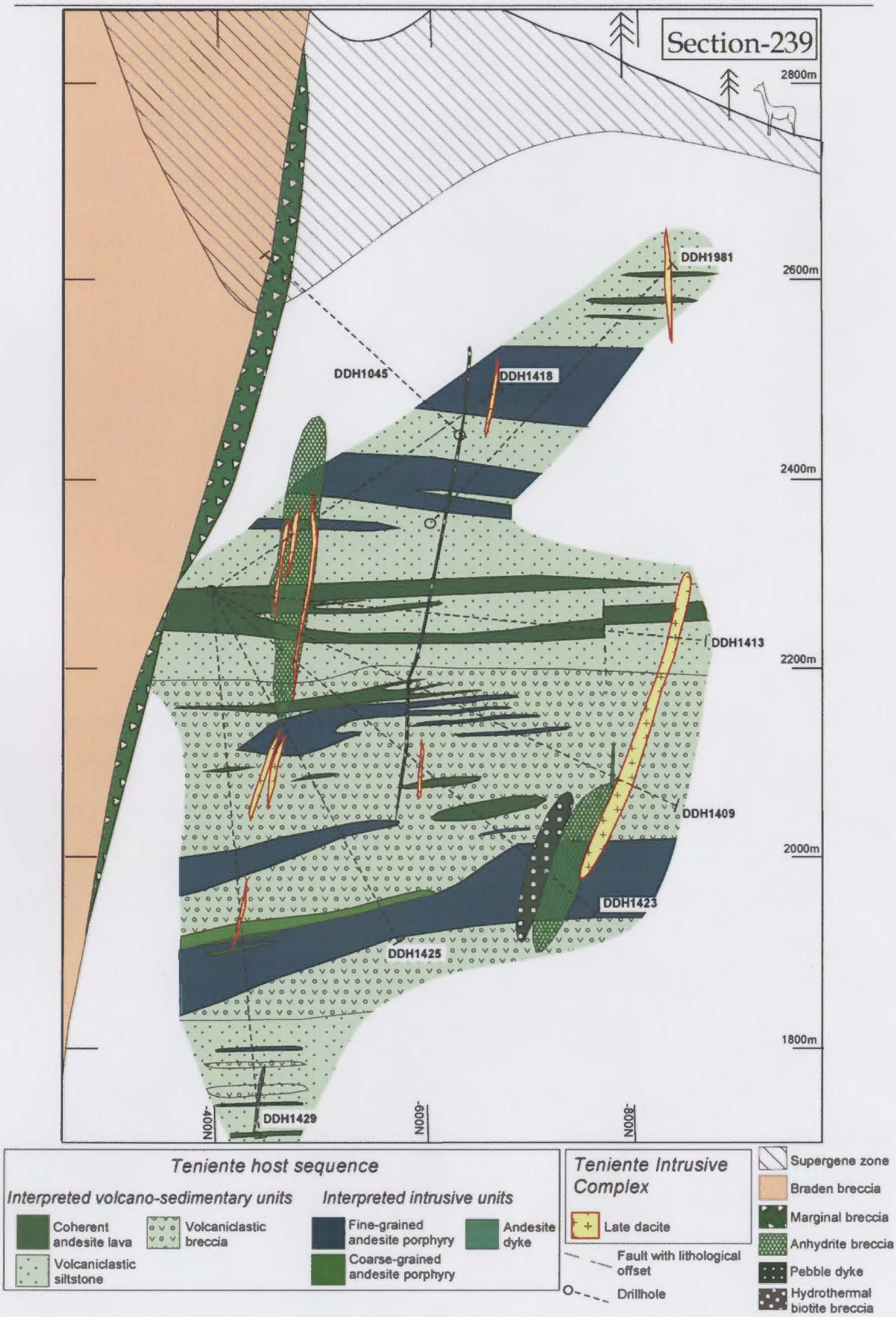

Section-124 (100N)
DDH1314
DDH1317
DDH1272
DDH1512
DDH855
DDH1473
DDH1319
DDH1463
DDH1486
DDH1529
2600m
2400m
2200m
2000m
1800m
1000E
1200E
1400E
1600E
Teniente host sequence
Interpreted volcano-sedimentary units
Coherent andesite lava
Volcaniclastic breccia
Volcaniclastic siltstone
Black biotitic siltstone
Interpreted intrusive units
Fine-grained andesite porphyry
chilled margin
Coarse-grained andesite porphyry
Diorite porphyry
Andesite dyke
Teniente Intrusive Complex
Sewell Diorite
Dacite pipes
Grey porphyry
Supergene zone
Braden breccia
Marginal breccia
Anhydrite breccia (type 2d)
Intense Na-K-feldspar alteration
Hydrothermal biotite breccias
Drillhole
Fault with lithological offset

Figure 3.4. Interpreted distribution of the Teniente host sequence on section-239. The section trace is shown in plan view on Figure 3.1. This section is based on the detailed logging of core from the eight diamond drillholes indicated by dashed lines. In contrast to sections 83 and 124, section-239 is dominated by volcano-sedimentary facies. Fine grained massive, generally aphanitic volcaniclastic siltstone occurs above 2200m. Matrix-supported, massive volcanic breccia units predominate from 2200m down to ~1800m elevation. Clasts included coherent andesite lavas, magnetite-bearing volcanic and sedimentary lithologies, and rare dacite, and andesite porphyry clasts. Minor coherent lava units also occur in this interval. Note that this brecciated zone has a subhorizontal upper contact with unbrecciated lithologies. It is interpreted to be a volcaniclastic breccia concordant with the volcano-sedimentary facies rather than a hydrothermal breccia, which would be expected to crosscut the sequence. In total, the breccia unit is ~400m thick, whereas on other sections the breccia unit is no more than ~30m thick. It is possible that this thick breccia package may have formed on the downthrown side of one of the district scale faults in the area (chapter 2). However, not enough is known about the local-scale structure or distribution of the volcaniclastic breccias to confirm this hypothesis, and further mapping is recommended, in particular to differentiate the volcaniclastic breccia facies from the biotite breccia facies.

Fine-grained andesite porphyry sills, <100m thick, appear to be horizontal to gently W-dipping, and approximately concordant with the stratigraphy. Only a thin zone (~10m thick) of coarse-grained andesite porphyry was encountered.

Thin late dacite dykes are subparallel to the Braden Pipe contact and are strongly altered. A thin pebble dyke, between 0.5 and 2m, is traceable vertically for several hundred metres at approximately –600N. In the east of the section a thicker pebble dyke was intersected in DDH1423.


Section-239
2800m
2600m
2400m
2200m
2000m
1800m
DDH1981
DDH1045
DDH1418
DDH1413
DDH1409
DDH1423
DDH1425
DDH1429
-400N
-600N
-800N
Teniente host sequence
Interpreted volcano-sedimentary units
Coherent andesite lava
Volcaniclastic breccia
Volcaniclastic siltstone
Interpreted intrusive units
Fine-grained andesite porphyry
Andesite dyke
Coarse-grained andesite porphyry
Teniente Intrusive Complex
Late dacite
Fault with lithological offset
Drillhole
Supergene zone
Braden breccia
Marginal breccia
Anhydrite breccia
Pebble dyke
Hydrothermal biotite breccia

Coherent andesite

Coherent andesites are a minor component of the Teniente host sequence. The coherent facies is composed of 5 to 30%, sub-euhedral, fine to medium grained plagioclase phenocrysts (< 2 mm - > 3.5 mm long), and minor preserved hornblende crystals (< 3%; Figs. 3.5A and 3.5B). The groundmass, comprising 70—95% of the rock, is composed of fine anhedral aggregates of plagioclase (< 0.05 mm) with local plagioclase microlites. The secondary biotite-stable alteration assemblage, with accessory anhydrite, sulfides, chlorite, sericite, quartz and rutile, comprises up to 50% of the groundmass. Round to irregular amygdales contain anhedral quartz, and variable amounts of magnetite-dusted feldspar, anhydrite, sericite, chlorite and sulfides. Relatively weakly altered coherent andesites were intersected in DDH1738, DDH1565, and DDH1525 (section-83, Fig. 3.2) to the west of the dacite porphyry. Individual units are up to 15 m in true thickness.

The porphyritic texture of the coherent andesite unit, fine crystalline groundmass, horizontal orientation, and apparent concordance with the other volcano-sedimentary units suggest that the coherent andesite units are either extrusive flows, or shallow sills. However, autobrecciation, flow banding, chilled margins or peperitic facies have not been identified to date.

Volcaniclastic siltstone and breccia

Volcaniclastic siltstones are massive, have a granular matrix typically only visible in thin section (Fig. 3.5C), and contain rare visible clasts. They have sparse, irregularly distributed subhedral to anhedral plagioclase crystals and crystal fragments. Subhorizontal bedding planes were observed in DDH1319, and DDH855 on section-124 (Fig. 3.3). However, bedding was not observed in most drillholes, probably due to intense, texturally destructive biotite alteration (Chapter 4). In thin section, sub-rounded quartz grains and feldspar crystals up to 2mm in diameter are surrounded by a fine grained (0.06 mm) anhedral quartz-feldspar (± anhydrite-magnetite-biotite) matrix (Fig. 3.5C). Secondary biotite clots are interpreted to have replaced lithics or mafic crystal fragments. Some thin units (< 10 m thick) are composed of > 80% secondary biotite, suggesting a more clay-rich original composition (e.g. black biotitic siltstone on

Figure 3.5. Volcano-sedimentary facies of the Teniente host sequence. Scale bar in core photos = 2cm, and in microphotographs = 1mm. Abbreviations: amph = amphibole, plag = plagioclase

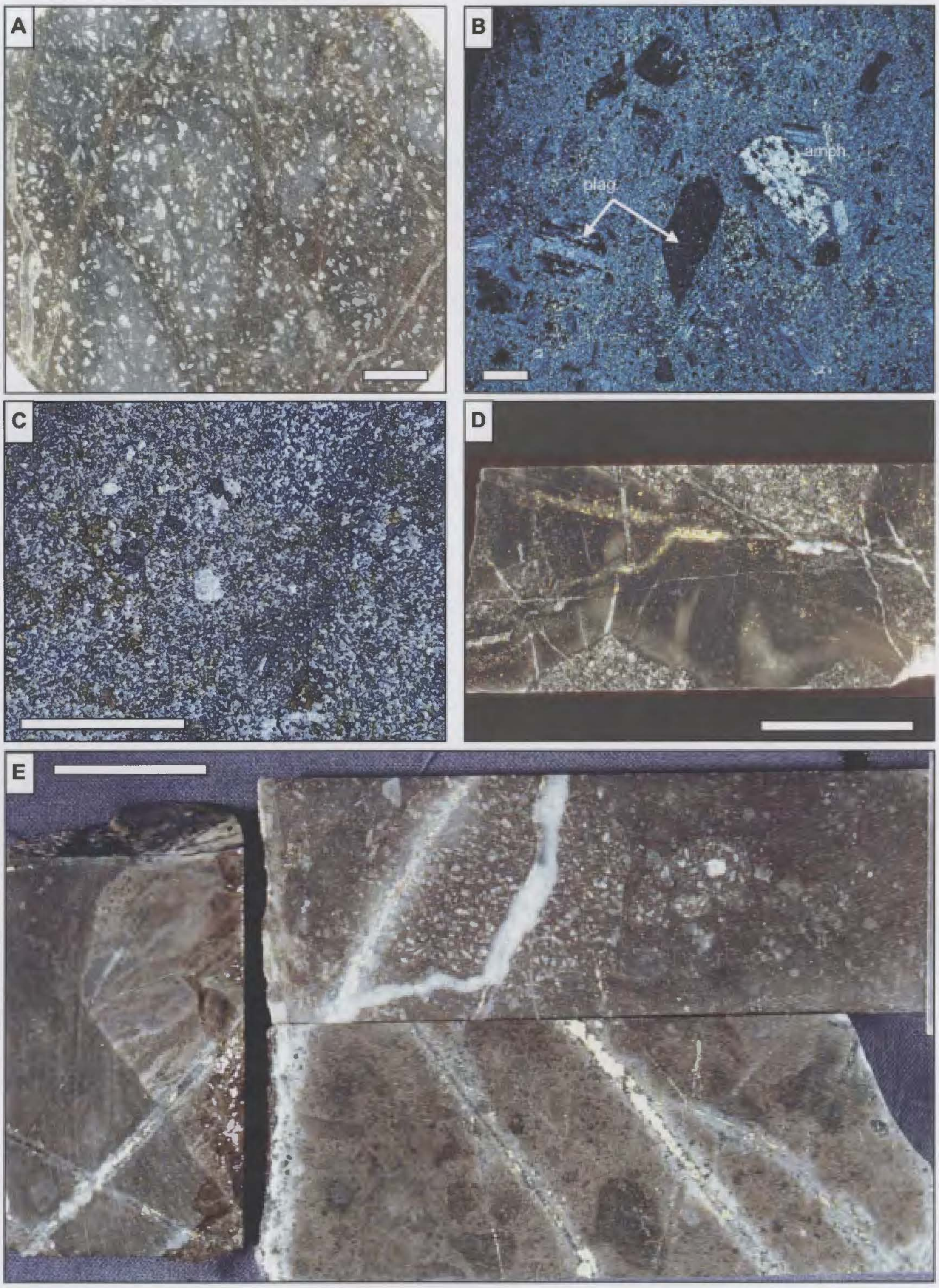
A) Coherent andesite facies, composed of evenly distributed plagioclase phenocrysts (30%). The crystal form of the plagioclase phenocrysts varies from euhedral laths to subequant crystals to irregular polycrystalline aggregates. The aphanitic groundmass (comprising 70% of the rock) is dark grey due to fine grained secondary biotite that occur around the quartz - anhydrite - sulfide veinlets. Away from the veinlets the groundmass is lighter grey coloured due to fine grained disseminated magnetite. Note the high degree of textural preservation (ET3, Ten-6 metallurgical core).

B) Photomicrograph of plagioclase-amphibole-phyric coherent porphyritic andesite. The amphibole crystal has been replaced by secondary actinolite. The fine-grained anhedral groundmass (<0.05mm) is composed of plagioclase, quartz, and secondary biotite and opaques (sulfides and magnetite; PPL; ET57, DDH1738, 341.6m).

C) Photomicrograph of volcaniclastic siltstone, composed of a fine granular matrix of quartz, feldspar and secondary biotite and rutile, with minor anhedral quartz and feldspar grains up to 0.2mm wide (ET296, DDH855, 103.9m).

D) Clasts of crystal-supported andesite porphyry in a fine grained, aphanitic mudstone matrix. Clast shapes in the breccia are globular to sub-angular, and the matrix around the clasts is visibly bleached. This sample is located at the contact between fine-grained andesite porphyry and volcaniclastic siltstone, and is interpreted to be a peperite. Cutting the breccia are quartz-sulfide veinlets (ET163, DDH1300, 111.9m).

E) Volcaniclastic breccia facies. Left, clast of a banded magnetite-bearing siliceous siltstone. (ET786, DDH1409, 293.7m). Top, monomictic breccia containing subangular andesite porphyry clasts, in a fine grained aphanitic secondary-biotite-rich matrix. The presence of the andesite porphyry clasts in the volcaniclastic breccia indicates that either the andesite porphyry was partly extrusive, or that it was unroofed after emplacement (ET649, DDH1698, 18.9m). Bottom, monomictic breccia composed of subangular dark to light grey aphanitic volcanic (?) clasts in a grey coloured fine grained matrix. Some of the clasts have curviplanar edges, suggesting they were derived from quench fragmentation of a lava (ET786, DDH1409, 293.7m). All the samples have biotite-altered clasts and matrix, and are cut by quartz—sulfide veins with thin phyllic halos.


A
B
plag.
amph
C
D
E

section-124, Fig. 3.3). The volcaniclastic siltstone unit is interbedded with coherent andesite facies (e.g., west side of section-83; Fig. 3.2).

Enclaves of volcanic siltstone up to 100 m wide, comprising anhedral plagioclase crystal fragments contained in a strongly biotite-altered silty matrix, occur enclosed in the intrusive lithotypes (see below). A notable example occurs to the east of the dacite porphyry on section 83 (Fig. 3.2). No faults were identified at the contacts of the siltstone units.

Volcaniclastic breccias are characterised by zones of highly variable phenocryst size and density, and are most easily recognized when obvious clasts are present (Figs. 3.5D, E). These breccias are matrix supported, polymict or monomict, with subrounded to subangular clasts. Clast types include andesite, volcaniclastic siltstones and sandstones, black, aphanitic, rocks that are too strongly altered to recognize the primary protolith, and minor crystal-rich andesite porphyry clasts (Fig. 3.5E). Some clasts have curviplanar edges (Fig. 3.5E), which are interpreted to be due to quench fragmentation of a lava (McPhie et al., 1993). The volcaniclastic breccias have sub-horizontal orientations. In places they are texturally and compositionally similar to the sub-vertically orientated biotite breccia units (Chapter 4), and correlation between adjacent drillholes is required to discriminate the sub-horizontal volcaniclastic breccias and the sub-vertical hydrothermal breccias. An extensive zone of volcaniclastic breccias occurs below 2200 m elevation on section-239, spanning a vertical interval of 400 m (Fig. 3.4). On other sections, volcanic breccia zones are up to 30 m in true thickness.

Intrusive lithofacies

The intrusive lithofacies comprise biotite-altered, massive, plagioclase-phyric, fine to medium grained andesites. The different varieties are distinguished by the size, form and percentage of plagioclase phenocrysts, and by their crystal- or groundmass-supported nature.

Andesite porphyry

The andesite porphyry is fine to medium grained (1mm - 4mm phenocrysts), and varies from phenocryst- to groundmass-supported (Figs. 3.6A - C). It contains 35 - 60%

euhedral to subhedral plagioclase phenocrysts which are elongate to equant. Hornblende phenocrysts comprise up to 10%, but at best are only partially preserved in some samples due to intense biotite alteration. The groundmass comprises 40 - 65% of the rock and contains anhedral plagioclase, and secondary biotite, anhydrite, quartz, and opaques (Fig. 3.6B). Groundmass feldspar crystals (typically 0.1mm wide) are coarser than those of the coherent andesite units. Rounded amygdales (Figs. 3.6D, E), up to 2cm wide, are predominantly filled with anhedral quartz.

The andesite porphyry can be subdivided into coarse-grained and fine-grained sub-units on the basis of phenocryst size. The coarse-grained unit (Figs. 3.6A, B) contains phenocrysts up to 3 mm in diameter. It only occurs on the eastern side of the dacite porphyry on section-83 (Fig. 3.2) and at depth on section-124 (Fig. 3.3). The coarse-grained andesite porphyry typically has a consistent, homogenous texture over intervals of >100m (e.g., DDH1666 and DDH1889, section-83, Fig. 3.2).

The fine-grained andesite porphyry (Figs. 3.6D, E) is characterized by phenocrysts mostly < 1mm. It occurs around the coarse-grained andesite porphyry (e.g. Fig. 3.2). The fine-grained unit is texturally heterogeneous, with phenocryst abundances and crystal forms varying considerably, possibly due to the presence of multiple intrusive phases. One distinctive variant of the fine-grained andesite porphyry is aphanitic in hand sample, with microscopic interlocking subhedral to elongate plagioclase phenocrysts. This variant was identified in all of the logged sections.

The andesite porphyry is at least 450m thick to the east of the dacite porphyry (Figs. 3.2 and 3.3). It is the predominant host rock to mineralisation below 2200m elevation on all sections studied. The andesite porphyry thins to the west of the dacite porphyry on section-89, and is discordant with respect to the subhorizontal sequence of coherent andesites and volcaniclastic siltstones (Fig. 3.2). Contacts between the andesite porphyry and the volcano-sedimentary units have been obscured by biotite and sericite alteration, although no obvious fault zones occur at these contacts. On the east side of section-83 (Fig. 3.2) and section-124 (Fig. 3.3) the fine-grained andesite porphyry conformably underlies a sequence of volcano-sedimentary units of the Teniente host sequence. A contact breccia occurs near the upper margin of the intrusive unit, composed of globular clasts of fine andesite porphyry surrounded by a fine silty matrix

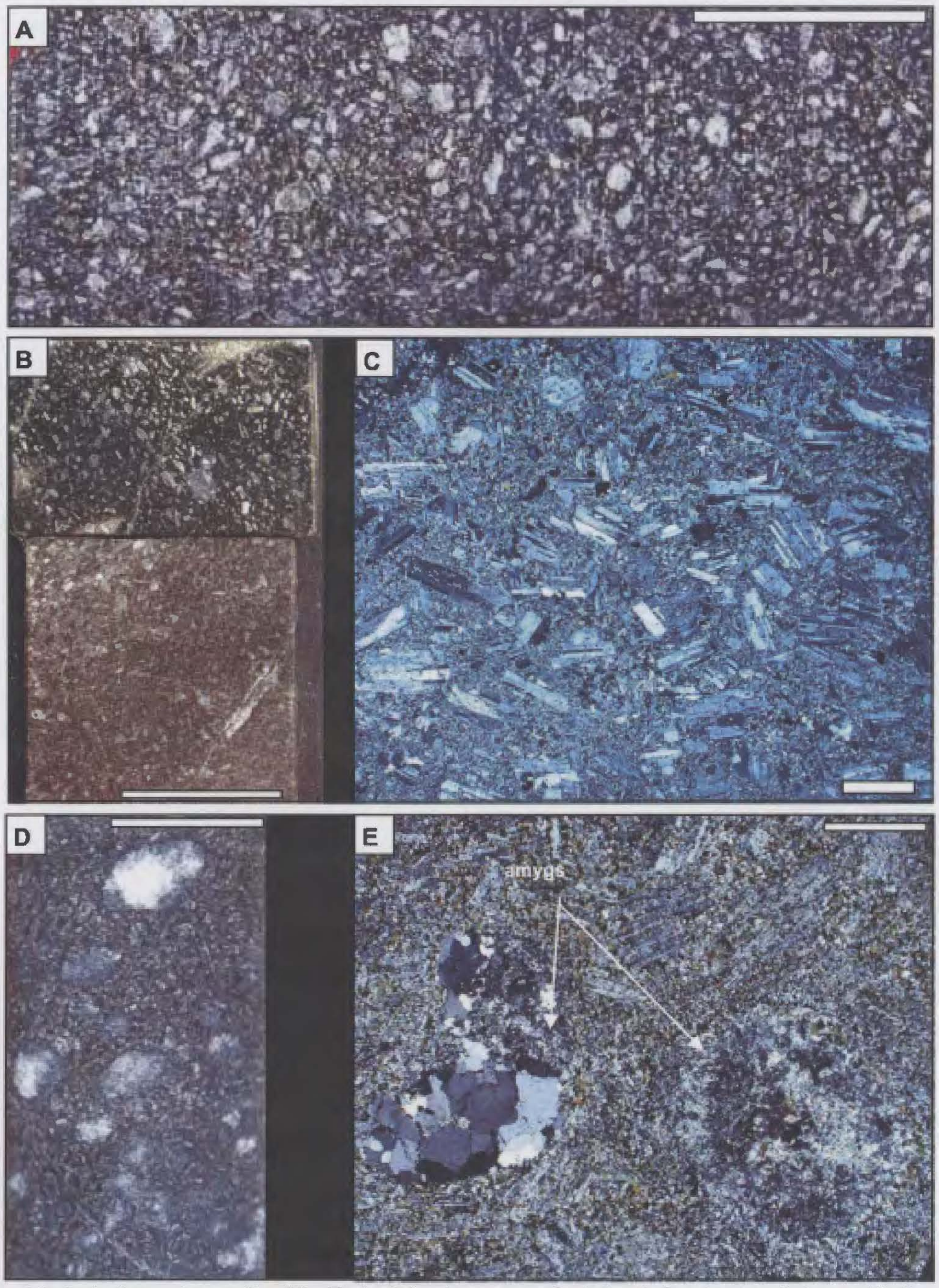


Figure 3.6. Andesite porphyry units of the Teniente host sequence. Scale bar is 2cm in core photos, and is 2mm in microphotographs. Abbreviations; amygs = amygdales.

A) Coarse-grained andesite porphyry, composed of 55% subhedral to euhedral, equant to elongate, tightly packed plagioclase phenocrysts, typically <3mm long, within a dark grey biotite-altered groundmass. Most of the rock is groundmass-supported, however there are crystal-supported domains visible in this sample (ET112, DDH1698, 14.6m).

B) Coarse-grained andesite porphyry, groundmass supported, composed of sub-euhedral, weakly aligned plagioclase phenocrysts in a biotitic groundmass. Note textural destructive biotite alteration at bottom of photo (ET93, DDH1689, 238 m).

C) Photomicrograph of coarse andesite porphyry in B), illustrating the euhedral, weakly aligned, elongate plagioclase phenocrysts and the fine grained groundmass. Anhedral plagioclase crystals in the groundmass are typically 0.1mm in diameter. This groundmass is coarser than that of the coherent andesite facies. Secondary pervasive biotite (20%) and sulfides (2%) are concentrated in the groundmass (PPL; ET93, DDH1689, 237.9m).

D) Fine-grained andesite porphyry with rounded amygdales up to 1cm wide filled with quartz, plagioclase, and magnetite. (ET109, DDH1689, 319.9m).

E) Microphotograph of fine-grained andesite porphyry in D). Subhedral plagioclase phenocrysts are partially surrounded by a finer grained biotite-altered groundmass. Note the textural destruction due to the biotite alteration. The amygdale on left side of photo is filled with anhedral clean quartz and lesser feldspar dusted with magnetite. The amygdale on the right comprises intergrown and concentric aggregates of quartz, magnetite, anhydrite, plagioclase, sericite and biotite (PPL; ET109, DDH1689, 319.9m).

(Fig. 3.5D). This breccia shows features consistent with a peperitic origin (e.g., McPhie et al., 1993).

Subhorizontal andesite porphyry units up to 100m thick occur within the volcano-sedimentary sequence on section-124 (Fig. 3.3), and section-239 (Fig. 3.4). Some of these sills have chilled margins, in which the porphyritic texture is accentuated. The chilled margins are up to 10m in apparent thickness below the upper contact of the sill (Fig. 3.3). Thin andesite porphyry dykes cut the stratigraphy on the east side of section-83 (Fig. 3.2) and section-124 (Fig. 3.2).

Gabbro

Gabbroic units were only encountered on the western side of section-83 (Fig. 3.2). They are medium grained, equigranular intrusions composed of approximately 35% mafic crystals (now altered to biotite and minor chlorite, anhydrite, sulfides), ~60% interlocking plagioclase crystals (Figs. 3.7A), and 5% skeletal opaque minerals (Fig. 3.7D). The gabbros have crosscut the fine-grained andesite porphyry.

Diorite Porphyry

The diorite porphyry is a medium grained plagioclase-rich (40-70%) unit with subhedral, equant to anhedral, crystal supported plagioclase phenocrysts (Fig. 3.7B). It is distinguished from the andesite porphyry by its lighter grey colour, anhedral plagioclase phenocrysts, and crystal-supported nature, and from the gabbro by its porphyritic texture.

The diorite porphyry occurs as a vertical stock that intruded the andesite porphyry sill complex on the eastern side of section-83 (Fig. 3.2, in DDH1698 and DDH945). On section-124 (Fig. 3.3) thin diorite porphyry dykes have intruded all other stratigraphic units.

Andesite dykes

Andesite dykes are typically 0.5 - 2m thick, (maximum of 10m), and have sharp, subvertical contacts with the wall rocks. They have crosscut all other volcano-sedimentary and intrusive units of the Teniente host sequence. The andesite dykes have

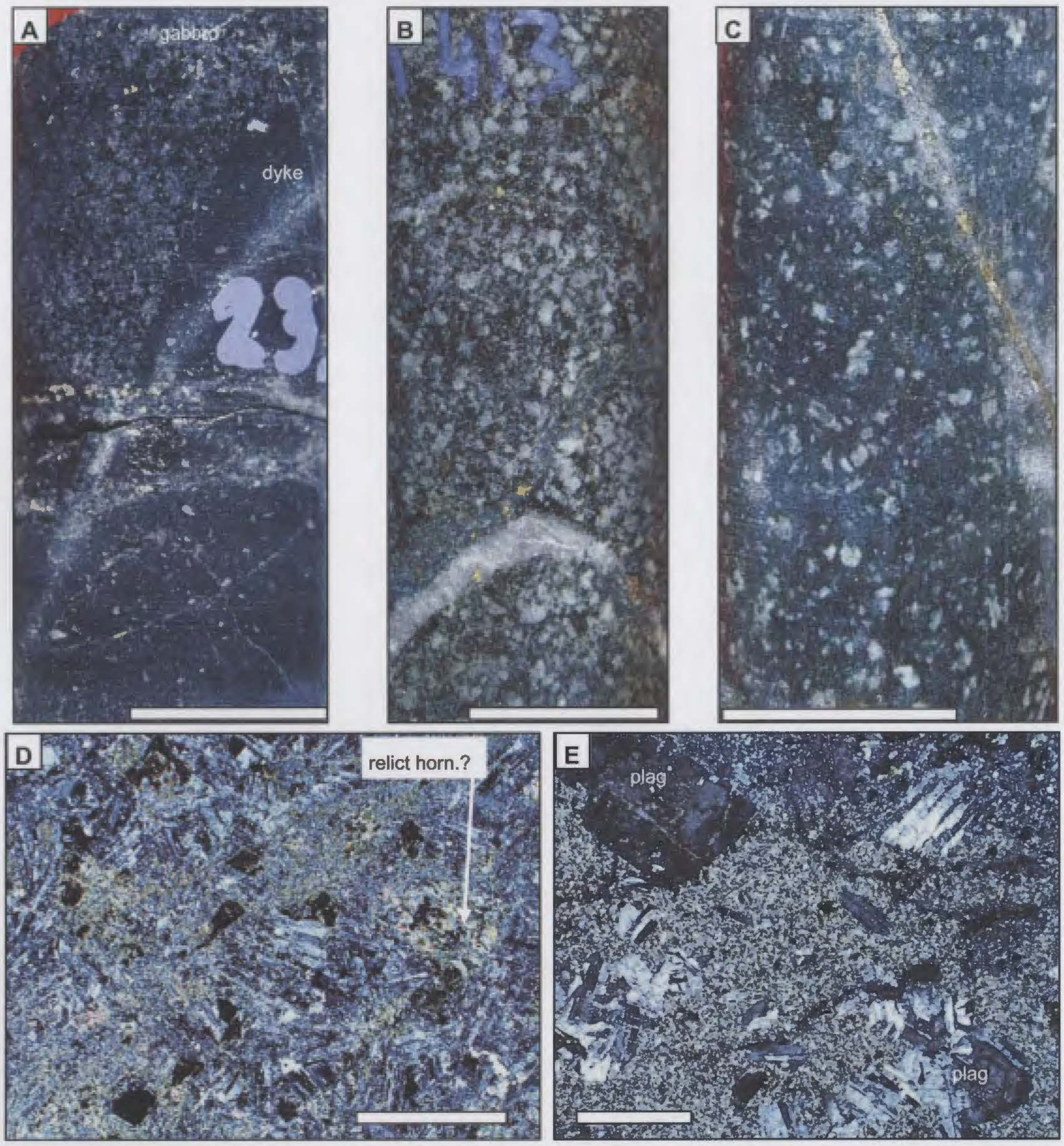


Figure 3.7. Intrusive facies of the Teniente host sequence. Scale bars in core photographs are 2cm, and in microphotos are 2mm. Abbreviations: horn = hornblende, plag = plagioclase.

A) Equigranular gabbro (upper left) containing 70% interlocking plagioclase crystals and 30% ex-mafic crystals replaced by secondary biotite. The gabbro has been cut by a fine-grained crystal-poor andesite dyke, (lower right), containing 10% sub-euhedral plagioclase phenocrysts, and minor mafic phenocrysts that have been replaced by biotite, set in an aphanitic groundmass (90%). Sharp intrusive contacts such as this are rarely preserved at Teniente (ET235, DDH1530, 622.1m).

B) Diorite porphyry, with 60% anhedral, equant plagioclase phenocrysts. Note the characteristically light grey colour, and crystal supported nature of the unit. Mafic phenocrysts are visible in the top of the photograph, which have been completely altered to biotite. The finer grained groundmass, comprising 40% of the rock, has been altered to biotite and chlorite, particularly adjacent to the anhydrite-quartz sulfide veins. (ET413, DDH855, 327.9m).

C) Coarse-grained andesite dyke, composed of an aphanitic groundmass up of plagioclase, biotite, quartz and opaques (75% of the rock), and 25% subequant polycrystalline plagioclase phenocrysts (ET263, DDH1529, 195.2m).

D) Photomicrograph of gabbro, composed of 60% equigranular interlocking plagioclase crystals up to 1mm long, 30% relict mafic (hornblende?) crystals altered to biotite, and 10% skeletal magnetite - ilmenite crystals, also partially altered to biotite. The biotite has preferentially altered the mafic crystals and finer-grained interstitial components (PPL, ET232, DDH1530, 585m).

E) Photomicrograph of coarse-grained andesite dyke, containing coarse polycrstalline aggregates composed of interlocking plagioclase crystals, in a fine anhedral groundmass composed of anhedral plagioclase, secondary biotite and magnetite. (PPL, ET54, DDH1738, 323.6m),

Abbreviations; horn. = hornblende, plag = plagioclase.

a hard, dark coloured and glassy groundmass composed mostly of fine grained (< 0.2mm long), aligned plagioclase microliths and anhedral interstitial plagioclase, quartz and secondary biotite. Sporadically distributed amygdales (< 0.5cm wide) are filled with quartz, feldspar, magnetite, sericitised feldspar and opaques.

The andesite dykes are subdivided here on the basis of phenocryst size into fine-grained and coarse-grained andesite dykes. Fine-grained andesite dykes contain between 0% (aphanitic) and 20% plagioclase phenocrysts < 2mm long (Fig. 3.7A). Coarse-grained andesite dykes are characterised by plagioclase phenocrysts between 2 and 6mm in length that comprise between 10 and 35% of the rock, (Fig. 3.7C). Coarse-grained andesite dykes contain sub-euhedral polycrystalline aggregates of plagioclase (Fig. 3.7E).

3.3 Teniente Intrusive Complex

The Teniente host sequence has been intruded by a series of intermediate to felsic intrusions, herein termed the Teniente intrusive complex (summarized in Table 3.2). They have been previously classified in the mine-site terminology according to modal phenocryst percentage. Most of the units are plagioclase-phyric, with minor quartz and/ or hornblende phenocrysts in some of the intrusive phases. However, quartz comprises up to 50% of the groundmass component in some of the dacites, and as a result some intrusive phases with a high bulk (groundmass + phenocryst) modal percentage of quartz have been historically classified as tonalites or quartz diorites. To avoid such ambiguities in the current study the Teniente intrusive complex units are named according to their bulk mineralogy, and their geochemical composition (Chapter 7).

Sewell Diorite

The plagioclase-hornblende-phyric Sewell Diorite occurs as a large stock in the SE corner of the deposit (Fig. 3.1). The diorite consists of an equigranular core and a porphyritic marginal phase (e.g., Ossandón, 1974; Camus, 1975; Guzman, 1991). The equigranular core is composed of subhedral plagioclase (An_{16-30}; Ossandón, 1974), hornblende, secondary biotite and interstital quartz (Fig. 3.8B). The porphyritic marginal phase has a more felsic mineralogy, comprising 30 - 60% plagioclase phenocrysts, 5% preserved or altered biotite phenocrysts and rare quartz eyes,

Intrusion	Sub-type	Location and occurrence	Mineralogy	Texture	Age	Reference
Sewell Dioriite	equi-granular	Stock in SE corner of deposit	Plag, horn, bt, K-fld, qz, ser, chl, ep	equigranular	5.59 ± 0.19 Ma (SHRIMP U-Pb on zircon, Maksaev et al., 2002), 7.4 ± 1.0 - 7.1 ± 1.5 Ma (K/Ar, Cuadra, 1986).	Camus (1975), Ojeda (1980), Faunes (1981), Guzman (1991), Kay and Kurtz (1995)
	porphyritic	Outer carapace to stock	Plag, bt, K-fld, qz, ser, chl, anh	Porphyritic, 30-50% phenos, aplitic gmass		
Grey porphyry		Has intruded the Sewell Diorite near its contact with Teniente host sequence	Plag, bt, K-fld (perthite), anh	Porphyritic, inequigranular groundmass	5.67 ± 0.19 Ma (SHRIMP U-Pb on zircon, Maksaev et al., 2002). 5.1 - 6.0 Ma (K/Ar on bt Cuadra, 1992).	Cuadra (1992), Skewes et al. (2002)
Dacite pipes		Various (>6) pipes E of dacite porphyry. Also has intruded Sewell Diorite along contacts?	Plag (An_{16-40}), qz, bt phenos in qz-plag-K-fld, gmass	Porph, 30-50% phenos, gmass is aplitic (<0.12mm), to coarse grained (up to 0.5mm).	5.50 ± 0.24 Ma, 5.48 ± 0.19 Ma (SHRIMP U-Pb on zircon, Maksaev et al., 2002)	Villalobos (1975), Guzman (1991),
Dacite porphyry	euhedral	Northern end of 1500m x 200m Dacite dyke	plag (An7-39), qz, bt phenos in qz-plag-K-fld, gmass	Euhedral phenos, aplitic gmass	5.28± 0.1Ma (SHRIMP U-Pb on zircon, Maksaev et al., 2002). 4.7-4.5Ma (K/Ar on bt. Clark et al, 1983, Cuadra, 1986, 1992).	Ossandon (1974), Ojeda (1980), Skewes et al. (2002), Rojas (2003)
	subhedral	Central portion of Dacite dyke		Subhedral phenos, coarse gmass		
	igneous breccia	Contacts of all intrusive units above	Plag, K-fld, bt, qz phenos in qz-fld-bt gmass	Wall rock xenoliths <20%	Undated	Ossandon (1974), Rojas (2003)
Late dacite dykes		Concentric to Braden Pipe, and NE trending thin dykes	Plag (An_{30-70}), qz, bt phenos in qz-plag-K-fld gmass, sericitised	Porph, 30-50% phenos, very fine aplitic gmass (<0.02mm)	4.82 ± 0.09Ma, (SHRIMP U-Pb on zircon, Maksaev et al., 2002). 5.3 (± 0.7) - 4.8 (± 0.6) Ma (K/Ar on bt, ser, plag Cuadra, 1992)	Ojeda (1980), Riveros (1989)
Late hornblende dykes		NE trending thin dykes	Horn, pyrox, oliv, plag	Fine grained, porphyritic	3.85 ± 0.18Ma (Ar^{40}/Ar^{39} on hornblende, Maksaev et al., 2002). 3.8 and 2.9 Ma (K/Ar Cuadra, 1986).	Ojeda (1980), Cuadra (1986)

Table 3.2. Summary of the Teniente intrusive complex units. Abbreviations: anh = anhydrite, bt = biotite, chl = chlorite, ep = epidote, fld = feldspar, gmass = groundmass, horn = hornblende, oliv = olivine, phenos = phenocrysts, plag = plagioclase, porph = porphyritic, pyrox = pyroxene, qz = quartz, ser = sericite.

surrounded by an aplitic quartz – plagioclase – K-feldspar groundmass comprising 35 - 65% of the rock. Both phases have been overprinted by sporadically distributed biotite-K-feldspar stable alteration assemblages, and ubiquitous sericitic (± chlorite, epidote, carbonate) alteration assemblages. The 0.5% copper grade contour approximately coincides with the boundary between the marginal porphyritic and the inner equigranular phases (Guzman, 1991). Copper grades decrease markedly in the inner equigranular facies (Fig. 3.1). In addition to the equigranular and porphyritic phases, other porphyritic textural variants have been identified close to the stock margin (Guzman, 1991; Arévalo and Floody, 1995). Consequently, uncertainty remains as to the number and relative timing of the different phases of the Sewell Diorite.

Contact metamorphic biotite and amphibole (tremolite-actinolite, and rare secondary hornblende) occur in the Teniente host sequence adjacent to the Sewell Diorite. These minerals are only identifiable in thin section. Contact metamorphic biotite occurs as ragged, dark brown, coarse-grained flakes up to 2mm wide that contain rutile needles. Metamorphic biotite has typically been replaced by retrograde chlorite or hydrothermal biotite, the latter of which is distinguished from metamorphic biotite by its finer grain size and pale brown - green colour.

Grey porphyry

The grey porphyry (formerly termed the A porphyry; Table 3.2) is a biotite - K-feldspar - plagioclase - phyric pipe that has intruded the Sewell Diorite near to its contact with the Teniente host sequence on section-83 (Figs. 3.1, 3.3). The grey porphyry has a strongly altered groundmass composed of anhedral biotite, K-feldspar, plagioclase, anhydrite, quartz and sulfides. Due to its strongly altered nature it has not been ascribed a systematic rock name. Mineralogically similar intrusions were observed in other drillholes within the Sewell Diorite, and it is considered likely that several grey porphyry pipes exist.

Dacite pipes

Plagioclase-phyric dacite pipes (formerly termed diorite apophyses or tonalite apophyses; Table 3.1) have intruded the Teniente host sequence to the east of the dacite porphyry and Braden pipe (Fig. 3.1). They are irregular in plan view, up to 100m wide, and vertically continuous. The dacite pipes are composed of 30-50% plagioclase phenocrysts (An_{16-33}; Ossandón, 1974; Skewes et al., 1997), minor biotite and amphibole phenocrysts (altered to chlorite, sericite, carbonate, quartz), rare quartz eyes, and 45-65% groundmass (Fig. 3.8C). The aplitic groundmass is composed of quartz, plagioclase microliths, K-feldspar, and minor copper-iron-sulfides, sericite, chlorite, (primary?) anhydrite, zircon and apatite. Most of the dacite pipes are porphyritic, although equigranular textures were described from the "central" dacite pipe (approximately 600N, Fig. 3.1) by Guzman (1991). Based on the modal mineralogy (phenocrysts + groundmass) these intrusions have been reclassified as dacite in the current study.

Rare unidirectional solidification textures (USTs; Shannon et al., 1982; Kirkham and Sinclair, 1988) occur in some of the dacite pipes near their outer margins. The USTs are centimeter-scale layers of aplitic-textured dacite and inward-pointing euhedral to anhedral quartz containing disseminated copper-iron-sulfides (Fig. 3.8D).

Dacite porphyry dyke

The dacite porphyry dyke (formerly known as the Teniente Porphyry; Table 3.1) is a NNW-trending tabular dyke up to 200m wide and 1,300m long. The southern end has been cut by the Braden pipe, close to the approximate geographic centre of the deposit (Fig. 3.1). To the north, the dyke continues beyond the limits of the 0.5% copper grade envelope, where it crops out (unaltered and unmineralised) on the northern side of the Teniente river valley. Historically, most workers have interpreted that the dacite porphyry was the source for the fluids, heat and metals of the Teniente deposit (e.g., Howell and Molloy, 1960; Camus, 1975; Cuadra, 1986).

The dacite porphyry is mineralogically and texturally similar to the dacite pipes. It is composed of 30-50% plagioclase phenocrysts (An_{7-39}; Ossandón, 1974; Skewes, 1997) typically <5mm long, variably altered biotite phenocrysts (<8%), and minor clear, rounded to embayed quartz eyes <3 mm wide, in a predominantly aplitic groundmass (60 - 40%; Figs. 3.8E - G). Aggregates of secondary biotite, chlorite, sulfides and anhydrite have replaced what were probably mafic crystals. Staining of samples of the dacite porphyry and dacite pipes with sodium cobaltinitrite has indicated that K-feldspar is a minor to non-existant phenocryst phase (Fig. 3.8H). K-feldspar can; however, be locally abundant in the groundmass or in zones of secondary pervasive / fracture controlled alteration. Primary biotite is typically preserved in the dacite porphyry, in contrast to the dacite pipes in which biotite is generally altered to chlorite (± sericite, carbonate).

The dacite porphyry dyke consists of multiple intrusive phases, which can be identified by abrupt textural changes and terminated veins. Ossandón (1974), Rojas (2002) and Duarte (2000) identified two main textural phases in the dacite porphyry. The "euhedral" phase has euhedral plagioclase phenocrysts in a fine aplitic groundmass (Fig. 3.8G). The "subhedral" phase has plagioclase phenocrysts with resorbed crystal edges in a relatively coarse-grained groundmass (Fig. 3.8F), containing more perthitic

Figure 3.8. Units of the Teniente intrusive complex. Scale bars in core photos are 2cm, and 2mm in microphotographs. Abbreviations: anh = anhydrite, bt = biotite, plag = plagioclase, qz = quartz

A) Unaltered, slightly weathered, porphyritic plagioclase-hornblende-phyric Sewell Diorite, cropping out near the Agua Amarga prospect. (CE 52, 3km west of the mine).

B) Photomicrograph of equigranular Sewell Diorite from the SE corner of the deposit. The rock is composed of 80% subhedral to anhedral plagioclase crystals between 5mm and 0.5mm long with a weak sericite + carbonate alteration overprint. Shreddy aggregates of biotite have pseudomorphed primary hornblende (15%). Minor interstitial quartz, anhydrite and opaques are also present. (ET720, DDH1463, 423.3m).

C) Photomicrograph of dacite from a dacite pipe, composed of unaltered euhedral plagioclase phenocrysts, rounded and embayed quartz eyes, and anhedral primary biotite phenocrysts. The fine grained (< 0.1 mm) aplitic groundmass is composed of quartz, plagioclase and K-feldspar. (PPL; ET769, DDH1297, 299.2m).

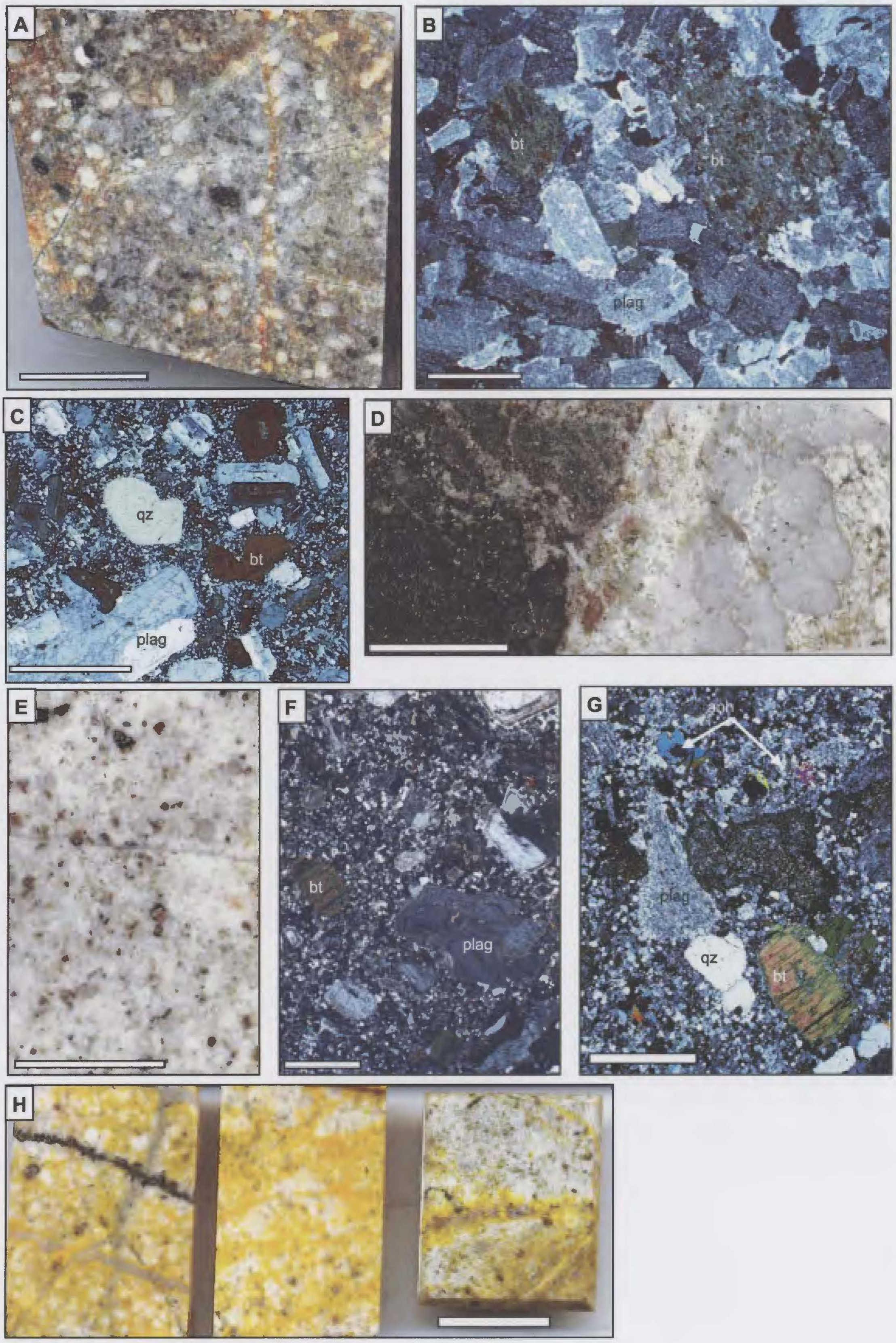
D) Unidirectional solidification texture (UST) in a dacite pipe adjacent to its contact with strongly altered Teniente host sequence. The UST is composed of a centimeter thick layer of siliceous aplitic dacite at the contact of the pipe, and inward-pointing eubhedral quartz crystals enclosing minor disseminated bornite. The dacite pipe has crosscut a diffuse Na-K-feldspar, biotite, chlorite, sulfide vein in the Teniente host sequence (ET697, DDH1889, 174.5m).

E) Subhedral phase of the dacite porphyry dyke, composed of plagioclase phenocrysts, rounded quartz eyes, biotite phenocrysts which have been partially altered to chlorite, sericite and carbonate, and 1-2% disseminated Cu-Fe sulfides (ET2, approx. 600N, 500E, 2350mRL).

F) Photomicrograph of euhedral phase (Ossandon, 1974; Rojas, 2003) of the dacite porphyry dyke. It is composed of well zoned plagioclase phenocrysts, and minor primary biotite and quartz phenocrysts, in a fine grained groundmass. The plagioclases in this sample have a composition of An_{23-31} (oligoclase; from electron microprobing), and are reversely zoned, with the more calcic compositions occurring at the rims. Sericite-carbonate alteration of plagioclase is concentrated in thin zones of more calcic and less sodic composition. Note the textural similarity between the dacite pipe sample in C and this sample (ET124, DDH 1134, 169.3m).

G) Photomicrograph of the subhedral phase (Ossandon, 1974; Rojas, 2003) of the dacite porphyry dyke. It is distinguished by coarser-grained groundmass crystals (<0.4mm) and anhedral / subhedral plagioclase phenocrysts in comparison to the euhedral dacite porphyry phase in F. The plagioclase has been weakly altered to sericite and carbonate. The secondary minerals are concentrated in the more calcic cores of the plagioclase phenocrysts. Note the primary (?) anhydrite that has poikilolitically enclosed groundmass feldspar crystals (PPL, ET849, DDH1505, 12.2m).

H) Plagioclase- (± lesser quartz - biotite) phyric dacite porphyry dyke (left), and dacite pipes (centre and right). The samples have been stained with sodium cobaltinitrite which colours K-feldspar yellow. Note that the phenocrysts are all unstained, indicating they are plagioclase. K-feldspar forms a significant primary groundmass component (left), and also occurs as secondary alteration around microfractures and veins (centre and right; from left to right, ET789, DDH1505, 10m; ET368, DDH1486, 1719'; ET557, DDH1666, 341.9m)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K-feldspar in the groundmass than the euhedral facies (Rojas, 2003). Relative timing relationships are provided by the presence of xenoliths of the subhedral phase (early) occuring in the euhedral phase (late; Rojas 2003). The subhedral variant occurs on the western side of the dacite porphyry, south of 1100N (Fig. 3.1; Rojas, 2003). The euhedral variant is located north of 1100N, and to the east of the subhedral phase south of 1100N. The euhedral phase typically has lower copper grades than the subhedral phase, and is essentially barren at its northern limits (Duarte, 2000).

Igneous breccias

Igneous-cemented breccias (e.g., Skewes, 2002) occur at the margins of the dacite porphyry, dacite pipes, Sewell Diorite and the grey porphyry. They are composed of up to 20%, centimetre- to metre-scale clasts of the local wall rock surrounded by a pale to medium grey to brown igneous crystalline cement. Some of the wall rock clasts contain veins that are terminated at the clast margins (Fig. 3.9A). The euhedral phase of the dacite porphyry has a continuous igneous breccia unit at its periphery, up to 100m thick, composed of clasts of altered Teniente host sequence in a euhedral dacite porphyry cement (Rojas, 2003). Partial assimilation of xenoliths into the igneous cement has produced domains of disseminated biotite enrichment (Ossandón, 1974; Rojas, 2003)

Late dacite dykes

Late dacite dykes (formerly known as the latite porphyry, Table 3.1) are in most cases no thicker than 5m wide, although they locally attain widths of 15m. They occur as incomplete concentric ring dykes around the Braden pipe, and as planar NE and NW trending dykes (Ojeda, 1980; Garrido, 1995). Two deep drillholes (DDH1068 and DDH1079) intersected up to 400m of the late dacite facies beneath the Braden pipe. Large (200m wide), brecciated masses of late dacite have been recorded from the upper part of the Braden pipe (Howell and Molloy, 1960; Camus, 1975; Chapter 3.3).

The late dacites are plagioclase (An $_{30-50}$; Riveros, 1991) ± quartz - phyric porphyries. Petrographically they are distinguished from the dacite porphyry and dacite pipes by strong sericite (± clay, carbonate) alteration of the plagioclase and biotite crystals (Fig. 3.9B), and an absence of quartz-anhydrite-sulfide veins, or biotite / K-

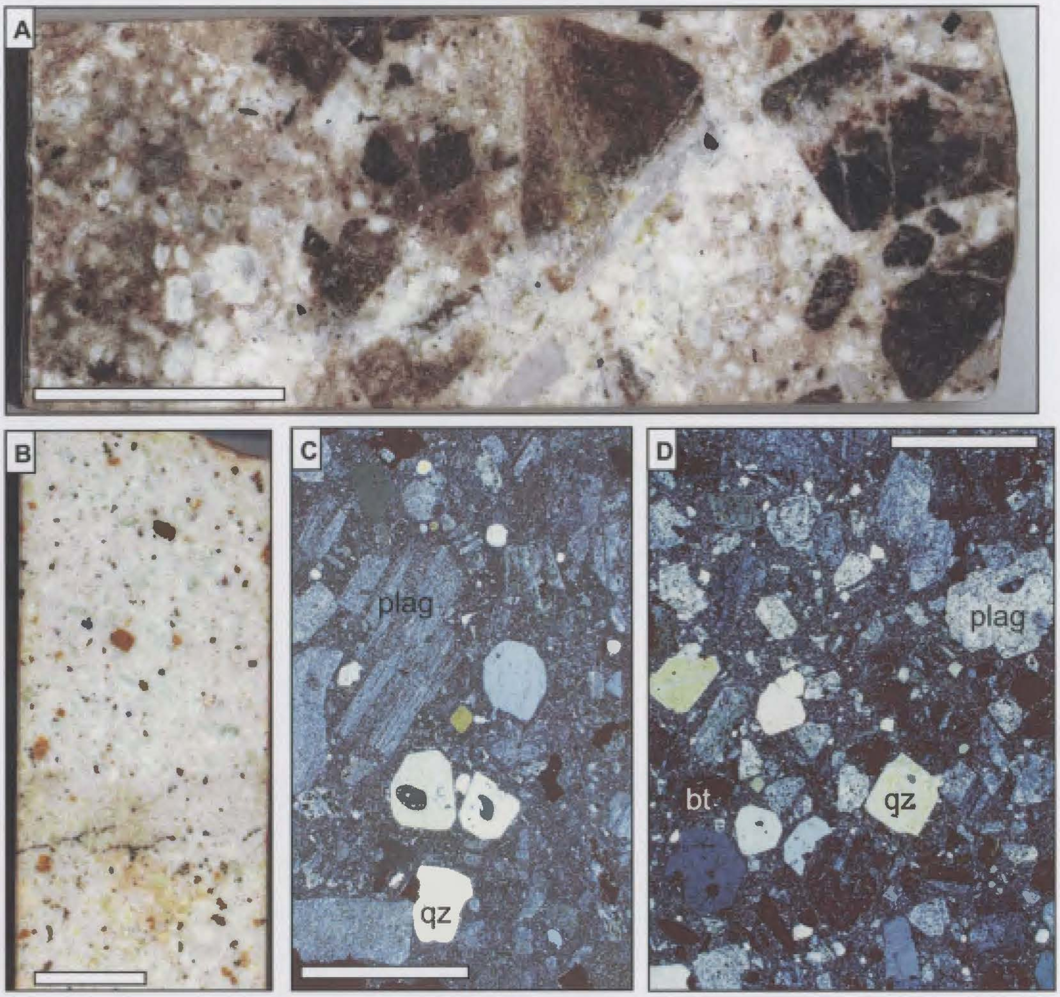

Figure 3.9. Units of the Teniente intrusive complex. Scale bars in core photos are 2cm, and 2mm in microphotographs.

A) Igneous cemented breccia. Clasts of veined and altered Teniente host sequence are surrounded by a plagioclase - quartz - phyric, dacitic igneous cement. Note the domains of disseminated biotite enrichment in the groundmass, interpreted to be due to assimilation of the wall rock clasts. Some of the veins are terminated at the clast edges, and fragments of quartz vein are present in the bottom of the photo. Other veins crosscut the clast contacts. This sample is from a dacitic intrusion that has intruded along the margin of the Sewell Diorite (ET533, DDH1676, 395.6m).

B) Late dacite dyke, composed of sericite-altered plagioclase phenocrysts (light green), and primary biotite phenocrysts (light brown) which have been altered to sericite and clay. No quartz phenocrysts are visible in the photo. Fine-grained black disseminated secondary pyrite and hematite occur in the sericitised groundmass (ET486, DDH1413, 471.5m).

C) Late dacite dyke with sericite-carbonate altered plagioclase phenocrysts, embayed and rounded quartz phenocrysts, secondary opaque sulfides and rutile, and a typically strongly sericite altered fine grained groundmass (ET782, DDH1079, 435.8m).

D) Weakly altered late dacite from beneath the Braden Pipe, comprising plagioclase phenocrysts with a weak sericite - carbonate wash, euhedral unresorbed quartz phenocrysts, and minor biotite phenocrysts, replaced by chlorite, carbonate and epidote, in a very fine (<0.01mm) aplitic groundmass. Some of the quartz phenocrysts have jagged edges, suggesting that they have been broken during emplacement of the intrusion (ET788, DDH1068, 1013.5m).

Abbreviations: bt = biotite, plag = plagioclase, qz = quartz feldspar-stable alteration assemblages. Most of the vein generations described in Chapter 4 have been crosscut by the late dacite dykes, illustrating the late-mineral timing of the dykes. Strongly embayed to euhedral quartz phenocrysts (between 0 and 10%), and sericitised biotite and plagioclase phenocrysts occur in a fine aplitic quartz - plagioclase - sericite dominated groundmass (Figs 3.9C). The deep late dacite body beneath the Braden pipe contains unresorbed, euhedral and broken quartz phenocrysts, and pristine biotite and plagioclase phenocrysts (Fig. 3.9D). Riveros (1989) concluded that multiple phases of late dacite dykes exist, based on variations in quartz content, mineralogy, texture and geochemistry.

Late hornblende dykes

The last intrusive stage in the Teniente deposit and district are post-mineralisation, post-alteration late hornblende (± pyroxene, plagioclase, olivine) dykes (formerly termed lamprophyre dykes; Table 3.1). These are subvertical, <2m thick, NW trending, and continuous for hundreds of metres within the deposit.

3.4 THE BRADEN PIPE

The Braden pipe is a stratified to massive, polymict breccia pipe. Copper grades within the breccia average < 0.5 %, and most of the observed veins and intrusions have been cut by the breccia, indicating a late-mineral timing. It has a funnel shape, 1,200m wide at surface, with 60-70° inward dipping northern, eastern and southern walls (Fig. 3.10). The pipe is slightly asymmetrical, with a subvertical eastern wall. Braden pipe facies crop out on surface between 3,140 m and 2,500 m elevation. They are also exposed on all underground mine levels, and have been intercepted at a depth of ~1,400 m elevation in a deep drillhole (DDH1068), totaling approximately 1,750 m of vertical extent. In addition ~1,200 m of erosion is estimated to have occurred since formation of the pipe (Skewes, 1985; Floody, 2000). Hence, if it erupted, the Braden pipe would have had a vertical extent of at least 2,900 m. The pipe has been subdivided by Floody (2000). These subdivisions are reclassified using the facies-based nomenclature of Davies et al. (2000; Table 3.2; Figure 3.10).

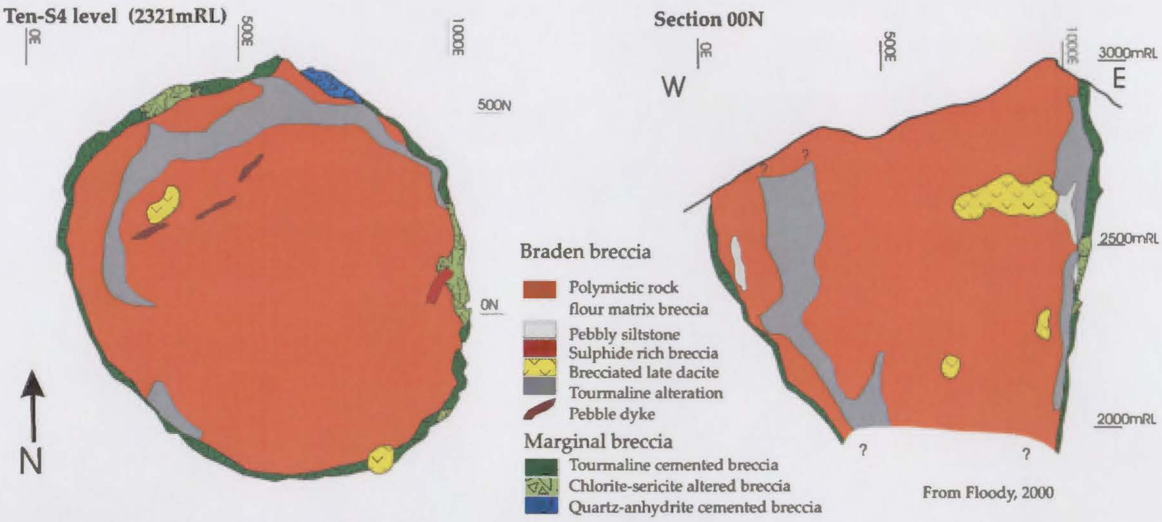

Figure 3.10. Plan and cross sectional view of the Braden pipe, showing the two major units of the Braden pipe, the inner Braden breccia, rimmed by the Marginal breccia. Note the sporadically distributed late dacite mega-clasts, and the internal concentric ring of tourmalinization in the pipe. Modified from Floody (2000).

Marginal breccia facies

The Marginal breccia is a 0 – 60m thick mineralised breccia that occurs as a ring around the Braden pipe. The Marginal breccia is predominantly a monomict, clast supported breccia, with sericite - quartz altered local wall rock clasts (Fig. 3.11A). In contrast to the Braden breccia, there is little or no evidence for clast transport or milling. The cement is composed of tourmaline and accessory sulfates (anhydrite, lesser gypsum), quartz, sulfides (mainly chalcopyrite, also bornite, pyrite) and sulfosalts (tennantite-tetrahedrite). Chlorite-sericite breccia and quartz-anhydrite breccia subfacies have also been defined by Floody (2000; Table 3.3), on the basis of the dominant cement phase.

Braden breccia facies

The Braden breccia occurs in the central part of the Braden pipe. It contains clasts of altered and mineralised Teniente host sequence, Teniente intrusive complex and minor exotic clasts, which are set in a rock flour matrix (Fig. 3.11B). Sharp discordant contacts between the Marginal and Braden breccias indicate that the Braden breccia is younger (Fig. 3.11C). Rare fragments of Marginal breccia within the Braden breccia further support this temporal relationship. However, gradational contacts were also reported by Floody (2000), characterized by a gradual decrease in the tourmaline

Facies	*Distribution*	*Features*	*Clasts*	*Matrix / cement*	*Terminology of Floody (2000)*
Marginal breccia					
Tourmaline cemented breccia	Outer margin of Braden pipe	Clast supported	Monomicitic, angular. Sericite – quartz altered local wall rock clasts (Teniente intrusive complex, or Teniente host sequence)	Tourmaline (± chalcopyrite, anhydrite, gypsum, bornite, tennantite) cement	Tourmaline Marginal breccia facies
Chlorite – sericite altered breccia	Sporadically overprints Marginal breccia	Clast Supported	As above, + strong sericite – chlorite alteration of clasts	Rock flour matrix. Cemented by sericite, chlorite, anhydrite, tourmaline, sulphides	Chlorite-sericite Marginal breccia facies
Quartz – anhydrite cemented breccia	Localised at the northern border of the pipe	Clast supported	As above	Quartz – anhydrite – sulfide cement	Quartz – anhydrite Marginal breccia facies
Braden breccia					
Stratified / massive polymictic rock flour matrix breccia	Main unit throughout pipe	Poorly sorted, matrix supported massiveto stratified.	Polymictic, sub-rounded to sub-angular. Up to 1m wide. Clasts include variably altered and mineralised Teniente host sequence, Teniente intrusive complex, and Marginal breccia. Minor exotic fragments include jasper, coarse porphyry	Rock flour matrix Cemented by sericite, minor quartz, tourmaline, anhydrite, gypsum, pyrite carbonates.	Agglomeratic breccia
Brecciated late dacite	Upper levels of breccia pipe		Blocks up to 250m wide of unmineralised, sericite (+ clay) altered late dacite, with brecciated margins		Brecciated latite porphyry unit
Pebbly siltstone	Arcuate zones near and parallel to pipe margin	Sharp contacts, weakly bedded	Clast poor (10-20%), <0.5 cm wide, strongly sericitised. Clasts have been finely milled.	Abundant rock flour matrix	Tuffaceous unit
Sulfide rich breccia	Concentrated near margin of pipe		Same as polymicitic facies	Tennantite, lesser chalcopyrite, bornite, pyrite, anhydrite cement	Sulfide breccia unit
Pebble dykes	Subvertical, NE trending, or concentric to pipe margins	Cuts other units, varies from clast to matrix supported	Up to 30cm wide, polymictic, well rounded and sorted clasts. Clasts mainly altered, unmineralised dacite.	Rock flour matrix Sericite cement	Pebble dykes

Table 3.3, Facies of the Braden Pipe, reclassified from Floody (2000). The facies are arranged in order from oldest at the top to youngest at the bottom.

content of the cement, and increase in the degree of rounding of the clasts from the Marginal breccia to the Braden breccia facies. Floody (2000) interpreted this relationship to be due to late-stage tourmaline alteration focused along the margins of the Braden breccia.

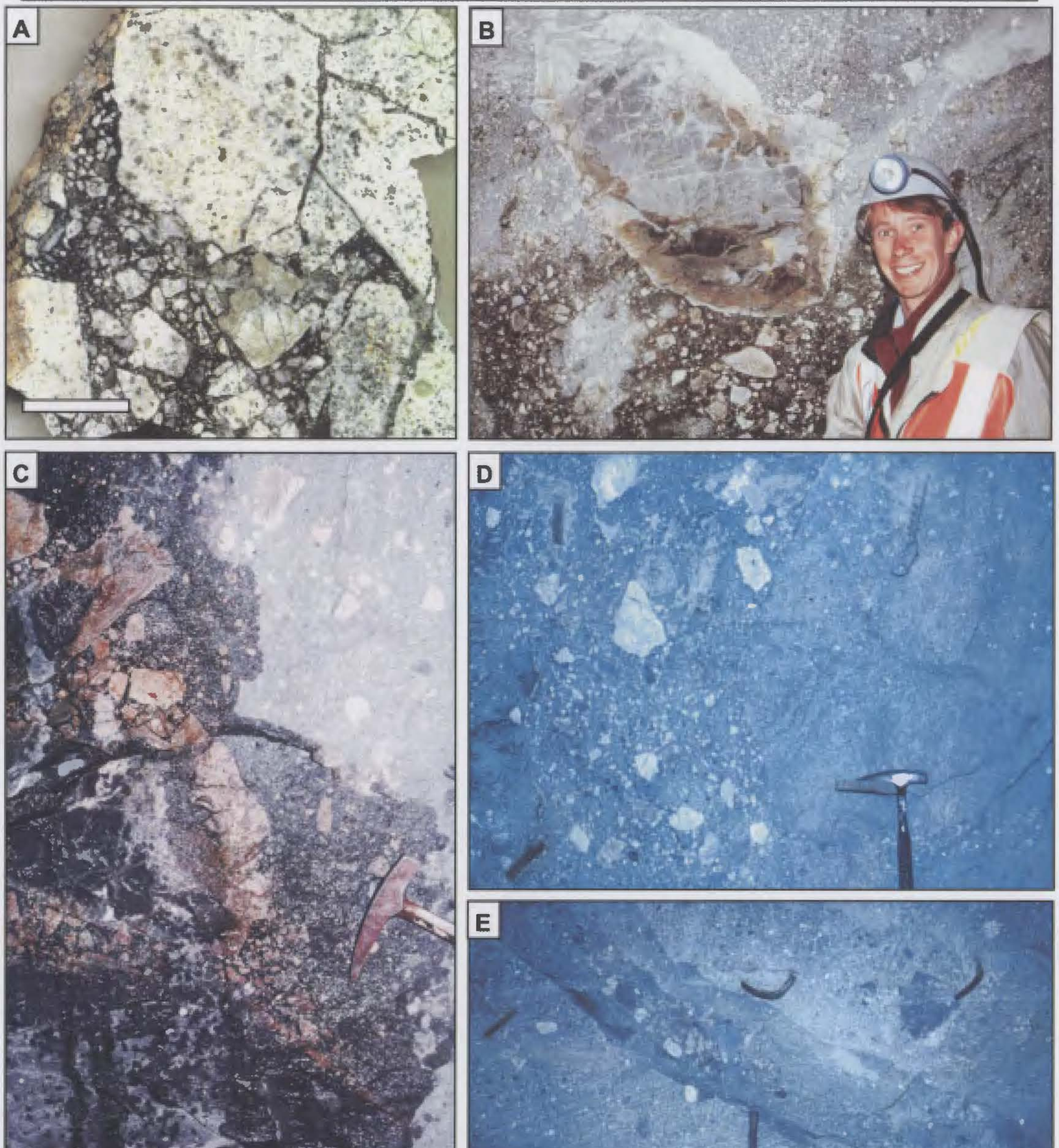

Figure 3.11. Braden pipe facies.

A) Marginal breccia, with a tourmaline (± Cu-Fe-sulfides, anhydrite, quartz) cement, and monolithic, sericite-altered, angular local wall rock clasts, in contact with the wall rock dacite porphyry. Some of the wall rock clasts have a jigsaw-fit (scale bar is 5cm, ET9, approximately 350N, 500E, 2350m RL).

B) Braden breccia polymictic facies, composed of subrounded to subangular, poorly sorted, altered, veined and mineralized Teniente host sequence clasts with sericite altered rims. The matrix is composed of rock flour, cemented by sericite. Note the terminated veins at the clasts margins.

C) Contact between the Marginal breccia (left), a monomictic, clast-supported breccia, and a crosscutting clast-poor, rock-flour-matrix supported variant of the polymictic unstratified facies of the Braden breccia (right). The contact of the Braden breccia is marked by a zone of sericite alteration.

D) Multiphase polymictic unstratified breccia facies. A clast-poor, weakly stratified polymictic facies on the right has been cut by a more clast-rich, coarser grained, poorly sorted polymicitic facies containing subrounded to angular clasts (left).

E) Poorly sorted polymictic breccia facies with subangular clasts up to 30cm wide, grading down to finer grained, moderately sorted stratified polymictic facies. Bedding layers dipping towards the pipe centre (to the left). A polymictic, weakly stratified sedimentary dyke has intruded the pipe facies at a shallow angle.

Polymictic rock flour matrix breccia is the main facies of the Braden breccia complex. The polymictic rock flour matrix facies is composed of crosscutting breccia bodies of differing clast sizes, shapes and abundance (Fig. 3.11D). It can be subdivided into massive and stratified subfacies. The stratified polymictic subfacies has bedding planes which dip gently towards the middle of the pipe (Fig. 3.11E), and occurs in an anular ring around a 350m wide cylindrical unit of massive polymictic facies in the centre of the pipe (Floody, 2000). Stratification is mainly developed at higher levels in the pipe, and diminishes and eventually disappears with depth (Floody, 2000). Stratified rock flour breccia dykes crosscut breccia units at irregular angles (Fig. 3.11E). Both the massive and stratified subfacies have been altered by tourmaline adjacent to irregular crosscutting veins and concentric zones within the pipe (Fig. 3.10).

The pebbly siltstone facies occurs in a discontinuous ring near the outer margin of the pipe. It has a strongly milled rock flour matrix (Table 3.3), interpreted by Floody (2000) to indicate strong comminution of the rock, possibly due to subsidence along arcuate normal faults within the pipe. The volumetrically minor sulfide-rich facies is composed of polymictic rock flour matrix breccia with abundant copper-Fe sulfides and sulfosalts occurring in the matrix (Table 3.2, Floody, 2000). The youngest facies are crosscutting subvertical pebble dykes that occur both within and outside of the pipe. Some pebble dykes trend NE (Fig. 3.10) whereas others occur concentric to the Braden pipe.

3.5 DISCUSSION

Environment of deposition for the Teniente host sequence

Little can be interpreted about the environment of deposition of the Teniente host sequence volcano-sedimentary units. Thiele et al. (1991), Koeppen and Godoy (1994) and Rivera and Falcón (1998) describe voluminous ash flows in the Farellones Formation in the Teniente region. The massive nature of the volcaniclastic siltstone unit of the Teniente host sequence is consistent with a sub-aerial ash fall deposit distal from the source vent (McPhie et al., 1993); however, no features such as juvenile pyroclasts, glass shards, or welded textures have been preserved for this to be assessed rigourously. Periods of subaqueous sedimentation are indicated by peperitic intrusive contacts, rare quench-fragmented volcanic clasts and thin black (now biotitic) siltstones, interpreted to have originally had a clay-rich composition. Thick volcaniclastic breccias in the south of the deposit may have accumulated in topographic lows, either bounded by faults or between volcanic centres. The features of the volcano-sedimentary units of the Teniente host sequence are broadly consistent with the district-scale geological setting proposed by Koeppen and Godoy (1994) and Rivera and Falcón (1998), in which volcano-sedimentary basins were infilled by the products of multiple volcanic centres (Fig. 3.12A).

The volcano-sedimentary sequence was intruded by a multiphase intermediate to mafic sill and stock complex. These units are interpreted to be intrusive based on their crystal-rich nature and discordant contact with volcano-sedimentary units on section-83 (Fig. 3.2). Interpreted peperitic contacts, and the presence of amygdales in the andesite porphyry indicate that the depth of emplacement of the sills was shallow (Mcphie et al., 1993). Clasts of andesite porphyry within the volcanic breccias indicate that some andesite porphyry units were at least partly extrusive, or that the sill complex was unroofed after emplacement. Intervals of volcanic siltstone within the fine-grained andesite porphyry are interpreted to be either enclaves of volcano-sedimentary wall rock, or a clast-poor variant of the hydrothermal biotite breccia unit. This intrusive complex was most likely a near-surface subvolcanic chamber, which was the magma source for extrusive coherent lavas (Fig. 3.12B).

Based on textural and mineralogical similarities, the andesite porphyry in the Teniente host sequence is correlated with mafic to intermediate subvolcanic rocks described and mapped to the east of Teniente (Rivera and Falcón, 1998; Fig. 2.3). These subvolcanic rocks occur close to relict volcanic centres localised along the Codegua Fault (Fig. 2.3). One such volcanic centre occurs only two kilometers east of the deposit. Coarse-grained andesite porphyry was also observed cropping out in the Agua Amarga prospect, within the Sewell Diorite complex (Fig. 2.4).

Relationship between the Braden pipe and the late dacite dykes

Late dacite dykes at Teniente are spatially and temporally related to the Braden pipe. As noted in section 3.2, late dacite dykes occur concentric to the pipe, and irregular masses up to 250m wide of sericite-clay altered late dacite occur in the upper parts of

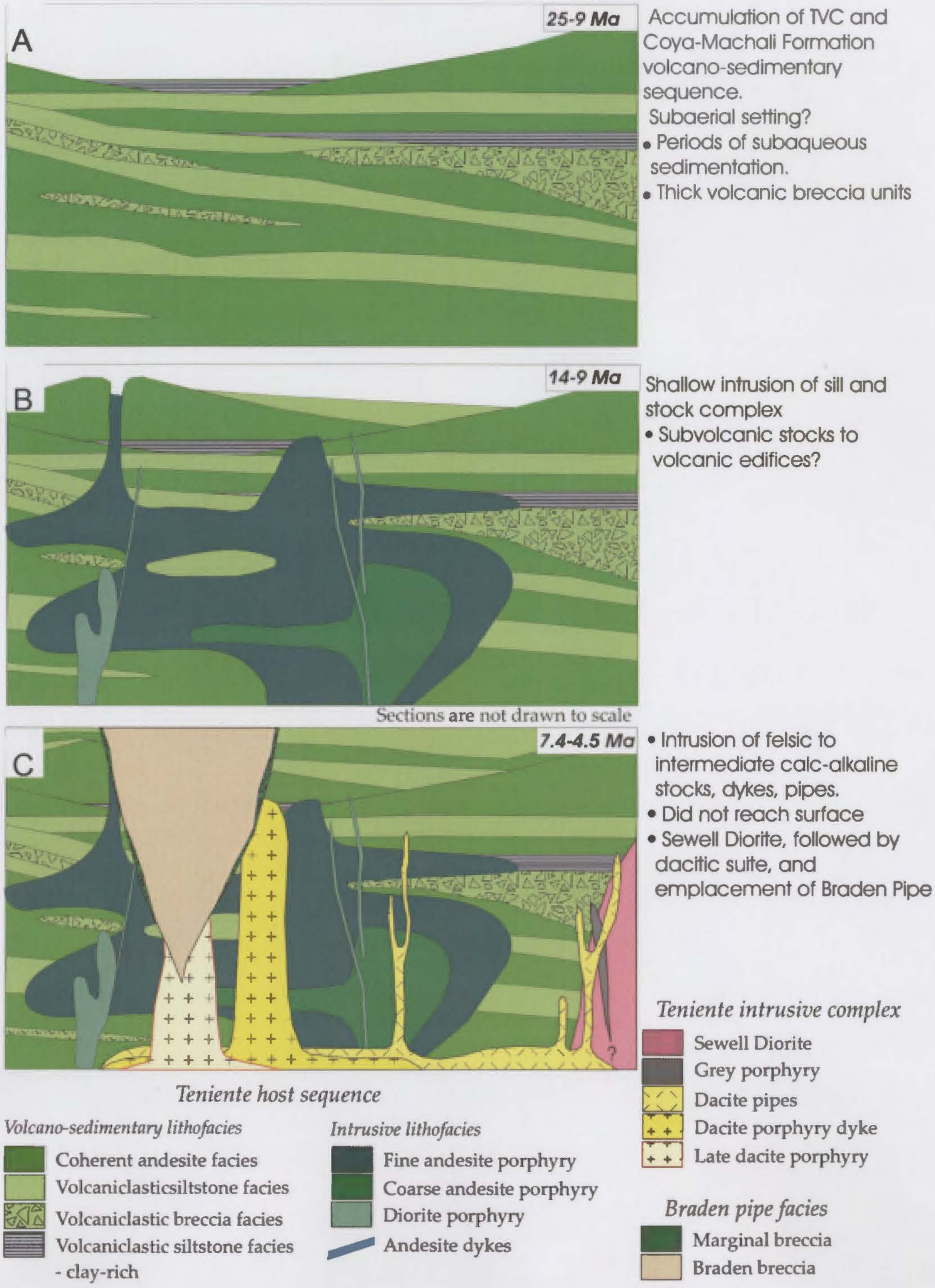

Figure 3.12, Schematic summary of the geological evolution of El Teniente. Note that detail in the Teniente host sequence is interpretive, and is based on the distribution of the Teniente host sequence in Figures 3.2, 3.3 and 3.4, and on Farellones Formation bedforms seen in the Teniente district. The spatial distribution of the felsic intrusions in the third panel is schematic, however the indicated temporal sequence is based on cross cutting relationships and geochronological data. Note that the Braden Pipe may or may not have vented at the surface. The depth of the parent magma chamber is unknown.

the Braden pipe (Camus, 1975; Fig. 3.10). These cannot be traced vertically, and appear to be mega-blocks incorporated into breccia pipe (Floody, 2000).

Although the bottom of the Braden pipe has not been delineated, several deep holes passed from the Braden pipe into a large late dacite body. In DDH1079, drilled from Ten-8 (1,983m elevation), this contact was intersected at around 1,600m elevation. Approximately 30m before the contact, the percentage of abraded late dacite clasts increases to the point that they become the dominant clast type. The late dacite in this drillhole is strongly sericitised, with weakly developed sulfidic veins and breccias localised at the contact with the breccia. No tourmaline breccia is present; however, minor disseminated tourmaline occurs at the contact. The late dacite continued from the breccia contact to the end of the hole (1,160 m asl). Similarly, in DDH1068 the contact between the Braden breccia and sericite - (+ tourmaline and pyrite) altered late dacite occurs at 1,400 m asl. The intensity of sericitic alteration decreases downhole. The hole ends in late dacite with pristine biotite and plagioclase phenocrysts at 970m asl. These long continuous intercepts of late dacite are interpreted to indicate the presence of a large late dacite stock at depth beneath the pipe. The consistent spatial relationship with the breccia implies that the late dacite is the source of the Braden breccia. The absolute temporal relationship of the two geological units is documented in Chapter 6. Breccia pipe formation is discussed below.

Breccia pipe formation

Breccia pipes are a common component of porphyry-related ore deposits (e.g., Davies et al., 2000; Tosdal and Richards, 2001) especially in the Miocene central Chile Cu belt (e.g., Sillitoe, 1985; Skewes and Stern, 1996; Frikken et al., submitted). Hydrothermal breccias occur when the combined fluid and magmatic pressure exceeds the lithostatic pressure, leading to hydraulic fracturing (Sillitoe, 1985; Tosdal and Richards, 2001). Of the various mechanisms proposed to generate hydrothermal brecciation, several are noted below:

- Second boiling in a porphyry body, and build up of fluid pressure around the carapace (e.g., Burnham, 1985)
- Rupturing of a pressure seal at the brittle-ductile transition (Fournier, 1999)

- Phreatomagmatic explosions, caused by interaction of relatively cool groundwater with magma, leading to irreversible steam generation (e.g., Sillitoe, 1985)
- Abrupt decrease in lithostatic load, for example glaciation, or collapse of an overlying volcanic edifice
- Local or remote seismic activity (Tosdal and Richards, 2001)

Many features observable in the Braden pipe are comparable to those generated by breccia pipe simulations formed by injecting compressed air into layered models (McCallum, 1985). McCallum (1985) found that steep-walled, funnel-shaped breccia pipes formed readily, sometimes accompanied by inward dipping fractures (Fig. 3.13). Fluidisation of the particulate matter leads to thorough mixing and rounding of the clasts, along with downward movement of the wall rock blocks along conduit margins (McCallum, 1985). Crude inward bedding is best developed in systems which broke through to the surface, or in which a large void is developed, and these beds can be transported downwards essentially intact (McCallum, 1985). Apart from surficial material such as fossils, there are no unique features to distinguish closed breccia pipes

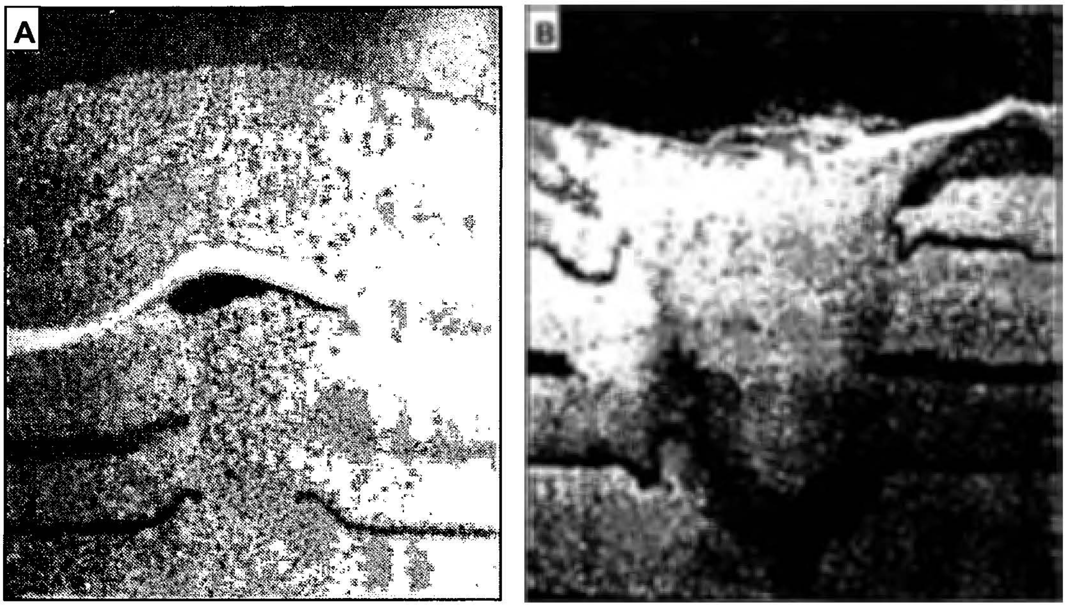

Figure 3.13. Simulations of fluidised breccia pipes, illustrating some of the structural features accompanying their formation (McCallum, 1985)

A) Closed breccia pipe developed beneath a cohesive (white) layer. A void has developed below the up-arched cohesive layer, and minor reverse faulting and folding occurs in the adjacent wall rocks.

B) Breccia pipe which has breached the surface, associated with generation of upward flaring reverse faults and sharp folds due to dragging of layers in the surrounding wall rocks. Note the annular zone of dark silt near the base that has descended along the conduit margins.

(Fig. 3.13A) from pipes that have broken through to the surface (Fig. 3.13B). By analogy with the simulations of McCallum (1985), the features of the Braden breccia indicate that it formed by fluidisation of particulate matter. The pipe may have breached the surface; however, there is no unequivocal evidence of this occurring. The formation of the Braden pipe in the context of the deposit evolution in detailed in Chapter 10.

3.6 SUMMARY

The major findings with regards to the Teniente host sequence are as follows:

- It is a sequence of feldspar-phyric, interpreted volcano-sedimentary and intrusive facies which have undergone significant textural destruction due to strong biotite alteration. The summarized geological evolution of the Teniente host sequence is shown schematically in Figures 3.12A-B.
- The volcano-sedimentary facies identified in the Teniente host sequence include coherent andesitic lavas, siltstones and volcanic breccias.
- Host sequence intrusive facies include fine- and coarse-grained andesite porphyry, gabbro, diorite porphyry, and andesite dykes.
- The main andesite porphyry intrusive complex is more than 450 m thick, and is located to the east of the dacite porphyry dyke. Sills or extrusive flows up to 100m thick are interlayered with the volcano-sedimentary sequences above and laterally to the main intrusive complex.
- To the east of the andesite porphyry intrusive complex a crystal-rich diorite porphyry stock intruded. To the west, an equigranular gabbroic unit was emplaced.
- Andesite dykes < 10 m thick are the youngest units of the Teniente host sequence.
- Although the spatial distribution of the mafic - intermediate intrusive complex is not well documented, the mafic complex may be correlatable with subvolcanic intrusions localised along the Codegua Fault. Alternatively, it may be associated with the Sewell Diorite complex.

With regards the Teniente intrusive complex the major findings are:

- It is a series of mafic to felsic intrusions emplaced into the Teniente host sequence

(Fig. 3.12C)

- The plagioclase- (+ minor quartz-biotite) phyric dacite porphyry dyke, dacite pipes and late dacites are all mineralogically and texturally similar. Intermediate to mafic intrusive phases include the equigranular plagioclase-hornblende-bearing Sewell Diorite, the biotite - K-feldspar phyric grey porphyry and late hornblende dykes.
- The Braden breccia complex is an enormous funnel-shaped, diatreme-like breccia pipe which formed approximately synchronously with the late dacites (Fig. 3.12C). The mineralised outer facies of the pipe is composed of angular, predominantly monomict local wall rock clasts cemented by tourmaline, sulfates and sulfides. The inner facies is composed of heterolithic clasts set in an unmineralised rock flour matrix.
- The intrusive sequence, shown schematically in Figure 3.12C, is as follows:

  1) Sewell Diorite stock in the SE corner of the deposit

  2) Dacite porphyry dyke, dacite pipes, and the grey porphyry. These intrusive phases are spatially separated; hence, relative timing relationships are speculative. It is interpreted that dacitic phases intruded along the margin of the Sewell Diorite, resulting in porphyritic marginal phases and an equigranular internal phase (e.g., Guzman, 1991)

  3) Late dacite dykes

  4) Braden pipe

  5) Late hornblende dykes

The paragenetic and structural relationship of the intrusive units and the mineralised vein array is detailed in Chapters 4 and 5 respectively. The geochronology of the host rocks, and their absolute temporal relationship to mineralisation is discussed in Chapter 6. The geochemical characteristics of the Teniente host sequence and the Teniente intrusive complex are documented and discussed in Chapter 7.