CHAPTER 5

Lithofacies associations in the Lienetz ore zone

5.1 Introduction

This chapter contains detailed descriptions and interpretations of lithofacies and facies associations of the Lienetz ore zone (Fig. 5.1). Mining activity in Lienetz at the time of data collection provided direct access to lithofacies within and peripheral to the ore zone in the core of the dissected Luise volcanic edifice. In contrast at Minifie (Chapter 4), data were collected below the main mineralised zone. As in the previous chapter, lithofacies are described using the scheme of McPhie et al. (1993) and Davies (2002).

The data for this research were collected by open pit mapping and drill core logging. Eight drill holes (DDHL1703, DDHL1704, DDHL1708, DDHL712, DDHL757, DDHL791, DDHL1160 and DDHL1476) were logged (Fig. 5.2), 1585 m in total. Open pit mapping from July to August 2007, April to May 2008 and November 2008 coincided with the mining.
of phases 6, 7 and 8 of the Lienetz ore zone (Fig. 5.2). As a consequence of active mining and potential geothermal outburst areas (PGOAs), benches had to be mapped in segments that spanned from bench 992 down to bench 824 (bench numbering corresponds roughly to the mine elevation; RL). A total of ~3750 m were mapped.

**The Lienetz ore zone**

The Lienetz ore zone has been mined since 2006 and is the current focus of mining. Mining activity to date has removed approximately half of the delineated resource. The Lienetz ore zone is steeply (~70°) north-dipping and vertically extensive, from 950 m RL to the extents of drilling at 600 m RL. Similar to the Minifie ore zone, Lienetz gold mineralisation is predominantly refractory; gold is hosted by pyrite and marcasite (Carman, 1994). Alteration associated with gold mineralisation is a weak to moderate (trace to 95%) replacement of precursor minerals by adularia + pyrite + marcasite + rutile ± illite ± calcite ± anhydrite ± apatite ± quartz ± vermiculite ± albite, the same mineralogy that is associated with Minifie shallow-level refractory ores (Carman, 1994). The vein stages and associated alteration in Lienetz were studied in detail by Carman (1994, 2003) and are summarised in Table 2.2.
5.2 Lithofacies associations in the Lienetz ore zone

At Lienetz, eleven principal lithofacies are exposed have been grouped into eight compositionally and texturally distinct lithofacies associations including: L1) polymictic, matrix-supported breccia to sandstone, L2) pyroxene-phyric coherent and clastic basalt facies association, L3) microdiorite, L4) anhydrite-biotite-orthoclase-cemented breccia facies association, L5) feldspar-phyric syenite, L6) pyrite-cemented breccia facies association, L7) polymictic, accretionary lapilli-bearing, matrix-supported breccia facies association, and L8) plagioclase-phyric andesite. Coherent and clastic lithofacies are described below in inferred order of formation (Figs. 5.5 to 5.19). Facies associations and interpretations are discussed in the associated text.

At shallow depths, host rocks of the Lienetz ore zone are obscured by texturally and compositionally destructive clay (kaolinite, smectite and illite; argillic and advanced argillic assemblages) alteration that extends from the pre-mining surface down to 850 m RL, forming a layer up to 200 m thick. These argillic and advanced argillic alteration assemblages are interpreted to be a product of a geothermal system (Carman, 1994). The variety of textures observed within the clay-altered zone is interpreted to reflect a combination of alteration intensity and varying host rock texture and lithology. Because the protolith is mostly obscured, the argillic and advanced argillic layer has not been included in the following lithofacies investigations.

Open-pit mapping data, drill hole logging data and information from the extensive LGL drill core image display database were compiled onto a plan map projected onto the most relevant mining surface (Fig. 5.3a) and an orthogonal section (7669) that transects the Lienetz ore zone (Fig. 5.4). North-south sections 9140 East, 9035 East and 9000 East (Figs. 5.3b, 5.3c and 5.3d) are shown to further highlight the variations in geometry of key lithofacies (L4 and L7) stepping towards the west.
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Figure 5.3 Lienetz geology map
(A) Geology map of the Lienetz ore zone. (B, C, D) North-south sections stepping to the west. (B) Section 9140 East, (C) Section 9035 East, and (D) Section 9000 East.
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Figure 5.4 Lienetz section 7669
(A) Geology of section 7669, and corresponding gold grades (B) and sulfur volume percent (C).
5.2.1 Polymictic, matrix-supported breccia to sandstone (L1)
The polymictic, matrix-supported breccia to sandstone facies (Fig. 5.5) is diffusely bedded (0.5 to 2 m thick beds) and contains abundant pyroxene-phyric basaltic clasts, as well as pyroxene and plagioclase crystal fragments in the matrix. Pyroxene-phyric basalt clasts are dense or contain calcite-filled amygdales. Some pyroxene-phyric clasts have amoeboid clast shapes (Fig. 5.5c). This lithofacies is encountered throughout and peripheral to the Lienetz ore zone (Figs. 5.3 and 5.4). Abundant veins and associated alteration extend into, and obscure, textural variation within this lithofacies adjacent to the anhydrite-biotite-orthoclase-cemented breccia facies (L4).

Interpretation: The diffuse, thick beds and normal grading observed in the L1 lithofacies are interpreted to have been produced by gravity-driven mass-flows. This lithofacies is the oldest package exposed at Lienetz and is interpreted to be correlative of the M4a lithofacies exposed in the Miniore ore zone. Characteristics that may have constrained the source of components or depositional setting were not observed for this lithofacies at Lienetz.

5.2.2 Pyroxene-phyric coherent and clastic basalt facies association (L2)
This facies association consists of one coherent facies (L2a) and spatially and compositionally related breccia facies (L2b). This facies association is best documented in open pit exposures along the eastern wall (Figs. 5.3 and 5.4) but is also observed west of the ore zone in DDHL1704. Altered and veined equivalents were observed along the margins of the L4 anhydrite-biotite-orthoclase-cemented breccia facies association, but were not differentiated. Exposures in the open pit, from 980 to 872 (current level of exposure), are green owing to the chlorite-calcite alteration assemblage. West of the ore zone in DDHL1704, from 1112 to 980 m RL, a purple hematite-chlorite-calcite alteration assemblage is present.
Lithofacies L1: Polymictic, matrix-supported breccia to sandstone

**Grain size** predominantly <4 cm; locally up to 40 cm
- pebble to boulder breccia

**Components Clasts:** 20 to 70%, sub-angular to sub-rounded
- polymictic, pyroxene-phyric basalt, plagioclase-phyric andesite (?), amphibole-phyric basalt (?), pink, purple and green aphanitic (basalt?) clasts
- some pyroxene-phyric basalt clasts have intricate, amoeboid clast shapes

**Matrix:** 10 to 20%, <2 mm (sand-sized)
- abundant plagioclase and pyroxene crystal fragments

**Cement:** <5%
- quartz and calcite

**Lithofacies**
- massive to weakly graded
- 0.5 to 2 m thick beds
- chaotic clast organisation
- matrix-supported
- moderately to poorly sorted

**Geometry Contacts:** Sharp to gradational with L2b and L2a facies. Sharp, irregular contacts locally with L2a basalt

**Distribution:** Best preserved localities are on the eastern wall (phase 8; Fig. 5.2) and west of L7 facies. Altered equivalents gradational to L4 facies; peripheral to ore zone.

**Alteration** Selective pervasive replacement of pyroxene phenocrysts by calcite. Fine grained chlorite and calcite alteration throughout matrix and in thin veinlets <0.2 mm wide.

**Associated Facies** Spatially and compositionally associated with pyroxene-phyric basalt (L2a) and gradational to monomictic, pyroxene-phyric basalt breccia (L2b).

**Interpretation:** Volcano-sedimentary facies
- Volcaniclastic debris flow deposit

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**Figure 5.5 Polymictic, matrix-supported breccia to sandstone (L1)**
(A) Graphic log from DDHL1704 (phase 7), showing the distribution of the L1c lithofacies and sharp contacts with L2a lithofacies. Also shown are sharp contacts with the L8 lithofacies. (B) Photomicrograph (PPL) of sample 08011 (3912N, 9782E, 920 m RL) showing the crystal-rich sandstone. (C) Hand sample photograph from bench open pit bench 884.
Pyroxene-phyric basalt (L2a)

The pyroxene-phyric basalt (Fig. 5.6) is the dominant lithology on the eastern pit wall (Fig. 5.3) and predominantly occurs as 5 to 15 m thick sheets or masses. Two near-vertical, sharp sided, dykes (~5 m wide) were also observed in the open pit at 4070 N. The most diagnostic feature of this coherent facies is the complete replacement of pyroxene phenocrysts by fine grained calcite (Fig. 5.6d), but this is not a primary feature. Immobile element ratios suggest the composition was basalt (Fig. 5.6a). Contacts with associated facies L2b and L1 are sharp and irregular to gradational. Both vesicular and dense basalts are observed as coherent units and as clasts in lithofacies L2b and L1.

Monomictic, pyroxene-phyric basalt breccia (L2b)

A monomictic, pyroxene-phyric basalt breccia facies is spatially associated with and gradational to the pyroxene-phyric basalt (L2a) on the Lienetz eastern wall (Figs. 5.3 and 5.6). This lithofacies is massive and predominantly non-bedded. Clasts are splintery to tabular with cuspat to curviplanar margins (Fig. 5.7b) and jigsaw-fit to clast-rotated clast organisation (Fig. 5.7c). Intervals of the monomictic, pyroxene-phyric breccia are typically <2 m thick and grade into L1, the polymictic, matrix-supported breccia to sandstone facies (Fig. 5.7a).

Interpretation: This facies association is interpreted to be the coherent and clastic facies associated with lavas and/or intrusions. Clasts within the monomictic, pyroxene-phyric breccia are interpreted to be products of quench fragmentation and the lithofacies is interpreted as in-situ and resedimented hyaloclastite deposited in a subaqueous depositional environment. Peperite breccias were documented by Herrmann (2002) at the eastern end of the Lienetz open pit, are interpreted to be part of this facies association.

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Lithofacies L2a: Pyroxene-phyric basalt

Sample 08022

Texture
Porphyritic with a plagioclase-microlitic groundmass

Components
- Plagioclase (40%), euhedral, lath-like phenocrysts, 0.2 to 1 mm in length
- Pyroxene (20%), euhedral phenocrysts, 1.5 to 0.1 mm, completely replaced by calcite
- Apatite (trace), euhedral, prismatic, up to 200 um, dominantly <50 um
- Microlitic groundmass (40%) composed of plagioclase laths (<100 um) and an aphanitic, homogenous opaque phase
- Opaques: pyrite, chalcopyrite

Alteration
Selective pervasive replacement of pyroxene phenocrysts by calcite. Fine grained chlorite and calcite alteration are found throughout the groundmass and in thin veinlets (<0.2 mm wide).

Associated Facies
Gradational contacts with the monomictic, pyroxene-phyric breccia (L2b). Sharp and irregular contacts with polymeric, matrix-supported breccia to sandstone (L1).

Interpretation: Coherent facies of basaltic lavas and shallow intrusions

Figure 5.6 Pyroxene-phyric basalt (L2a)
(A) Trace element discrimination diagram after Pearce (1996). Coloured symbols represent XRF results (Table C.1). (B) Irregular contact between L2a and L1 on bench 884. (C) Hand sample photograph from open pit bench 884. (D) Photomicrograph (XPL) of calcite-altered pyroxene phenocrysts and pristine plagioclase phenocrysts in sample 08022 (3885N, 9755E, 920 m RL). (E) Reflected light photomicrograph of chalcopyrite and pyrite in sample 08022.
Lithofacies L2b: Monomictic, pyroxene-phyric basalt breccia

Grain size  
- <10 cm predominantly; locally up to 25 cm
- pebble to boulder breccia

Components  
**Clasts:** 70 to 80%, angular to sub-angular  
- monomictic, pyroxene-phyric basalt  
- splintery to tabular clast shapes with curviplanar margins  
**Matrix:** 10 to 20%, <2 mm (sand-sized)  
- abundant plagioclase and pyroxene crystal fragments  
**Cement:** <5%  
- quartz and calcite

Lithofacies  
- predominantly massive and non-bedded  
- locally weakly graded near top contacts with L1 lithofacies  
- jigsaw-fit to clast-rotated organisation  
- clast- to matrix-supported  
- poorly to very poorly sorted

Geometry  
**Contacts:** Gradational to sharp with L2a (pyroxene-phyric basalt) and L1 (polymictic, matrix-supported breccia to sandstone).  
**Distribution:** Eastern wall of Lienetz; spatially associated with L2a.

Alteration  
Selective pervasive replacement of pyroxene phenocrysts by calcite. Fine grained chlorite and calcite alteration throughout matrix and in veinlets <0.2 mm wide.

Associated Facies  
Pyroxene-phyric basalt (L2a) and polymictic, matrix-supported breccia to sandstone (L1).

Interpretation: Autoclastic facies associated with the L2a basalt lavas and shallow intrusions  
- In-situ and reseđimented hyaloclastite

**Figure 5.7 Monomictic, pyroxene-phyric basalt breccia (L2b)**  
(A) Generalised graphic log through the L2 and L1 facies association from open pit bench 920, showing the distribution of the L2b lithofacies with gradational to sharp contacts with L2a and L1 lithofacies.  
(B) Photomicrograph (PPL) highlighting the angular and splintery to shard-like clast shapes (sample 08008; 3899N, 9767E, 920 m RL).  
(C) Jigsaw-fit to clast-rotated clast organisation of hand sample 08008 from the Lienetz open pit bench 920.
5.2.3 Microdiorite (L3)

The southern extent of the Lienetz ore zone is marked by weakly mineralised (<1 g/t Au) and altered microdiorite (Fig. 5.8) that has dimensions of approximately 200 m x 100 m with a vertical extent of at least 200 m (Figs. 5.3 and 5.4). This lithofacies plots as basaltic andesite on the immobile trace element plot of Pearce (1996; Fig. 5.8a), but the rock name “microdiorite” is chosen to reflect its medium grained, equigranular character and the modal mineralogy of plagioclase + biotite (primary) + pyroxene + amphibole ± olivine, following the method of Streckeisen (1976). A sample of this lithofacies was submitted for dating at the UBC geochronology laboratory but no zircon or monazite was found. Hornblende was not used for Ar-Ar dating due to the presence of high-temperature alteration minerals (secondary biotite and chalcopyrite).

Interpretation: This microdiorite is interpreted to be an intrusion. The margins of the microdiorite are irregular and thin dyke-like fingers (10 cm to 1 m wide) protrude from the main body into the host stratigraphy. Despite the relatively “fresh” appearance and low gold grade of this coherent facies, secondary biotite and associated chalcopyrite, magnetite and pyrite are found throughout. As well, veins of anhydrite-calcite-quartz-orthoclase, transitional to the L4 anhydrite-biotite-orthoclase-cemented breccia facies association, are found throughout the microdiorite, decreasing in intensity away from the margins.

5.2.4 Anhydrite-biotite-orthoclase-cemented breccia facies association (L4)

This facies association consists of two polymictic clastic lithofacies (L4a and L4b) that are spatially and compositionally associated with anhydrite veins. The anhydrite veins contain anhydrite, calcite, quartz, orthoclase, biotite, actinolite / chlorite, adularia, pyrite, chalcopyrite, magnetite, sphalerite and marcasite. Anhydrite occurs as large pods, in steeply oriented veins and most commonly, in shallowly north-dipping veins (Fig. 5.9). These veins range up to ~1 m wide and are described as the “anhydrite seal” by some geologists at Lihir.

Lithofacies L4a is anhydrite-biotite-orthoclase-cemented breccia and lithofacies L4b is laminated to massive, quartz-calcite sandstone to breccia. This facies association is
Lithofacies L3: Microdiorite

Sample 08023
Texture Equigranular, holocrystalline <1.5 mm grain size

Components
- Plagioclase (50-60%) euhedral to subhedral, equant to stubby crystals up to 1.5 mm in size
- Biotite (10%) anhedral, <0.5 mm
- Orthopyroxene (10%) subhedral to euhedral, 0.5 to 1 mm
- Clinopyroxene (15-20%) subhedral, <0.5 mm
- Amphibole (5 %), <0.5 mm, subhedral, turbid appearance
- Apatite (<0.5%), euhedral, prismatic, 50-200 um
- Opaques (<1%): magnetite, chalcopyrite, pyrite

Lithofacies Massive, light grey to greenish
Interpretation: Igneous intrusion

Alteration: Selective, weak alteration of plagioclase to white micas. Some biotite is secondary and is observed within fractures and cleavage of the pyroxene crystals. Magnetite and chalcopyrite are partially to almost completely replaced by pyrite and associated with biotite.

Figure 5.8 Microdiorite (L3)
(A) Trace element discrimination diagram from Pearce (1996). Coloured symbols represent XRF results generated (Table C.1). (B) Photomicrograph (XPL) showing the equigranular texture of clinopyroxene, orthopyroxene and plagioclase in sample 08023 (4007N, 9755E). (C) Photomicrograph (XPL) of biotite and apatite in sample 08023. (D) Photomicrograph (PPL) of an entirely replaced olivine crystal with a chlorite / serpentine halo and opaques in the relict cleavage, sample 08023. (E) Reflected light photomicrograph showing magnetite, pyrite and chalcopyrite in sample 08023.
restricted to the central ore zone in Lienetz and is characterised by moderate gold grades of 1.5 to 4 g/t over 12 m blast hole composites.

**Anhydrite-biotite-orthoclase-cemented breccia (L4a)**

The anhydrite-biotite-orthoclase-cemented breccia facies (Figs. 5.10 and 5.11) is a vertically extensive body that occupies a central region in the Lienetz ore zone (Figs. 5.3 and 5.4). The upper portions are obscured by the argillic and advanced argillic alteration layer and the lower limits have not yet been intersected by the drilling program. The breccia is poorly sorted and characterised by ubiquitous jigsaw-fit to clast-rotated organisation.
Lithofacies L4a: Anhydrite-biotite-orthoclase-cemented breccia

**Grain size** 2 mm to 30 cm
- granule to boulder breccia

**Components**
- **Clasts:** 5 to 90%, angular to round
  - polymictic depending on the host rock stratigraphy (L1, L2, L3 and L5 facies associations)
  - biotite-orthoclase-anhydrite-altered clasts with disseminated sulfides
  - equant blocky to tabular, splintery, ragged and irregular clast shapes
- **Matrix:** 10 to 45%, <2 mm (sand-sized)  
  - composition same as clasts
  - biotite-orthoclase-anhydrite-altered with disseminated sulfides
- **Cement:** 5 to 60%
  - anhydrite, calcite, orthoclase, quartz, apatite, biotite, adularia
  - pyrite, chalcopyrite, magnetite, sphalerite, marcasite
  - grades into veins of cement composition
  - locally bladed anhydrite
  - drusy (open space fill) textures

**Open Space:** <5%

**Lithofacies**
- massive to weakly stratified (~270°/40° N)
- jigsaw-fit to clast rotated
- clast- to cement- to matrix-supported
- poorly sorted

**Geometry**
- **Contacts:** Gradational contacts; often broken in drill core. Southern contact with L1 is oriented ~280°/70° N.
- **Distribution:** Centre of the Lienetz open pit and centred on ore zone.
- **Morphology:** Vertically extensive, elongate NE and up to 300 m wide.

**Alteration**
- Clasts and matrix are pervasively orthoclase-biotite-anhydrite altered. Upper 200 m overprinted by texturally destructive argillic and advanced argillic alteration.

**Associated Facies**
- Spatially associated with feldspar-phyric syenite (L5) and anhydrite veins. Spatially and compositionally associated with laminated to massive, quartz-calcite sandstone to breccia (L4b).

**Interpretation:** Hydrothermal breccia with magmatic-hydrothermal cement mineralogy

Figure 5.10 (caption on next page)
Figure 5.10 Anhydrite-biotite-orthoclase-cemented breccia (L4a)

(A) Hand sample photograph of sample DDHL791_170.86 m. (B) Hand sample photograph of DDHL791_293.48 m. (C) Hand sample photograph of DDHL791_238.05 m with inset highlighting the jigsaw-fit organisation of clasts and matrix. (D) Graphic logs from DDHL791 and DDHL1160, showing the textural variation within the L4a lithofacies. Inset figure on log DDHL791 highlights the ragged, jigsaw-fit clast organisation separated by cement. (E) Photomicrograph (XPL) of sample DDHL757_327.80 m, showing the biotite, orthoclase and anhydrite cement. (F) Hand sample photograph of sample DDH757_324.55 m showing the overprint of L4a facies on the host L1 polymictic breccia. Note: the inset false colour images (in C and D) are drawn to highlight the clast organisation of breccias. Clasts are the coloured polygons.
Figure 5.11 L4a cement mineralogy and textures

(A) Photomicrograph (PPL) of apatite + actinolite cement in sample DDHL791_242.26 m. (B) Photomicrograph (PPL) of biotite + anhydrite in sample DDHL1160_173.05 m. (C) Photomicrograph (XPL) of anhydrite (bladed) + orthoclase cement in sample DDHL791_238.05 m. (D) Photomicrograph (XPL) of coarse anhydrite + orthoclase in sample DDHL1160_145.48 m. (E) Reflected light photomicrograph of pyrite surrounding magnetite cement in sample DDHL791_242.26 m. (F) Reflected light photomicrograph of marcasite surrounding magnetite cement in sample DDHL791_242.26 m. (G) Reflected light photomicrograph of sphalerite +pyrite + chalcopyrite in sample DDHL1160_173.05 m. Inset photomicrograph is the same field of view in PPL showing the pale sphalerite. (H) Hand sample photograph of free gold hosted in the bladed anhydrite of sample DDHL1484_271.0 m.
The proportion of cement varies markedly, as does the grain size, from pebble breccia up to boulder breccia. Thick anhydrite veins or pods are concentrated near the centre of the L4a body. Their abundance decreases away from the centre of the body. The margins of the breccia are surrounded by a network of thin (<20 cm) anhydrite veins. The breccia consists of clasts of the microdiorite (L3), the polymictic, matrix-supported breccia to sandstone (L1), the pyroxene-phyric coherent and clastic basalt facies association (L2) and feldspar-phyric syenite (L5). Clasts of these lithofacies are predominantly strongly altered and disrupted so the original contacts cannot be recognised. The centre of the anhydrite-biotite-orthoclase-cemented breccia (L4a) has been intruded by the feldspar-phyric syenite (L5) dyke. Zones of abundant anhydrite cement and veins are also spatially associated with the syenite (Fig. 5.4a).

Thin (<1 mm) dark bands within anhydrite record the incremental opening and incorporation of wall rock or breccia clasts in the anhydrite pods, veins and cemented breccia (Figs. 5.10a, top corner of 5.10c and 5.11a). Most of the banded anhydrite veins are shallowly north-dipping, and the bands are parallel to the margins of the vein walls. Bands are composed of apatite, pyrite, magnetite, marcasite and actinolite (locally chlorite) and have a wispy styolitic appearance. This shallow dip is also evident in the clast organisation in the breccia, which defines a weak stratification of alternating grain-size domains (Figs. 5.10c and 5.10d).

Laminated to massive, quartz-calcite sandstone to breccia (L4b)
The laminated to massive, quartz-calcite sandstone and breccia occurs as thin (10 cm up to 2 m) dykes that are variably discordant to, but contained within the L4a breccia facies (Fig. 5.4a). This lithofacies has moderate to steep dips and predominantly sharp contacts (Fig. 5.12). The hydrothermal minerals (calcite, quartz, anhydrite and adularia) are granular (the calcite is sub-rounded) and interpreted to be clasts. Although not bedded, the lack of a crystalline texture and of a jigsaw fit texture suggest transport as clasts. Elongate fine quartz crystals are arranged in a cross-hatched pattern (Fig. 5.12c). Non-hydrothermal mineral clasts are similar to those contained in the L4a breccia, but also include plagioclase and pyroxene.
Lithofacies L4b: Laminated to massive, quartz-calcite sandstone to breccia

**Grain size**  
<3 cm; predominantly <2 mm  
- pebble breccia to sandstone

**Components**  
- *Clasts*: 0 to 70%, angular to round  
  - polymictic; anhydrite-calcite-orthoclase vein fragments, biotite-orthoclase altered plagioclase-phyric clasts, clay-altered clasts  
  - blocky to wispy clast shapes  
- *Matrix*: 30 to 100%, <2 mm (sand-sized)  
  - broken feldspar and pyroxene crystals  
  - calcite vein fragments  
  - subhedral to euhedral quartz, calcite and minor anhydrite

**Lithofacies**  
- stratified to graded  
- chaotic clast organisation  
- matrix-supported  
- moderately to well sorted

**Geometry**  
- *Contacts*: Sharp to gradational to anhydrite veins and L4a breccia.  
- *Distribution*: Spatially restricted to the L4a breccia distribution. Typically near or within anhydrite veins.  
- *Morphology*: Discrete, discordant dykes and veins are <2 m wide.

**Alteration**  
Lithic fragments are biotite-orthoclase altered. Vein fragments are locally clay altered.

**Associated Facies**  
Spatially and compositionally related to the anhydrite-biotite-orthoclase-cemented breccia (L4a) and associated anhydrite veins.

**Interpretation:** Hydrothermal clastic facies produced by high fragmentation efficiency and significant transport. Deposition in a subsurface environment as dykes and veins.

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**Figure 5.12** (caption on next page)
crystal fragments (Fig. 5.12d), as well as anhydrite + calcite + orthoclase vein fragments (Fig. 5.12f). Anhydrite clasts are rimmed by minor orthoclase and surrounded by calcite (Fig. 5.12g). The outer calcite shell of the anhydrite clasts has irregular, sharp to diffuse margins, giving the clasts wispy, irregular shapes. Only minor sulfides occur in L4b.
Interpretation: The anhydrite-biotite-orthoclase-cemented breccia facies association occupies the central portion of the Lienetz ore zone and is associated with moderate gold grades, typically <4 g/t Au. Anomalous grades occur where free gold is located within bladed anhydrite domains (Fig. 5.11h). The biotite-orthoclase cement mineralogy is consistent with magmatic-hydrothermal conditions (Carman, 1994; Seedorff et al., 2005). The jigsaw-fit to clast-rotated organisation of L4a suggest minimal to no transportation, even though fragmentation is interpreted to have been efficient based on the presence of a fine-sand-sized fraction. L4a is interpreted to be a magmatic-hydrothermal breccia (e.g. Sillitoe, 1985). Pyrite, magnetite, chalcopyrite and sphalerite were deposited during this stage. This facies hosts gold mineralisation (1 to 4 g/t Au) that is considered low-grade at Lihir, but is high grade when compared to most porphyry copper-gold deposits (e.g. average grades of 1.05 g/t at Grasberg, Irian Jaya; 1.42 g/t at Lepanto-Far South East, N. Luzon; 0.77 g/t at Cadia, NSW; Cooke et al., 2005).

The L4b lithofacies is interpreted as a hydrothermal clastic facies produced by high fragmentation efficiency and significant transport. The discordant, dyke-like geometry reflects deposition in the subsurface environment. The spatial association of this facies with the fine-grained intervals of the L4a lithofacies and the vein / cement dominant zones suggests that they formed in zones of high and sustained fluid flow. The components may have been winnowed from the surrounding L4a lithofacies (e.g. Bryner, 1962) with no new cement crystallising.

The top of this facies association is obscured by the overprint of the argillic and advanced argillic alteration layer. Currently this unit is associated with anomalously “hot” areas within the open pit. Anhydrite dissolution may be creating pore space that is being exploited by the active geothermal system.

5.2.5 Feldspar-phyric syenite (L5)
The centre of the Lienetz ore zone contains a phaneritic, feldspar-phyric coherent facies (Fig. 5.13) with a dyke-like geometry and indistinct margins (Figs. 5.3 and 5.4). The dyke-like geometry was confirmed by correlation of the unit along drill core and open pit exposures.
Lithofacies L5: Feldspar-phyric syenite

Sample 08024
Texture Porphyritic with a holocrystalline fine grained groundmass

Components
- Feldspar phenocrysts (20 to 35%), simple twinned euhedral to subhedral laths from 1 to 4 mm in length
- Plagioclase (40%), euhedral to subhedral, equant crystals from 1 to 0.5 mm
- Relict ferromagnesian phases (25%; pyroxene?, biotite and amphibole shapes) replaced by biotite and anhydrite
- Apatite (<0.5%), euhedral, prismatic, <0.5 mm with one observed crystal 2 mm in length
- Opaques: magnetite, chalcopyrite, pyrite

Lithofacies Massive

Interpretation: Igneous dyke

Alteration: Selective pervasive, strong alteration. Feldspars replaced by white mica, calcite and anhydrite. Ferromagnesian minerals replaced by biotite. Orthoclase and biotite alteration throughout.

Figure 5.13 Feldspar-phyric syenite (L5)
(A) Trace element discrimination diagram after Pearce (1996). Coloured symbols represent XRF results (Table C.1). (B) Photomicrograph (XPL) showing the feldspar phenocrysts in a fine grained holocrystalline groundmass, sample 08024 (4104N, 9109E). Note the large apatite phenocryst. (C) Photomicrograph (XPL) of simple twinning of feldspar phenocrysts and the white mica + carbonate + anhydrite alteration in sample 08024. (D) Hand sample photograph of sample DDHL791_186.73m. (E) Photomicrograph (PPL) of orthoclase + biotite alteration in sample 08024.

Chapter 5 - Lithofacies associations in the Lienetz ore zone
There appears to be either more than one intrusion or one intrusion segmented by faults that have not been recognised within the ore zone. Each unit appears to be <25 m wide, vertically extensive and dipping slightly to the northwest. This lithofacies is strongly altered by biotite + orthoclase + white mica + calcite + anhydrite and plots as having an andesitic composition on the immobile trace element plot of Pearce (1996; Fig. 5.13a). The feldspar phenocrysts are ubiquitously simple twinned and are most likely sanidine or orthoclase. The ferromagnesian minerals are completely replaced by biotite and orthoclase; crystal habits of biotite and amphibole are observed. This relict mineralogy and phaneritic texture is reflected in the “syenite” rock name, chosen following the method of Streckeisen (1976). A sample of this lithofacies submitted for dating at the UBC geochronology laboratory contained no zircon or monazite. Biotite in this sample is secondary, and is not suitable for dating the age of the intrusion.

*Interpretation:* This feldspar-phyric syenite is interpreted to be a dyke. A network of anhydrite-calcite-quartz-orthoclase veins, transitional to the L4 anhydrite-biotite-orthoclase-cemented breccia facies, is hosted within it. Particularly well developed veins (greater than 2 m thick) are condensed peripheral to the syenite. It is unclear whether this lithofacies post- or pre-dates the L4 anhydrite-biotite-orthoclase-cemented breccia facies association but it is clear that there is a spatial link between the two. On the eastern edge of the open pit, a small outcrop of syenite has an associated monomictic breccia facies. Detailed facies analysis was impossible at the time of data collection, but it is speculated that this could be a brecciated intrusion.

### 5.2.6 Pyrite-cemented breccia facies association (L6)

This facies association consists of two clastic facies (L6a and L6b) defined on the presence of a pyrite-dominated cement, a sooty-black appearance and association with high-grade gold mineralisation (4 to >7 g/t Au).
Pyrite-cemented, apparently monomictic breccia (L6a)

This lithofacies occurs as a 10- to 50-m wide layer at the boundary between the L4 facies association and the overlying argillic blanket (Figs. 5.3b, 5.3c, 5.3d and 5.4a). Contacts between both are gradational and highly variable. The pyrite-cemented, apparently monomictic breccia facies (Fig. 5.14) characteristically has abundant (up to 30%) open space and is associated with the high grade core of the Lienetz ore zone (Fig. 5.14h). The open space and porous character results in zones of broken drill core and poor recovery and is termed by LGL mine geologists as “the boiling zone” (Fig. 5.14h).

The cement component is a very fine-grained assemblage of pyrite + quartz + anhydrite + orthoclase + biotite + calcite + apatite + sphalerite + galena + chalcopyrite + magnetite + pyrrhotite + marcasite + realgar. Pyrite occurs in many forms: porous to homogenous and euhedral to anhedral. Pyrite locally has inclusions of chalcopyrite ± magnetite ± sphalerite ± galena, and displays ragged margins, fibrous textures (Fig. 5.14g), and pyrite overgrowth around pyrite cores (core and rim texture; Fig. 5.14f). The clasts are altered by biotite + orthoclase + anhydrite + pyrite + illite. Locally the clast protolith appears to have been polymictic, matrix-supported breccia to sandstone (L1) and pyroxene-phyric basalt (L2) but may also include microdiorite (L3) and feldspar-phyric syenite (L5). The internal organisation appears to be mainly jigsaw-fit to clast-rotated. A weak, shallowly dipping, stratification is also observed and is parallel to that of the L4a lithofacies.

Discordant, pyrite-cemented, polymictic breccia to sandstone (L6b)

The pyrite-cemented breccia to sandstone L6b lithofacies ranges in thickness from 40 cm up to ~5 m and is discordant to L6a, L1, L2, L3 and L4a lithofacies, and also the argillic blanket. Lithofacies L6b predominantly strikes north-south in the pit (Fig. 5.3a) and drill core evaluation suggests that this lithofacies is best developed on the margins of the ore zone (Fig. 5.4a). The cement is dominated by pyrite and quartz crystals (<1 mm; Fig. 5.15g). This breccia contains quartz-calcite vein clasts, pyrite clasts, and clay (argillic)-altered clasts as well as variably altered clasts of L1 and L2 lithofacies. Pyrite occurs as both clasts and cement. Because of the narrow width, it is unclear (based on the 2 m sampling composites) whether
Lithofacies L6a: Pyrite-cemented, apparently monomictic breccia

**Grain size**
- Predominantly <8 cm
  - pebble to cobble breccia

**Components**

*Clasts*: 20 to 90%, angular to sub-round
- apparently monomictic; biotite-orthoclase-anhydrite ± clay (illite) -altered clasts
- blocky to equant clast shapes

*Matrix*: 10 to 70%, <2 mm (sand-sized)
- same as clast component

*Cement*: 5 to 80%
- anhydrite, orthoclase, biotite, quartz, calcite, apatite
- pyrite, sphalerite, galena, chalcopyrite, magnetite, pyrrhotite, marcasite, realgar

*Open space*: 1 to 30%

**Lithofacies**
- predominantly massive with stratified intervals
- jigsaw-fit to clast-rotated organisation
- fine grained intervals appear to be chaotically organised
- clast- to matrix- to cement-supported
- poorly to very poorly sorted

**Geometry**

*Contacts*: Gradational and broken in core

*Distribution*: Stratigraphically above the L4 facies association.

*Morphology*: A 10- to 50-m-thick layer at the boundary between the clay alteration and the L4 facies association.

**Alteration**
- Weak to moderate (trace to 95%) replacement of precursor minerals by adularia + pyrite + marcasite + rutile ± illite ± calcite ± anhydrite ± apatite ± quartz ± vermiculite ± albite (Carman, 1994).

**Associated Facies**
- Associated with high gold grade (4 to 7 g/t Au) and high porosity zone. Texturally associated with the L4 facies association.

**Interpretation**: Alteration of the L4 facies association?
- Hydrothermal breccia

![Map Symbol](image)

![Figure 5.14](image)
Figure 5.14 Pyrite-cemented, apparently monomictic breccia (L6a)
(A) Graphic log of DDHL757 showing the position of this facies stratigraphically above the L4 facies association. (B) Reflected light photomicrograph of sample DDHL757_224.7 m showing textural relationships between pyrite, chalcopyrite and galena. (C) Reflected light photomicrograph of sample DDHL757_224.7 m showing chalcopyrite inclusions within sphalerite. Inset photomicrograph is the same field of view in PPL and shows the transparent sphalerite. (D) Hand sample photograph of the texture in sample DDHL757_224.7 m. (E) Photomicrograph (XPL) of anhydrite and orthoclase cement in sample DDHL757_246.13 m. (F) Pyrite in sample DDHL791_152.10 m showing an overgrowth of pyrite around a pyrite core. (G) Pyrite in sample DDHL791_152.10 m showing a fibrous crystal habit (after marcasite). (H) Section 7669 showing gold grades and the location of the “boiling zone” ore-type (LGL) that corresponds to abundant open space of the L6a lithofacies.
Lithofacies L6b: Discordant, pyrite-cemented, polymictic breccia to sandstone

Grain size  
Predominantly <4 cm; locally up to 10 cm  
• pebble breccia to sandstone

Components Clasts: 20 to 90%, angular to round  
• polymictic; variably altered lithic fragments (L1 and L2) and quartz-calcite vein clasts  
• pyrite clasts  
• clay (illite) -altered clasts  
• blocky, tabular and wispy clast shapes

Matrix: 10 to 80%, <2 mm (sand-sized)  
• same as clast components

Cement: 0 to 70%  
• very fine grained, <1 mm  
• quartz, orthoclase, anhydrite  
• pyrite, chalcopyrite, sphalerite, galena, realgar, pyrrhotite

Open Space: 0 to 5%

Lithofacies  
• massive to stratified parallel to unit margins  
• clast rotated to chaotic organisation; locally jigsaw fit near margins  
• matrix- to cement-supported  
• locally graded from coarse, crowded, jigsaw fit domains to finer grained polymictic domains  
• poorly to moderately sorted

Geometry Contacts: Sharp discordant margins; locally irregular in orientation.

Distribution: On the margins of the Lienetz ore zone.

Morphology: Discrete, discordant dykes / veins are <5 m wide.

Alteration Many clasts are clay (illite) -altered

Associated Facies Statigraphically occur from the base of the L6a facies and upwards.

Interpretation: Several generations of hydrothermal brecciation, transport and deposition subsurface  
• Hydrothermal breccia

Figure 5.15 Discordant, pyrite-cemented, polymictic breccia to sandstone (L6b) (caption on next page)
Chapter 5 - Lithofacies associations in the Lienetz ore zone

Figure 5.15 (continued)
(A) Graphic log of DDHL757 showing the sharp discordant contacts with polymictic, matrix-supported breccia and sandstone (L1), pyrite-cemented, monomictic breccia (L6a) and anhydrite-biotite-orthoclase-cemented breccia (L4a). (B) Graphic log of DDHL712 showing the sharp discordant contacts with the pyroxene-phyric basalt (L2a). (C) Hand sample photograph of DDHL757_260.40 m showing the polymictic clasts and chaotic clast organisation. (D) Hand sample photograph of DDHL757_254.07 m. (E) View facing north of phase 6 benches with the distribution of L6b outlined. (F) Photograph of the L6b breccia exposed on bench 884 (location shown on E). (G) Photomicrograph (XPL) of quartz-cement and clast organisation in sample DDHL757_260.04 m. (H) Reflected light photomicrograph of pyrite arrangement in sample DDHL757_260.75 m. (I) Porous pyrite texture with small inclusions of chalcopyrite from sample DDHL252.72 m. (J) Porous pyrite texture and margins from sample DDHL712_214.04 m. (K) Realgar in sample DDHL757_252.72 m.
elevated gold grades are associated with this facies. However, based on the abundance of pyrite and realgar, this lithofacies probably hosts gold mineralisation.

*Interpretation:* The pyrite-cemented breccia facies association is encountered above ~800 m RL. Based on the pyrite-dominated cement mineral assemblages, L6 is interpreted to have been formed in a low-sulfidation epithermal-style environment (e.g. White and Hedenquist, 1990).

L6a formed at the boundary between the overlying argillic and advanced argillic alteration layer and L4a, and contains high-temperature minerals (e.g. biotite and orthoclase). These minerals are interpreted to have been inherited from the L4a lithofacies and associated magmatic-hydrothermal alteration. L6a also mimics the clast organisation and clast-matrix proportions of L4a. The L6a lithofacies is interpreted to be the product of an alteration overprint on the L4a lithofacies and the abundant open-space is interpreted to have been generated via dissolution of anhydrite-calcite cement in L4a. No fragmentation or transportation accompanied the formation of L6a lithofacies.

L6b differs from L6a in its internal organisation, clast components and contacts. The L6b lithofacies has sharp discordant margins and chaotic organisation interpreted to reflect transportation and deposition in the subsurface. The pyrite clasts and quartz-calcite vein clasts that are incorporated in the breccia record several generations of hydrothermal precipitation and subsequent brecciation. L6b locally cross cuts the L1, L2, L6a and L4a lithofacies and the argillic blanket. As well, associated veins cross cut the polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7). The L6b lithofacies is interpreted to represent the youngest geologic facies in the Lienetz ore zone.

### 5.2.7 Polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7)

The polymictic, accretionary lapilli-bearing, matrix-supported breccia facies (Fig. 5.16) is located on the western margin of the Lienetz open pit (Figs. 5.3 and 5.4). Breccia clasts include plagioclase-phryic andesite (L8), vesicular and dense pyroxene-phryic basalt (L2a),
laminated to massive mudstone, altered and mineralised microdiorite (L3), and more rarely accretionary lapilli, anhydrite-biotite-orthoclase-cemented breccia (L4), pyrite-cemented breccia and vein (L6) clasts, charcoal fragments, massive kaolinite-dickite clasts, and polymictic, matrix-supported breccia (L1). Minor quartz veins are observed in the matrix of this breccia and more rarely cross-cut the clasts. Variations within this facies are marked by the presence or absence of accretionary lapilli (Figs. 5.16a, 5.16b and 5.17b), the proportion of fine sand to mud matrix and monomictic zones of splintery andesite (L8) clasts (Fig. 5.17e).

Accretionary lapilli are both intact and broken and range in size up to 8 mm (Fig. 5.16a and 5.16b. They have ~1 mm thick, mud-sized dark grey rinds that surround a sand-sized core that is rich in broken plagioclase crystals. In this lithofacies, accretionary lapilli are predominantly randomly distributed and only rarely occur along a bedding plane. Charcoal fragments range in size up to several cms and are composed of elongate wispy fibres (Fig. 5.17d). Charcoal fragments are found predominantly along the eastern margin, in DDHL1703 and in open pit samples.

The predominant clast lithology, in both monomictic and polymictic domains, is similar in texture and composition to the plagioclase-phyric andesite (L8). In monomictic zones, plagioclase-phyric andesite clasts are tabular to splintery and close packed (compose up to ~90% of the mode), and show chaotic to clast-rotated internal organisation (Fig. 5.17e). In polymictic zones, the plagioclase-phyric andesite clasts are angular and have a thin (up to 5 mm) coating of fine sand to mud around their perimeter (Fig. 5.16b), which is similar in appearance and grain size to the outer rim of the accretionary lapilli (Figs. 5.16a and 5.16b). Many of the plagioclase-phyric andesite clasts (especially the larger clasts) have fine grained and fluidal margins (Figs. 5.17h and 5.17i).

This lithofacies is predominantly massive but beds are present in two locations in the open pit and dip 40° northeast. Beds are >1 m thick and diffuse. A well bedded variation of this lithofacies was encountered in drill hole DDHL1285 (collared at 8870E, 3653N; ~200 m south of the Lienetz mapping area). Here L7 is an accretionary lapilli-bearing laminated to thickly bedded sandstone to breccia (Fig. 5.18). Dips of beds were measured using oriented
Lithofacies L7: Polymictic, accretionary lapilli-bearing, matrix-supported breccia

<table>
<thead>
<tr>
<th>Grain size</th>
<th>2 mm to 25 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• pebble to boulder breccia</td>
</tr>
</tbody>
</table>

**Components Clasts:** 20 to 80%, angular to sub-rounded

- polymictic; L8 andesite, biotite-orthoclase-altered microdiorite (L3), vesicular basalt (L2a), laminated mudstone, charcoal fragments, accretionary lapilli (intact and broken), armoured lapilli with andesite (L8) cores
- rare L4 breccia clasts and rare pyrite-kaolinite-dickite vein clasts
- polymictic, matrix-supported breccia (L1) clasts, concentrated along the W margin
- ragged, tabular / splintery andesite clasts (L8)

**Matrix:** 20 to 80%, <2 mm (sand-to mud-sized)

- feldspar crystal fragments

**Lithofacies**

- massive to weakly graded, locally stratified (dipping 40° NE)
- chaotic clast organisation; locally clast-rotated organisation of andesite (L8) clasts
- matrix-supported
- poorly to very poorly sorted

**Geometry Contacts:** Gradational to sharp with L2a and L1 on western margin. Steep (80°) and sharp with L4a (Fig. 5.18f) on eastern margin.

**Distribution:** Western wall of Lienetz (Phase 7)

**Morphology:** Dyke (N elongate?)

**Alteration**

Weak to moderate argillic alteration (kaolinite / smectite).

Low in gold grade, <1 g/t Au.

**Associated Facies**

Plagioclase-phyric andesite (L8) is spatially associated and is the predominant clast component.

**Interpretation:** Hydrothermal eruption breccia. Contains hydrothermally cemented breccias (L4 and L6) and vein clasts of a previously (prior to fragmentation) active hydrothermal system. Accretionary lapilli and armoured lapilli produced during transport by suspension of ash and steam (in a subaerial eruption or possibly in a subsurface environment). Plagioclase-phyric andesite (L8) clasts in monomictic intervals are interpreted as blocky peperite produced by quench fragmentation during andesite dyke emplacement. Charcoal fragments are evidence of subaerial provenance and a connection to the surface during the hydrothermal eruption.

**Figure 5.16** Polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7) (caption on next page)
Figure 5.16 (continued)
(A) Accretionary lapilli in outcrop on bench 968. (B) Photomicrograph (PPL) of accretionary lapilli from sample L968_29JUL06 (4293N, 8876E, 968 m RL). (C) Photomicrograph (PPL) of plagioclase-phyric andesite (L8) clast armoured with a coating of fine mud; interpreted to be an armoured lapilli (sample L968_29JUL06). Note also the jagged irregular clast margins. (D) Graphic logs from west to east through the L8 lithofacies. In DDHL1704, a < 2 m wide discordant body of L7 is observed. Based on this relationship and field data, the western extent of the L7 facies is near 8500 E (represented in Figure 5.18). In DDHL1708, the fine mud-matrix rich zone near the centre of the lithofacies is represented. DDHL1703 is representative of the eastern margin of facies L7. Note the presence of L4 breccia clasts and pyrite vein clasts (related to the L6 facies association). (E) Pyrite-dickite-kaolinite vein clast in hand sample DDHL1703_50.35 m. (F) Mudstone clast in hand sample DDHL1703_55.0 m.
Figure 5.17 Textural variation and geometry of lithofacies L7
(A) Section 4200 N through the interpreted geometry and textural variation of the L7 lithofacies. Textural variations in matrix grain-size and compositional variations are highlighted. (B) Hand sample 07021 (8868E, 4262N, 980 m RL) showing the polymictic, matrix-supported lithofacies with abundant accretionary lapilli. (C) Hand sample DDHL1703_43.75 m showing a L4 breccia clast. (D) Charcoal fragment in hand sample 07016 (8944E, 4321E, 968 m RL) with mud-sized matrix component and ragged clast shapes. Inset shows a fragment of charcoal from hand sample 07008 (8882E, 4169N, 956 m RL). (E) Hand sample DDHL1703_32.95 m showing the tabular and splintery shapes of the andesite (L8) clasts that are moderately clay altered (argillic). The matrix is also argillically altered.

Chapter 5 - Lithofacies associations in the Lienetz ore zone
Figure 5.17 (continued)

(F) Near vertical contact between L7 lithofacies and L4 facies association from Lienetz open pit bench 834. The 30-cm-wide zone between the two is altered L4 lithofacies. (G) View of L7 in the western wall of phase 7. Note: 4WD in the foreground for scale; bench heights are 12 m. (H) Ragged plagioclase-phyric andesite (L8) clast in hand sample 07018 (4191N, 8871E, 968 m RL). (I) An armoured (fine grained coating), ragged L8 clast with a fine grained or altered margin in hand sample DDHL1703_99.10m. (J) Polymictic, matrix-supported breccia (L1) clast in hand sample DDHL1708_92.9 m. (K) Polymictic, matrix-supported breccia (L1) clast in hand sample DDHL1703_123.0 m.
core and a down-hole camera. They dip between 30 and 60° towards the southeast (Choi, D.R., personal communication, May 2nd, 2008), which is similar to but slightly steeper than the regional trend.

The polymictic, accretionary lapilli-bearing, matrix-supported breccia occupies a ~500-m-wide by >600-m-long area (Fig. 5.17a) that has a well-defined, sharp eastern margin and less well-defined western margin. The northern and southern extents were not resolved in this study. Thin “fingers” (10 cm to 5 m wide and up to 100 m vertical extent) extend from the main body (Figs. 5.3a and 5.3c). Two examples outcrop at, or near, the centre of the L4 facies association (Fig. 5.3a).

The eastern margin of this breccia is marked by a sharp drop in gold grade; L8 always has gold grades <1 g/t (based on 12 m composite blast hole samples). The contact is sharp and steep adjacent to the L4 facies association and argillic blanket. The contact is interpreted to be slightly irregular. It was measured and mapped as steeply east (340°/70°) dipping in the open pit (Figs. 5.3a and 5.4a) whereas drill hole reconstruction below the level of the open pit is west dipping based on drill hole reconstructions suggests a steep east dip (Figs. 5.3b, 5.3b, 5.3c and 5.4a). The apparent irregularity may be the result of the amalgamation of more
steam. Plagioclase-phyric andesite clasts are too altered to confidently determine whether the ragged clast shape is the product of corrosion or quench fragmentation of a molten andesite intrusion. In monomictic zones, the plagioclase-phyric andesite clasts are interpreted as blocky peperite produced by quench fragmentation associated with intrusion of plagioclase-phyric dykes (L8) into wet L7. In this case, the plagioclase-phyric andesite is a post-breccia intrusion that is similar to the plagioclase-phyric andesite clasts of the L7 lithofacies.

The formation of accretionary lapilli and the armouring of clasts requires the ideal conditions of grain size, moisture, turbulence, and electric charge (Reimer, 1983). In volcanic ash eruptions (ash suspended in the atmosphere), these conditions are met in the lower part of the laterally spreading ash cloud, once velocities have decreased and moisture starts to condense. Ash particles and droplets of moisture are drawn together by electrostatic attraction (Gilbert and Lane, 1994). The outer fine-grained, dense coating or rind may result from the fall through a dry cloud of fine ash (Reimer, 1983). Accretionary lapilli may also form in the subsurface, consistent with the interpretation of Carman (1994) based on drill core observations. Accretionary lapilli have been produced in fluidisation experiments in which significant quantities of clay-sized material were used and gas flow was maintained at a constant moderate rate (McCallum, 1985). Once formed, accretionary lapilli are fairly robust and are capable of withstanding fairly energetic transportation (Boulter, 1987).

Charcoal fragments are evidence of subaerial provenance and imply that, although a large proportion of the L7 lithofacies were deposited below the ground surface level, the depositional environment was connected to the surface.

5.2.8 Plagioclase-phyric andesite (L8)

This coherent facies (Fig. 5.19) crops out above 940m RL on the western (phase 7) pit wall (Fig. 5.3) and is separated from the polymictic, accretionary lapilli-bearing, matrix-supported breccia facies (L7) by sharp, kaolinite-altered contacts (Fig. 5.19d). The pit map distribution of the andesite suggests that it occurs as a number of near-vertical (80° dip measured in the pit) to steeply east-tilted, discrete dyke-like bodies up to 10 m width (Figs. 5.3 and 5.4).
Although the margins of the plagioclase-phyric andesite bodies appear to have been a focal point for kaolinite alteration, the centres are unaltered. Primary melt inclusions observed within hornblende phenocrysts further substantiate the "fresh" state of this lithofacies (Fig. 5.19c). As a result, a sample of the andesite has been submitted for Ar-Ar age dating at the UBC geochronology laboratory. A preliminary age of 1.09 ± 0.49 Ma has been obtained, but it is considered imprecise because of the young age and low K concentrations in the hornblende. The sample was being re-analysed in attempt to improve the precision at the time of completion of this thesis. The results available at this time indicate that the age has to be <1.58 Ma. Analytical methods and expanded results are presented in Appendix E.

The plagioclase-phyric andesite is a major clast component of the L7 facies association, and relationships in drill core show that andesite clasts (L8) with curviplanar to cuspate margins locally compose monomictic zones within the L7 lithofacies. As a clast component, L8 is discussed in more detail in the L7 lithofacies association section (5.2.7).

**Interpretation:** L8 is interpreted to be a shallow level intrusion or dyke network with a broad north-south elongation and steep east dip. There is a spatial and temporal association between the L8 andesite and L7 breccia facies association. Overall L8 lacks hydrothermal alteration and is interpreted to reflect late-stage emplacement, after the bulk of hydrothermal activity. This interpretation is favoured over a distal relationship to the ore-forming system due to the proximity to ore (<50 m) and proximity to the currently geothermal system as evidenced by the kaolinite altered margins and modern presence of hot mud pools, fumaroles and geysers. The large error on the Ar-Ar dating, as a result of low K in the hornblende, supports a young age (<1.58 Ma) for the crystallisation of this andesite. Limestone ages that constrain the timing of volcanic-sector collapse (chapter 3), suggest that the emplacement of the L7 breccia and L8 andesite occurred after the sector collapse.

### 5.2.9 Other lithofacies

Outside of the area of mapping, to the west of the Lienetz pit in Phase 7 upper, there is a distinctively bedded outcrop. Lithofacies exposed here have not been studied in detail because of the lack of mapping control in this area. It is unknown whether this rock package
Lithofacies L8: Plagioclase-phyric andesite

Sample 08020

Texture Porphyritic with a holocrystalline plagioclase-microlitic groundmass

Components
- Plagioclase (20-30%), euhedral to subhedral phenocrysts, lath-like or columnar crystals 0.1 to 1 mm in length
- Amphibole (~5%), euhedral to anhedral phenocrysts, <0.5 mm
- Clinopyroxene (10%), subhedral, 3 mm to <0.25 mm
- Microlitic groundmass (50%) of plagioclase laths and former glass (clay-altered)
- Opaques: pyrite

Lithofacies Massive; weak conchoidal fracture and spheroidal weathering in open pit exposures.

Alteration Clay alteration zones along margins in open pit exposures.

Interpretation: Igneous dyke

Figure 5.19 Plagioclase-phyric andesite (L8)
(A) Trace element discrimination diagram after Pearce (1996). Coloured symbols represent XRF results from this study (Table C.1). (B) Photomicrograph (XPL) showing zoned plagioclase phenocrysts and clinopyroxene phenocrysts in a fine grained holocrystalline groundmass, sample 08020 (8791E, 4156N, 992 m RL). (C) Photomicrograph (PPL) of a melt inclusion in hornblende in sample 08020, which has been submitted for Ar-Ar dating at UBC. (D) Phase 7 benches showing the “bowl” outcrop shape of L8 and the kaolinite altered margins. (E) Outcrop photo from bench 992 showing the typical jointing observed.

Associated Facies Spatially associated with the polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7). Also occurs as clasts in the L7 breccia facies.

Ar-Ar age <1.58 Ma (1.09 ± 0.49 Ma; Appendix E)
is a slumped block or an in-situ outcrop.

**Phase 7 upper**

A pervasively kaolinite-altered breccia outcrop at 4436 N, 8515 E, 977 m RL (Fig. 5.17a), is well-preserved texturally. It is discussed here because of the proximity to the western margin of the L7 lithofacies. The outcrop is composed ~5-m-thick, charcoal fragment-rich pebble breccia to sandstone that overlies an apparently closely packed cobble conglomerate (Fig. 5.20). Draped over the uneven top contact of the cobble conglomerate is poorly sorted, charcoal-rich, polymictic pebble breccia to sandstone that has very thin to thick beds. Faint cross bedding is observed throughout the thinly bedded intervals (Fig. 5.20e). Planar beds dip 20° → 330° and 300°. The orientation of foreset beds was not measured. Kaolinite alteration of this lithofacies masks the composition of the clastic components, except the charcoal. Charcoal fragments (Figs. 5.20b and 5.20c), ubiquitous throughout this unit, are aligned parallel to bedding and in places intact logs are up to 40 cm long. Plant debris was burnt prior to deposition but what caused the combustion was not resolved in this study.

There is not enough data for confident genetic interpretation but it is preliminarily interpreted. There are two possible interpretations. One interpretation is that the plant debris was burnt by a bush fire prior to deposition in a shoreline or fluvial depositional environment. Based on the cobble conglomerate facies association, this is the favoured interpretation. The other possible interpretation is that the plant debris was burnt, transported and deposited by hot pyroclastic surges. The spatial association with L7, and presence of charcoal in, both L7 and the phase 7 upper deposit could suggest this deposit is the surficial near-vent facies of a diatreme represented by the L7 breccia. The northwest-dipping bedding of the phase 7 outcrop is not consistent with the southerly dip of beds observed in other volcano-sedimentary lithofacies (i.e. Minifie M3 and M4 facies associations) or to that measured in the southern periphery of the L7 lithofacies. The phase 7 upper outcrop is not conclusively determined to be in-situ and so the bedding data and resultant interpretation of a central vent are not substantiated.

If affected by the southerly regional tilt, the primary bedding would be dipping at or
Figure 5.20 Section from Lienetz phase 7 upper. This section is pervasively kaolinite altered and the primary mineralogy is not preserved. (A) Graphic log showing two units; a lower boulder conglomerate draped by a pebble breccia to sandstone that contains abundant charcoal fragments. (B) A 40-cm-long charcoal log (removed from the deposit) partially replaced by pyrite and marcasite. (C) Charcoal fragment partially replaced by pyrite and marcasite. (D) Photograph of the section logged. This unit is only observed laterally over ~25 m and it is unclear as to whether it is a slumped block or an in-situ outcrop. (E) Faint cross bedding observed in the thinly bedded intervals. Note: all the dark black material is charcoal. (F) Pebble breccia interval. (G and H) Boulder conglomerate that has been entirely replaced by kaolinite. (H) Many of the boulders have apparent rinds (2 cm thick).
greater than ~ 50° to the north. This orientation could not be attained by either pyroclastic
surge or fluvial or shoreline deposits. This outcrop is either not in situ or was deposited after
regional tilting.

5.3 Evolution of the Lienetz ore zone

Lithofacies in the Lienetz ore zone record the host volcano-sedimentary stratigraphy,
development of a magmatic-hydrothermal breccia, an overprint of low-sulfidation epithermal
facies, a late hydrothermal eruption and an even magmatic activity (intrusion; Fig. 5.21).

Volcano-sedimentary stratigraphy and subvolcanic intrusions

Polymictic breccias and sandstones (L1) dominate the oldest parts of the volcano-sedimentary
succession at Lienetz, as was the case at Minifie (chapter 4). Basaltic coherent facies (L2a)
and associated monomictic breccia facies (L2b) intruded into and erupted onto the polymictic
breccias and sandstones (L1). The polymictic breccias and sandstones formed as gravity-
driven mass-flow deposits, incorporating basaltic clasts from the autoclastic and unstable
parts of lavas. These basaltic lavas and shallow intrusions, and associated hyaloclastite and
peperite are interpreted to have been deposited in a subaqueous environment. The subaqueous
depositional setting is based on the presence L2a hyaloclastite. The components and
lithofacies of this facies association are similar to the Minifie pyroxene-phyric coherent and
clastic basalt facies of association M2 and polymictic, weakly graded breccia to sandstone
M4a.

Once the volcanic pile built up the constructional edifice (Fig. 5.21a), the microdiorite
(L3) intruded along the southern margin of the Lienetz ore zone. The microdiorite is interpreted
as a shallow-level pluton because of its dimensions, medium grain size and equigranular
texture.

Syenite intrusion and gold-rich magmatic-hydrothermal breccia development

The anhydrite-biotite-orthoclase-cemented breccia facies association (L4) intruded the
host stratigraphy under porphyry-style conditions (T >300°C, depth >1 km; Carman, 1994;
Figure 5.21 Schematic evolution of the Lienetz ore zone

(A) Simplified geomorphology of the Luise volcano prior to the sector collapse event, with the outline of the study area. Deposition of polymictic, matrix-supported breccia to sandstone (L1) as volcaniclastic debris flow deposits. Intrusion and eruption of pyroxene-phyric basalt (L2a) and monomictic, pyroxene-phyric basalt breccia (L2b) in a subaqueous environment.

(B) Development of the porphyry-style magmatic hydrothermal breccias (L4a and L4b) associated with the intrusion of syenite dykes (L5) and anhydrite veins. Subsequent tilting (30° S) of the stratigraphy (not shown), is consistent with the dip of bedding in Minifie and the dip of the TLTF fringing limestone.

(C) Simplified geomorphology of the modern Luise volcanic edifice, after the sector collapse event. The debris avalanche deposit is shown on the sea floor and the study area is shown in the current near-surface configuration.

(D) Epithermal-style pyrite-cemented breccias (L6a) occur at the boundary between L4 lithofacies and the argillic blanket. The argillic alteration blanket consists of texturally and compositionally destructive argillic and advanced argillic alteration assemblages (including kaolinite, smectite and illite) that is related to a geothermal system.

(E) Hydrothermal eruption and deposition of the polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7) destroying a portion of the Lienetz ore zone and the argillic blanket. Intrusion of plagioclase-phyric andesite dykes (L8) into a wet L7 producing peperitic contacts. Plagioclase-phyric andesite is too young to be accurately dated using Ar-Ar but is certainly younger than 1.58 Ma.
Seedorff et al., 2005) and defines the Lienetz ore zone. The feldspar-phyric syenite (L5) intruded as several dykes (<25 m wide) in the centre of the L4 lithofacies (Fig. 5.21b). These dykes are surrounded by cement-dominated breccia and a well-developed anhydrite-vein network zone.

The anhydrite-biotite-orthoclase-cemented breccia facies association (L4a) is interpreted as a magmatic-hydrothermal breccia body (genetic classification of Sillitoe, 1985). The involvement of magmatic fluids is suggested by the biotite-orthoclase cement which implies relatively high temperatures (>300°C; Seedorff et al., 2005). The jigsaw-fit to clast-rotated organisation of clasts and the infill of cement are interpreted to reflect hydraulic fragmentation that varied in efficiency throughout the body producing variations in grain size.

The L4 facies association hosts moderate gold grades (1 to 4 g/t gold) and locally bonanza grades (up to 180 g/t Au) where free gold occurs. Despite the low copper grades, the gangue mineralogy is consistent with a porphyry-style environment (e.g. biotite and orthoclase) and the gold grades are higher than any other reported gold-rich porphyry deposit.

The L4 breccias and L5 feldspar-phyric syenite are currently dipping ~70° to the north. Magmatic-hydrothermal breccias are typically emplaced near vertical (Sillitoe, 1985). Vertical orientation of these breccias would require a southward tilt of ~30°. This corresponds to the regional dip observed on the fringing TLTF limestone and in the volcano-sedimentary beds at Minifie. The implication is that regional tilting occurred after brecciation in the porphyry environment, and the associated shallowly north dipping anhydrite veins were emplaced in a steeper orientation.

**Low sulfdation epithermal mineralisation and development of the argillic layer**

The pyrite-quartz-calcite cement assemblage and the adularia + pyrite + marcasite + quartz alteration assemblage of the L6 pyrite-cemented breccia facies association (Fig. 5.21d) are interpreted to have been deposited under epithermal conditions. These lithofacies are
encountered above ~800 m RL and form a 10- to 50-m-thick layer (L6a lithofacies) and discordant dyke-like geometry (L6b lithofacies). The L6a pyrite-cemented, apparently monomictic breccias occur between the argillic layer and the underlying L6a lithofacies, and are interpreted to have formed as the result of alteration and leaching of the L4a lithofacies. Acid leaching of the L4a lithofacies produced open space. Gold accumulated at the base of the acid-leached zone forming the high-grade core (>4 g/t Au) to the deposit.

**Hydrothermal eruption and andesite intrusion**

A hydrothermal eruption disrupted the stratigraphy (Fig. 5.21e) and the argillic layer of the Lienetz ore zone. The surficial eruptive deposits associated with this breccia have been eroded, and the only possible surficial deposits are in phase 7 upper, but their association is inconclusive. The subsurface facies of this eruption is recorded by the ~600-m-wide and >500-m-deep, polymictic, accretionary lapilli-bearing, matrix-supported breccia facies association (L7). Plagioclase-phyric andesite is the dominant clast type in the breccia and is similar in texture and composition to post breccia plagioclase-phyric andesite (L8) dykes. Accretionary lapilli and the armouring of clasts occurred during transportation in suspended slurry of clasts, fine ash and steam. In the absence of associated surficial deposits, charcoal fragments in the breccia are indicative of a surficial eruption.

Plagioclase-phyric andesite dykes with peperite margins intruded the L7 lithofacies <1.58 Ma. The L7 and L8 lithofacies at Lienetz are cut only by epithermal-style quartz-pyrite veins and black sulfide-rich shear zones.

### 5.4 Conclusion

The evolution of the Lienetz ore zone contrasts from that described in the Minifie ore zone. Minifie is significant for resolving facies variations within the volcano-sedimentary stratigraphy and to a lesser extent, the hydrothermal facies, whereas Lienetz is dominated by subvolcanic and hydrothermal lithofacies. Volcano-sedimentary lithofacies (L1 and L2) that are host to the Lienetz ore zone do not provide further resolution on the volcanic
environment and only the presence of hyaloclastite (M2b) constrains deposition to a subaqueous environment.

In Lienetz, the bulk of the gold mineralisation occurs in an anhydrite-biotite-orthoclase-cemented magmatic-hydrothermal breccia facies association (L4) with a high grade core of pyrite-cemented, apparently monomictic breccia (L6a). In contrast, at Minifie gold is hosted ubiquitous in epithermal-style breccias and veins. The bulk of the gold mineralisation at Lienetz is porphyry-style (anhydrite-biotite-orthoclase-cemented breccias) in contrast to the widespread opinion that Ladolam is an epithermal gold deposit (Davies and Ballantyne, 1987; Moyle et al., 1990; Carman, 1994; Muller et al., 2002; Carman, 2003).

After porphyry and the bulk of epithermal activity, a hydrothermal eruption deposited the polymictic, accretionary lapilli-bearing, matrix-supported breccia (L7). The L7 lithofacies is responsible for destroying some of the Lienetz ore zone and the argillic blanket. Charcoal fragments constrain the pre-eruptive surface to a subaerial setting and the accretionary lapilli indicate that the eruption was subaerial or breached the water-air interface. Shortly after the hydrothermal eruption, plagioclase-phyric andesite dykes (L8) intrude the L7 lithofacies. Plagioclase-phyric andesite dykes are too young to be accurately dated by the Ar-Ar method but they are certainly <1.58 Ma. Geothermal activity continues today, adding to the argillic alteration and probably continues to cause near-surface acid leaching of gold.