CHAPTER 4
Lithofacies associations in the Minifie ore zone

4.1 Introduction
This chapter focuses on the facies associations that host the Minifie ore zone (Fig. 4.1) and their relationships to the hydrothermally cemented breccias and veins that formed during porphyry-style alteration and epithermal gold mineralisation. The following sections provide detailed lithofacies descriptions and a synthesis of lateral and vertical facies variations.

The data for this research were collected by open pit mapping of Minifie benches 872, 884 and 980 m RL (3020 m mapped) during June and July of 2006 and by drill core logging of eight drill holes (1144 m logged) along north-oriented section 9500 through 900 to 700 m RL (drill holes DDHL1408, DDHL1415, DDHL1446, DDHL1448, DDHL1449, DDHL1450, DDHL1455 and DDHL1456; Fig. 4.2). Lithofacies are described using the scheme of McPhie et al. (1993) and Davies (2002).
Figure 4.2 Minifie data collection
(A) Minifie open pit with mapped benches (872, 884, 968 and 980) highlighted in red. (B) Section 9500 E; drill core section logged through the Minifie ore zone. Drill holes logged as part of this study are highlighted in black. Corresponding drill holes studied by G. Carman (1994) are displayed in grey.
The Minifie ore zone

The Minifie ore zone is the largest ore zone of the Ladolam deposit and was mined from 1997 to 2006. Previous work has focused on the characteristics of the ore deposit and associated alteration facies (Davies and Ballantyne, 1987; Lottermoser, 1990; Moyle et al., 1990; Corbett, 1991, 2000a,b, 2001, 2006; Hoogvliet, 1993; Rytuba et al., 1993; Carman, 1994, 2003; Leach, 1998, 2006; Corbett et al., 2001; Muller et al., 2001; Herrmann, 2002; Muller et al., 2002; Petersen and Herzig, 2002; Kidd and Robinson, 2004; Heinrich, 2006; Leach, 2006; Simmons and Brown, 2006).

There are two main styles of epithermal gold mineralisation in Minifie: 1) the shallow levels, from the pre-mining surface at 100 m above sea level to 200 m below sea level (now predominantly removed by mining), contain refractory gold in fine-grained pyrite (<20 μm) associated with pervasive adularia-sulfide alteration, and 2) the deeper levels contain a quartz-calcite vein stockwork with associated alteration haloes of quartz ± mixed-layer clay ± adularia ± anhydrite ± pyrite (Carman, 1994). The quartz-calcite stockwork has overprinted earlier, poorly mineralised, porphyry-style alteration characterised by pervasive biotite and a transitional porphyry-epithermal assemblage composed of orthoclase alteration selvages that surround stage 1B and stage 2 porphyry-style veins (Carman, 1994). The vein stages and associated alteration were studied in detail by Carman (1994, 2003) and are summarised in Table 2.2.

4.2 Lithofacies associations in the Minifie ore zone

Previous workers at Ladolam were restricted to drill core observations and were unable to resolve field relationships among volcanic and hydrothermal units. In the current study, open pit mapping combined with drill core logging, has revealed that the host rocks to the Minifie ore zone include several volcaniclastic and coherent facies that define a shallowly south-dipping (20 to 30°) stratigraphy (Figs. 4.3 and 4.4). Biotite-orthoclase alteration has obscured large parts of the sequence. Faults dipping 60 to 70° to the NNW have provided a focus for epithermal gold mineralisation (Moyle et al., 1990; Corbett et al., 2001).

In this study, 16 principal lithofacies have been grouped into five texturally and
Figure 4.3 Minifie open pit map of principal lithofacies identified in this study
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Figure 4.4 Mini fi e section 9500 E geology
compositionally distinct lithofacies associations including: M1) plagioclase-phyric coherent and clastic facies association; M2) pyroxene-phyric coherent and clastic facies association; M3) mudstone facies association; M4) polymictic breccia to sandstone facies association; and M5) hydrothermally cemented breccia facies association. A detailed description of each of the 16 lithofacies can be found in Figures 4.5 through 4.21. The facies associations and interpretations are discussed in the associated text. Whole rock geochemical analyses (X-ray fluorescence) are used to classify least-altered samples geochemically. These geochemical data are listed in Appendix C.

4.2.1 Plagioclase-phyric coherent and clastic facies association (M1)

This facies association consists of plagioclase-phyric andesite (M1a) and monomictic plagioclase-phyric andesite breccias (M1b, M1c, M1d).

Plagioclase-phyric andesite (M1a)
The plagioclase-phyric andesite is holocrystalline and porphyritic; the phenocrysts are zoned and twinned plagioclase and lesser clinopyroxene (Fig. 4.5). This lithofacies plots as andesite on the immobile trace element diagram (Fig. 4.5a) of Pearce (1996). A sample of this lithofacies was submitted for dating at the UBC geochronology laboratory but no dateable minerals were found in the sample.

The plagioclase-phyric andesite occurs as 1) a tabular body on the southern margin of the open pit and section, and 2) as three altered units that have 10 to 20% relict primary mineralogy (Figs. 4.3 and 4.4). Intervals of plagioclase-phyric andesite are 10 to 40 m thick. In outcrop, this coherent facies displays spheroidal weathering as well as polyhedral joints. The least-altered unit of this facies extends from ~3150 N to 3440 N and from 860 to 880 m RL. At this locality, the lower contact is intermingled with the underlying mudstone to produce a monomictic mud-matrix breccia (M1b). The top contact is exposed in only one locality as a sharp, planar contact with overlying mudstone (M3a) and mud-matrix breccia (M3c). A gradation to monomictic polyhedral breccia facies (M1d) is observed on the
Lithofacies M1a: Plagioclase-phyric andesite

Sample 08021
Texture Porphyritic with a plagioclase-microlitic groundmass

Components
- Plagioclase (35%), euhedral to subhedral phenocrysts, 1 - 3 mm in length, twinned (25%) and zoned (10%). Sieve texture occurs in the centre of some zoned plagioclase crystals.
- Clinopyroxene (10%), euhedral to subhedral phenocrysts, < 1 mm
- Microlitic groundmass (40 - 50%) with plagioclase laths 100 to 150 um in length

Lithofacies Massive, spheroidal and conchoidal fractures weakly developed. Polyhedral joints (with curvilinear margins) locally present in the open pit exposures.

Interpretation: coherent lava and / or shallow intrusion

Alteration Illite-altered phenocrysts, pervasive K-feldspar alteration, locally pervasive illite alteration, disseminated pyrite. Mineralogy and texture completely biotite-orthoclase altered at deep levels in section 9500E.

Thickness Distribution Largest body exposed on the southern margin of the Minifie open pit where the upper contact is not exposed and the bottom contact is gradational with monomictic breccia facies.

Associated facies Monomictic breccia facies that have this plagioclase-phyric andesite as the clast component (M1b, M1c, M1d), and monomictic, mud-matrix-supported breccia (M3c)

Figure 4.5 Plagioclase-phyric andesite (M1a)
(A) Trace element discrimination diagram after Pearce (1996). Coloured symbols represent XRF results as part of this study (Table C.1). (B) Photomicrograph (XPL) showing zoned and twinned plagioclase and clinopyroxene phenocrysts in a fine-grained holocrystalline groundmass. (C) Photomicrograph (XPL) of twinned plagioclase and twinned clinopyroxene. (D) Photomicrograph (PPL) of selective zonal alteration of plagioclase by biotite.

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Margins. In zones of intense alteration, contact relationships with upper and lower clastic facies can only be described as gradational.

Monomictic, mud-matrix-supported andesite breccia (M1b)
The base of plagioclase-phyric andesite (M1a) passes into a zone of jigsaw-fit to clast-rotated breccia composed of clasts of the same andesite composition (Fig. 4.6). This monomictic breccia is massive over a 2- to 28-m-thick interval that varies from 840 to 870 m RL and easting 3280 to 3350 N (Fig. 4.4). Clasts range in size from 1 to 30 cm and have smooth to irregular and intricate margins. The mud matrix displays distorted laminae, thin beds or is massive. The laminae and thin beds in the mud matrix are diffusely graded from clay to silt and contain minor plagioclase crystal fragments.

Monomictic, in-situ to clast-rotated andesite breccia (M1c)
The monomictic, in-situ to clast-rotated andesite breccia is characterised by jigsaw-fit to clast-rotated plagioclase-phyric andesite (M1a) clasts in a sand- to mud-sized matrix (Fig. 4.7). This unit is 15 to 20 m thick and ~40 m wide, and is situated 5 to 20 m beneath the M1a, M1b and M1d lithofacies (Fig. 4.4). It is predominantly massive and has a diffuse bottom contact and sharp upper contact. The upper contact of this unit is normally graded and clast grain size decreases from ~8 cm to 32 mm over a 40 cm interval in DDHL1446 (Fig. 4.7a). Plagioclase-phyric andesite (M1a) clasts are 5 mm to 10 cm, comprise 30 to 90% of the rock and have blocky to intricately irregular clast shapes. Clast margins locally have a 250- to 500-μm-thick rind of fine-grained clay alteration (Fig. 4.7c).

Monomictic, polyhedral andesite boulder breccia (M1d)
The monomictic polyhedral boulder andesite breccia is best preserved on the southern Minifie pit wall from 980 to 872 m RL (Fig. 4.3) and is characterised by distinctive, internally jointed, polygonal blocks of plagioclase-phyric coherent facies (M1a; Fig. 4.8). The shape and texture of the clasts is most apparent at the open pit scale of observation and
Lithofacies M1b: Monomictic, mud-matrix-supported andesite breccia

**Grain size** 1 to 30 cm
- pebble to boulder breccia

**Components Clasts:** 50 to 95%, angular to sub-round
- monomictic, plagioclase-phyric andesite (M1a)
- locally very irregular clast margins
- possible pseudo-rounding of clasts

**Matrix:** 5 to 50%, <1/16 mm (mud-sized)
- predominantly massive although locally distorted laminated to thin beds
- rare plagioclase crystal fragments

**Lithofacies**
- massive
- mud-matrix-supported
- jigsaw-fit to clast-rotated organisation; minor chaotic organisation in mud-rich intervals

**Geometry**
- Contacts: Upper contact is gradational with overlying plagioclase-phyric andesite (M1a) and lower contact is gradational to the mudstone facies association (M3).
- **Thickness:** 2 to 28 m
- **Distribution:** Laterally continuous along the base of plagioclase-phyric andesite (M1a); from 840 to 870 m RL and 3280 to 3350 N.

**Alteration**
- Pervasive adularia-quartz alteration, disseminated pyrite, selective pervasive illite alteration of plagioclase phenocrysts in clasts.

**Associated Facies**
- Occurs at the boundary between plagioclase-phyric andesite (M1a) and the laminated to massive mudstone (M3a). Clast component is the M1a lithofacies and the matrix component is the M3a lithofacies.

**Interpretation:** Peperite

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Figure 4.6 Monomictic, mud-matrix-supported andesite breccia (M1b)

(A) Composite graphic log drawn from DDHL1446, 1448, 1449, showing the distribution of the M1b lithofacies and sharp to gradational contacts with M1a lithofacies and the M3 facies association. (B) Hand sample photograph of sample DDHL1448_50.0 m showing the M1a clasts and mudstone matrix. (C) Hand sample photograph of sample DDHL1446_37.7 m showing the distorted laminae in the mudstone matrix.
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**Lithofacies M1c: Monomictic, in-situ to clast-rotated andesite breccia**

**Grain size** 5 mm to 10 cm; outsized clasts up to 60 cm
- pebble to boulder breccia

**Components Clasts:** 30 to 90%, angular to sub-round
- monomictic, plagioclase-phyric andesite (M1a)
- locally jagged and irregular clast shapes

**Matrix:** 10 to 70%, <2 mm (sand-sized)
- minor mud sized component

**Lithofacies**
- massive
- jigsaw-fit to chaotic clast organisation
- clast- to matrix-supported
- upper 40 cm of unit is locally normal graded

**Geometry Contacts:** Upper and lower contacts (to the M4 polymictic breccia to sandstone facies association) are sharp to diffuse, gradational and altered.

**Thickness:** Single interval, 15 to 20 m thick.

**Distribution:** 50 m by 20 m zone in the centre of section 9500 E.

**Alteration**
- Pervasive adularia-quartz-calcite alteration and disseminated pyrite.

**Associated Facies**
- Clasts are mineralogically and texturally identical to the plagioclase-phyric andesite (M1a).

**Interpretation:** Mainly autoclastic facies, minor peperite

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**Figure 4.7 Monomictic, in-situ to clast-rotated andesite breccia (M1c)**

(A) Composite graphic log from DDHL1446 and 1448 showing the texture and thickness of the M1c lithofacies, the normal graded top of the unit and the diffuse contact at the base with M4a lithofacies.

(B) Hand sample photograph of DDHL1446_70.43 m showing the delicate clast margins.

(C) Hand sample photograph of DDHL1446_77.40 m showing the M1a clasts with thin alteration rinds on clasts.
Lithofacies M1d: Monomictic, polyhedral andesite boulder breccia

**Grain size**
- Bimodal clast size; predominantly <64 mm with blocks up to 2 m
  - pebble to boulder breccia

**Components Clasts**
- 80 to 90%, angular to sub-angular
  - monomictic, plagioclase-phyric andesite (M1a)
  - polyhedral shapes with straight to curviplanar margins and internal fractures

**Matrix**
- 10 to 15%, <2 mm (sand- to mud-sized)
  - plagioclase crystal-rich

**Cement**
- 5 to 10%
  - quartz, adularia and pyrite

**Lithofacies**
- massive
- chaotic clast organisation
- matrix- to clast-supported
- poorly sorted

**Geometry Contacts**
- gradational contacts to the plagioclase-phyric andesite (M1a) and to the polymictic breccia to sandstone facies association (M4).

**Thickness**
- >10 m

**Distribution**
- only observed in open pit scale of observation; above 872 m RL.

**Alteration**
- Pervasive adularia-quartz alteration, disseminated pyrite, abundant jarosite and illite alteration and staining. Large clasts have less-altered cores.

**Associated Facies**
- Spatially and compositionally associated with plagioclase-phyric andesite (M1a). Gradational contacts with the polymictic breccia to sandstone facies association (M4).

**Interpretation: Autoclastic facies**
- Hyaloclastite

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Figure 4.8 Monomictic, polyhedral andesite boulder breccia (M1d)
(A) Composite graphic log open pit bench 884, ~ 3300 N showing the gradational contact between plagioclase-phyric andesite (M1a) and this lithofacies (M1d). (B) Photograph from bench 980 of a boulder clasts with curviplanar margins and internal polygonal fracture pattern. (C) Photograph from bench 884 showing the internal joint pattern in clasts. (D) Photograph from bench 884 showing the polyhedral clast shape with planar to curviplanar clast margins.
is not recognised in drill core. The lithofacies is massive and poorly sorted and has a clast-rotated to chaotic clast organisation and varies from clast- to matrix-supported. The size of plagioclase-phyric andesite (M1a) clasts is bimodal, mostly ranging from 2 m to 64 mm, but with outsized blocks up to 2 m in diameter. Clasts are outlined by straight to curviplanar joints and also have short joints perpendicular to the surface (Figs. 4.8b, 4.8c and 4.8d). The matrix is sand- to mud-sized, feldspar-crystal-rich and massive.

**Interpretation:** The plagioclase-phyric coherent and clastic facies association is interpreted to be the coherent and clastic component of lavas and shallow intrusions. The tabular plagioclase-phyric andesite (M1a) on the southern margin of the Minifie ore zone is interpreted to be at least in part a ~20-m-thick lava or shallow intrusion (the upper contact was not observed). Where the coherent facies is encountered at depth in section 9500 E, it is unclear as to whether the units were emplaced as lavas or as shallow intrusions.

Collectively the monomictic breccias are interpreted to be autoclastic facies, and include hyaloclastite (M1c and M1d) and blocky peperite (M1b and portions of M1c). The clasts within the monomictic breccia facies show jigsaw-fit to clast-rotated textures and have sharp and angular blocky shapes indicative of brittle fragmentation. The general lack of bed forms, angular clast shapes, monomictic clast population and jigsaw-fit organisation indicate little to no transport post-fragmentation.

The monomictic, mud-matrix-supported andesite breccia (M1b) is laterally continuous at the base of the plagioclase-phyric andesite (M1a) and is interpreted as an intrusive peperite that formed in response to the burrowing of the plagioclase-phyric andesite into the underlying wet mud (mudstone facies association, M3). The monomictic, polyhedral andesite boulder breccia (M1d) occurs on the periphery of the coherent andesite lava or shallow intrusion. The polyhedral blocks and internal joints characteristic of this lithofacies are interpreted to have formed in response to cooling contraction in either a subaerial or subaqueous or shallow intrusive environment. The joint pattern strongly resembles that of “pseudo-pillows” commonly found in andesitic lavas and intrusions (e.g. Watanabe and
The monomictic, in-situ to clast-rotated andesite breccia (M1c) occurs as an isolated unit beneath the M1a, M1b and M1d lithofacies and although it is not associated with a coherent facies on section 9500 E, the clast composition is mineralogically and texturally identical to the plagioclase-phyric andesite (M1a). This lithofacies is interpreted to be the autoclastic facies associated with a plagioclase-phyric andesite lava or shallow intrusion. The blocky and irregularly shaped clasts and coarse grainsize are characteristic of an autoclastic facies in which quench fragmentation dominates (McPhie et al., 1993). Locally, the clasts are blocky and splintery and mud matrix is present, possibly representing a peperitic component. The normally graded upper contact is interpreted to be the result of reworking and implies that this lithofacies was at least partially extrusive.

4.2.2 Pyroxene-phyric coherent and clastic facies association (M2)
This facies association consists of texturally and compositionally related pyroxene-phyric basalt (M2a), monomictic pyroxene-phyric breccia (M2b) and polymictic breccia with outsized pyroxene-phyric basalt clasts (M2c).

**Pyroxene-phyric basalt (M2a)**
There are two pyroxene-phyric coherent basalt (Fig. 4.9) units that cut across the Minifie stratigraphy. The pyroxene-phyric basalt encountered from 850 to 810 m RL along northing ~3325 to 3375 is a shallowly dipping, <4-m-thick, tabular body (Fig. 4.4). North of ~3500 on section 9500, the pyroxene-phyric basalt is steeply oriented and <10 m wide and has a vertical extent of >180 m (Figs. 4.3 and 4.4). This lithofacies plots as a basalt on the immobile trace element diagram of Pearce (1996; Fig. 4.9a). A sample of this lithofacies was submitted for dating at the UBC geochronology laboratory but no zircon or monazite was found. Biotite alteration has affected the plagioclase microlitic groundmass, making this sample unsuitable for Ar-Ar dating of the primary rock age.
Lithofacies M2a: Pyroxene-phyric basalt

Sample DDHL1415_166.12 m
Texture Porphyrity with a holocrystalline groundmass

Components
- Clinopyroxene (30 - 40%), euhedral phenocrysts 0.5 to 4 mm in length
- Relict amphibole (5 - 10%) phenocrysts, euhedral to subhedral crystal shapes. Replaced by fine-grained biotite, chlorite and anhydrite surrounded by halo of fine-grained pyrite and biotite.
- Microlitic groundmass (40 - 50%) of euhedral plagioclase laths <0.2 mm
- Opaques: pyrite, magnetite, chalcopyrite

Lithofacies Massive

Interpretation: Intrusions (dykes)

Distribution
1) Thin (<4 m) tabular body cross cutting but largely conformable to monomictic breccia facies (M1c)
2) Steeply oriented, narrow and NE elongate in the Minifie open pit and corresponding occurrence on the northern margin of section 9500.

Alteration Weak biotite and K-feldspar alteration where exposed in the Minifie open pit. Disseminated pyrite preferentially in phenocrysts.

Associated facies Clasts of this texture, mineralogy and composition are found in the monomictic, pyroxene-phyric breccia (M2b) and polymictic breccia with outsized pyroxene-phyric clasts (M2c).

Figure 4.9 Pyroxene-phyric basalt (M2a)
(A) Trace element discrimination diagram after Pearce (1996). Coloured symbols represent XRF results as part of this study (Table C.1). (B) Photomicrograph (PPL) showing the clinopyroxene-phenocrysts in the plagioclase microlitic groundmass. (C) Photomicrograph (XPL) of clinopyroxene-phenocrysts, (D) Photomicrograph (PPL) of biotite alteration in the plagioclase-microlitic groundmass.
**Monomictic, pyroxene-phyric basalt breccia (M2b)**

The monomictic, pyroxene-phyric basalt breccia (Fig. 4.10) occurs as a 10-m-thick interval that is laterally restricted to the north and south (Fig. 4.4). Pyroxene-phyric basalt clasts have a heterogeneous distribution of vesicles and calcite-filled amygdales. Many clast shapes are irregular and cuspate where the fracture or margin intersects a vesicle wall. The breccia is massive, clast- to matrix-supported and has a clast-rotated to chaotic organisation. The upper contact is marked by a 2-cm-thick normally graded top.

**Polymictic breccia with outsized pyroxene-phyric basalt clasts (M2c)**

This lithofacies is limited to the southern extent of section 9500E and is distinguished by outsized pyroxene-phyric basalt clasts up to 2 m in diameter (Fig. 4.11). The entire lithofacies is 24 m thick and has a lens geometry (Fig. 4.4). The outsized clasts occur in polymictic, matrix-supported, poorly to moderately well-sorted, massive to very thickly bedded breccia of similar characteristics to that of the polymictic, weakly graded breccia to sandstone (M4a).

**Interpretation:** Both occurrences of the pyroxene-phyric basalt are interpreted to be dykes that have cross cut the stratigraphy (M1c and M4a lithofacies). The pyroxene-phyric basalt dykes are spatially separated from the monomictic and polymictic breccia facies but the basalt clasts in the breccia have similar texture and mineralogy to the coherent basalt facies (M2a). The monomictic, pyroxene-phyric basalt breccia (M2b) has angular clasts with cuspate margins, only partial clast-rotated organisation and large clast size, up to 80 cm in length. The clast shapes are characteristic of brittle fragmentation. In general, the angular clast shapes, monomictic clast population and the clast organisation suggest little transport, however, a thin (2 cm thick), normally graded interval at the top has a minor polymictic component and clast shapes have been slightly modified, implying that at least this part has undergone transportation. The monomictic, pyroxene-phyric basalt breccia (M2b) is interpreted to be an in situ to slightly resedimented autoclastic breccia. The southern pyroxene-phyric basalt (M2a) dyke could be a feeder to the M2b monomictic breccia.
Lithofacies M2b: Monomictic, pyroxene-phyric basalt breccia

**Grain size**  2 to 64 mm with outsized clasts up to 80 cm
  - pebble to boulder breccia

**Components**  *Clasts*: 80%, angular to round
  - monomictic, pyroxene-phyric basalt (M2a) with calcite-filled amygdales
  - locally bleached clast margins; irregular to jagged clast margins locally

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

**Lithofacies**
  - predominantly massive
  - 2-cm-thick, fine-grained top (upper contact)
  - chaotic clast organisation
  - matrix- to clast-supported
  - moderately to poorly sorted

**Geometry**  *Contacts*: Bottom contact is gradational to polymictic, breccia to sandstone facies association (M4). Upper contact is sharp with a 2-cm-thick normally graded contact with M4 facies association.

*Thickness*: 10 m

*Distribution*: Laterally restricted to the N and S to <30 m.

**Alteration**  Pervasive adularia-quartz-calcite alteration and disseminated pyrite.

**Associated Facies**  Pyroxene-phyric basalt (M2a) clasts are the components of this lithofacies. The pyroxene-phyric basalt (M2a) dyke and the polymictic breccia with outsized pyroxene-phyric basalt clasts (M2c).

**Interpretation**: Autoclastic facies
  - At least partially extrusive

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**Figure 4.10 Monomictic, pyroxene-phyric basalt breccia (M2b)**

(A) Graphic log from DDHL1448 showing the thickness, gradational lower contact and sharp, normally graded upper contact with the polymictic, weakly graded breccia to sandstone (M4a).

(B) Photomicrograph (PPL) of sample DDHL1448_61.80 m showing the clast margins defined by vesicle walls. (C) Photomicrograph (PPL) of sample DDHL1448_61.80 m showing the M2a clasts and matrix component.
Lithofacies M2c: Polymictic breccia with outsized pyroxene-phyric basalt clasts

**Grain size**  
2 mm to 64 mm with outsized clasts up to 40 cm  
- pebble to boulder breccia

**Components**  
- **Clasts**: 10 to 30%, sub-angular to sub-round  
  - polymictic, dense and calcite-amygdaloidal pyroxene-phyric basalt (M2a), plagioclase-phyric basalt (M1a)  
  - outsized clasts are pyroxene-phyric basalt (M2a)

  **Matrix**: 70 to 90%, <2 mm (sand-sized)  
  - same as clast components

**Lithofacies**  
- massive to very thickly bedded (>4 m)  
- chaotic clast organisation  
- matrix-supported  
- moderately well to poorly sorted

**Geometry**  
- **Contacts**: Diffuse upper contact and sharp lower contact to polymictic breccia to sandstone facies association (M4).
- **Thickness**: 24 m
- **Distribution**: Isolated and laterally restricted to DDHL1450 (the southern most drill hole logged on section 9500 E).

**Alteration**  
Pervasive chlorite, pervasive K-feldspar and disseminated pyrite.

**Associated Facies**  
Outsized clasts are closely similar to the pyroxene-phyric basalt (M2a).

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

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**Figure 4.11 Polymictic breccia with outsized pyroxene-phyric basalt clasts (M2c)**  
(A) Graphic log from DDHL1450 shows the thickness and massive bed form of the M2c lithofacies. (B) Hand sample photograph from DDHL1450_ 108.05 m.
The polymictic breccia with outsized pyroxene-phyric basalt clasts (M2c) occurs in a 24-m-thick, lensoid unit that is spatially associated with the monomictic, pyroxene-phyric breccia. This lithofacies is interpreted to be a debris-flow deposit. The texturally immature clasts and outsized pyroxene-phyric basalt clasts suggest minimal transport and reworking. The coarse basalt clasts could be derived from contemporaneous pyroxene-phyric basalt autoclastic facies.

### 4.2.3 Mudstone facies association (M3)

Facies association M3 consists of laminated to massive mudstone (M3a) interbedded with polymictic, mud-matrix-supported breccia (M3b) and minor monomictic, mud-matrix breccia (M3c). The mud matrix of both the polymictic and monomictic breccias is texturally the same as the laminated to massive mudstone (M3a). This facies association is 5 to 10 m thick and occurs from ~820 m RL to ~880 m RL.

#### Laminated to massive mudstone (M3a)

The base of the laminated to massive mudstone facies (M3a) is laterally continuous across four drill holes and dips 20 to 30° to the south (Fig. 4.4). The laminated to massive mudstone facies (M3a) is normal graded locally (Figs. 4.12b and 4.12c) with thin beds that grade from silt to clay. Laminae and thin beds in some intervals have been disturbed and are now convolute. Rare, bedding parallel, opaque lenses (possibly fine carbonaceous detritus) are preserved in the mudstone, as well as rare feldspar crystal fragments up to 0.5 mm in length. The upper contact is gradational to the monomictic, mud-matrix-supported breccia (M1b) lithofacies (Figs. 4.4 and 4.12a).

#### Polymictic, mud-matrix-supported breccia (M3b)

The polymictic mud-matrix supported breccia facies is interbedded with the laminated to massive mudstone (M3a; Fig. 4.13). This breccia is poorly to moderately well sorted, massive to thinly bedded and has diffuse to sharp, planar and deformed boundaries. This
Lithofacies M3a: Laminated to massive mudstone

**Grain size**  
$< 0.0625 \text{ mm}$  
- mudstone

**Components**  
- locally plagioclase crystal fragments, up to 0.5 mm  
- locally carbonaceous lenses or mudstone rip-up clasts?

**Lithofacies**  
- laminated, thinly bedded, thickly bedded to massive  
- normally graded (silt to clay)  
- bedding in some intervals is disturbed and convolute  
- bedding measured as 70 to 65° to core axis, ~ 20 to 30° dip to the south (from section 9500 E)

**Geometry**  
*Contacts:* Upper and lower contacts are very sharp and many are irregular. Flame structures at upper contact with overlying polymictic, mud-matrix-supported breccia (M3b). Conformable upper and lower contacts.

*Thickness:* 5 to 10 m (inclusive of M3b lithofacies)

*Distribution:* At the interface between upper M1 facies association and M4 facies association. Planar, laterally continuous distribution.

**Alteration**  
Pervasive (moderate to strong) K-feldspar alteration and disseminated pyrite throughout. Locally high gold grades (7 to 9 g/t Au), which may be related to quartz veins.

**Associated Facies**  
Interbedded with polymictic, mud-matrix-supported breccia (M3b) and stratified, monomictic, mud-matrix-supported breccia (M3c). Gradational upper and lower contacts with M1 facies association and M4 facies association, respectively.

**Interpretation:** Sedimentary facies, subaqueous  
- Suspension settled mudstone or mudstone turbidite deposit

**Figure 4.12 Laminated to massive mudstone (M3a)**
(A) Composite graphic log from DDHL1446, 1448, 1449 and 1450 showing the interbedded M3a and M3b lithofacies, as well as the upper contact with the M1 facies association and lower contact with the M4 facies association. (B) Hand sample photograph of sample DDHL1450.77.10 m showing the laminated bed forms and bedding parallel quartz-calcite vein. (C) Photomicrograph (XPL) of normally graded thin beds and bedding parallel quartz-calcite veins.
lithofacies is laterally continuous within the mudstone facies association (Fig. 4.4). Pebble-sized clasts at the base of this unit have compacted the underlying laminated to massive mudstone (M3a), creating load structures. Clasts are polymictic and composed of pyroxene-phyric, plagioclase-phyric and variably altered lithologies. Clasts vary from angular to round shapes and the pyroxene-phyric component locally has delicately irregular and amoeboid shapes. Clast margins have been obscured by alteration to pyrite, clay and opaque fine grained alteration minerals (possibly iron oxides; Figs. 4.13b and 4.13c).

**Monomictic, mud-matrix-supported breccia (M3c)**

The monomictic mud-matrix-supported breccia (Fig. 4.13) occurs as a <5-m-thick isolated lens in the south western portion of the open pit at 872 m RL (Fig. 4.3). The breccia is bound by laminated mudstone (M3a lithofacies) interbedded with thinly bedded sandstone (M4a lithofacies). This sequence overlies the plagioclase-phyric andesite (M1a) with a sharp contact. Plagioclase-phenocrysts along the margin of the basalt are oriented parallel to the contact orientation. Where exposed, the upper laminated mudstone (M3a) lithofacies contact with the plagioclase-phyric andesite (M1a) is sharp and planar.

Clasts of the M3c breccia facies compose 5 to 60% of the mode and are dominantly plagioclase-phyric andesite with minor, blocky mudstone clasts. Plagioclase-phyric andesite clast shapes are angular, jagged and amoeboid. Thin-section observations have shown that fragments are defined by intersections between vesicle walls, creating intricate, cuspate and amoeboid shapes. The groundmass of these clasts is locally microlitic with fine feldspar crystals. Both vesicular and non-vesicular textures are present in clasts. Hematite alteration obscures most of the groundmass textures and has locally created the appearance of false clast boundaries.

*Interpretation:* The mudstone (M3a) is interpreted to have been deposited in a subaqueous environment through suspension settling and / or turbidity currents. The beds were probably originally deposited in a near-horizontal orientation. The moderate dip is consistent with the
Lithofacies M3b: Polymictic, mud-matrix-supported breccia

**Grain size** 2 mm to 64 mm
- granule to pebble breccia

**Components**
- Clasts: 10 to 60%, angular to round
  - polymictic, pyroxene-phyric basalt (M2a), plagioclase-phyric andesite (M1a) and variably clay-altered clasts
  - irregular, embayed clast margins (especially M2a clasts)
  - clast margins locally obscured by alteration
- Matrix: 30 to 90%, < 0.0625 mm (mud-sized)
  - a minor fine-sand-sized component

**Lithofacies**
- medium to thickly bedded (20 to 100 cm)
- massive to weakly normally graded
- matrix-supported
- moderately well- to poorly sorted
- soft-sediment deformation of beds

**Geometry**
- Contacts: Upper contacts are sharp to diffuse and lower contacts are sharp and wavy.
- Thickness: 5 to 10 m (inclusive of interbedded M3a lithofacies).
- Distribution: At the interface between upper M1 facies association and lower M4 facies association. Planar and laterally continuous, ~ 850 to 820 m RL.

**Alteration**
- Pervasive adularia-quartz alteration and disseminated pyrite. Clasts are variably clay (illite) altered. Disseminated pyrite is concentrated in the finest-grain-size matrix component.

**Associated Facies**
- Interbedded with the laminated to massive mudstone (M3a). Diffuse lower and upper contacts with the M4 and M1 facies associations, respectively.

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

**Figure 4.13 Polymictic, mud-matrix-supported breccia (M3b)**
(A) Composite graphic log from DDHL1446, 1448, 1449 and 1450 showing the interbedded M3a and M3b lithofacies. Note the soft-sediment structures at the base of M3b lithofacies when overlying M3a lithofacies. (B) Hand sample photograph of sample DDHL1448_56.23 m, the clast margins are locally irregular and embayed. (C) Hand sample photograph of sample DDHL1446_60.33 m showing the clay-altered clasts. This sample is cut by a quartz-pyrite vein.
Lithofacies M3c: Monomictic, mud-matrix-supported breccia

Grain size < 64 mm; strongly bimodal (clasts 1/16 to 64 mm, matrix < 0.0625 mm)
• pebble breccia

Components Clasts: 5 to 60%, angular to sub-round
• monomictic, plagioclase-phyric andesite (M1a) and plagioclase crystal fragments
• rare mudstone clasts
• M1a clasts are amoeboid with jagged and irregular margins, locally intersecting vesicle walls

Matrix: 40 to 95%, < 0.0625 mm (mud-sized)
• laminated to massive
• locally laminations are disrupted and contorted

Lithofacies
• massive
• interbedded with laminated mudstone (M3a)
• matrix-supported
• poorly to moderately well-sorted
• chaotic clast organisation

Geometry Contacts: Sharp top and bottom contacts with interbedded laminated to massive mudstone (M3a). Package (M3a and M3c) is bound by sharp contacts with plagioclase-phyric andesite (M1a).

Thickness: < 5 m (one bed)
Distribution: Isolated lens in the southwestern portion of the open pit at 872 m RL.

Alteration Weak disseminated pyrite and weak illite-alteration.

Associated Facies Clast component is the plagioclase-phyric andesite (M1a). Interbedded with the laminated to massive mudstone (M3a) and this facies association is bound by sharp upper and lower contacts to the M1a lithofacies.

Interpretation: Autoclastic facies
• Globular (fluidal) peperite

Figure 4.14 Monomictic, mud-matrix-supported breccia (M3c)
(A) Graphic log from open pit bench 872 showing the sharp contacts between M3a and M3c lithofacies. (B) Photograph from open pit bench 872 showing the amoeboid-shaped clasts and clasts with irregular clast margins in the mudstone matrix. (C) Photomicrograph (PPL) of sample M872Jun1606 (3483E, 9675N, 872m RL) highlighting the clast shape with margins controlled by vesicle walls.
dip of the stratigraphy, indicating post-depositional tilting to the south.

Clast shapes in the polymictic, mud-matrix-supported breccia (M3b) vary from angular to round. The clasts are interpreted to have been delivered to the mud depocentre from more than one source area, outside of the depositional environment. It is possible that the emplacement of the M1a plagioclase-phyric andesite and associated autoclastic facies destabilised the overlying strata, causing erosion and gravitational collapse.

The jagged and irregular plagioclase-phyric andesite clasts in the monomictic, mud-matrix-supported breccia (M3c) are interpreted to be juvenile clasts derived from the molten plagioclase-phyric andesite (M1a). Both fluidal and sub-planar clast margins have been observed. They are interpreted to have resulted from a combination of ductile and brittle fragmentation during andesite emplacement (e.g. Skilling et al., 2002). Juvenile clasts are dispersed and have a weak alignment in the mudstone host. The host mudstone is predominantly massive with diffuse lenses of laminated mudstone and laminated mudstone clasts. This lithofacies (M3c) is interpreted to be a fluidal peperite that formed during the emplacement of the M1a plagioclase-phyric andesite.

4.2.4 Polymictic breccia to sandstone facies association (M4)
This association consists of three polymictic breccia to sandstone facies. It is the most volumetrically significant unit in the Minifie ore zone. It varies from 30 to 150 m thick (Figs. 4.3 and 4.4). Strong pervasive biotite + orthoclase alteration has obscured primary textures and most likely masks the textural complexity of these units. Hydrothermal alteration is stronger north of 3300E and is centred around the steeply (60°) north-dipping Minifie Shear.

Polymictic, weakly graded breccia to sandstone (M4a)
This lithofacies (Fig. 4.15) occurs from the lower southern limits of section 9500 E to the base of the M3 mudstone facies association (Fig. 4.4), and is exposed throughout most of the open pit (Fig. 4.3). Laterally continuous units are thickly to very thickly bedded and
normally graded. Bedding measured in the open pit dips 20° towards 170° (Fig. 4.15b). Clasts are composed of plagioclase-phryic andesite, pyroxene-phryic basalt, variably altered (and texturally obscured) lithic clasts and rare mudstone. The matrix is predominantly fine to medium sand with minor intervals dominated by mud matrix.

Accretionary lapilli-bearing pebble breccia to sandstone (M4b)
A 10- to 30-m-thick interval of accretionary lapilli-bearing facies (Fig. 4.16) is interbedded with the diffusely graded polymictic breccia to sandstone facies (M4a), and observed only in the least-altered drill holes (DDHL1449 and 1450) of section 9500 E (Fig. 4.4). This lithofacies differs from the polymictic, weakly graded breccia to sandstone (M4a) in that it is finer grained overall (sandstone dominated with minor pebble breccia intervals) and beds are thinner (internally laminated beds up to 2 m thick). Plagioclase-phryic andesite clasts are predominant in polymictic zones, and are the sole clast component in the rare monomictic zones (Fig. 4.16d). Clasts are angular and plagioclase crystal fragments are prevalent in the matrix (Fig. 4.16g). Beds are locally deformed around the base of outsized plagioclase-phryic andesite clasts. The accretionary lapilli are predominantly intact and range in size up to 8 mm in diameter. They occur in diffusely laminated to thick beds that are generally poorly sorted (Figs. 4.16e and 4.16f).

Strongly altered polymictic breccia to sandstone (M4c)
The strongly altered polymictic breccia to sandstone (Fig. 4.17) accounts for a 100- to 150-m-thick interval (Fig. 4.4) that grades laterally and vertically into the polymictic, weakly graded breccia to sandstone (M4a). This lithofacies is strongly altered by pervasive biotite-orthoclase-anhydrite alteration, which has masked textures and composition in many examples (Figs. 4.17b and 4.17c). Thick to very thick south-dipping beds have been observed in the open pit (Fig. 4.15b).
Lithofacies M4a: Polymictic, weakly graded breccia to sandstone

Grain size  
<80 cm predominantly; outsized clasts up to 1 m  
• fine sandstone to cobble breccia

Components Clasts: 10 to 90%, angular to sub-round  
• polymictic, pyroxene-phyric basalt (M2a), plagioclase-phyric andesite (M1a) and rare mudstone clasts  
• blocky clast shapes, locally jagged, irregular clast margins

Matrix: 5 to 95%, <2 mm (sand-sized)  
• minor mud-sized component  
• plagioclase and pyroxene crystal fragments

Lithofacies  
• massive to weakly graded  
• thick to very thickly bedded, 080°/20°S  
• chaotic clast organisation  
• matrix-supported, locally clast-supported at base of beds  
• well- to poorly sorted  
• diffuse to gradational contacts throughout the stratigraphy

Geometry Contacts: Upper and lower contacts are diffuse.  
Thickness: 100 to 150 m (inclusive of M4 facies association).  
Distribution: Throughout the stratigraphy; dominant facies association in the open pit and section 9500 E.

Alteration Weak to strong, pervasive biotite-orthoclase-anhydrite alteration. Disseminated pyrite and jarosite stain throughout. Patchy illite and chlorite alteration.

Associated Facies Interbedded with the accretionary lapilli-bearing pebble breccia to sandstone (M4b). Gradational to the apparent, polymictic breccia to sandstone (M4c).

Interpretation: Volcanogenic sedimentary facies  
• Volcaniclastic debris flow deposit

Figure 4.15 Polymictic, weakly graded breccia to sandstone (M4a)  
(A) Composite graphic log drawn from DDHL1448, 1449 and 1450.  
(B) South-dipping beds in the Minifie open pit; photo taken on bench 872.  
(C) Hand sample photograph of hematite-stained and plagioclase crystal-rich-matrix in sample M972_16Jun06 (3976N, 10038E, 972m RL).
Lithofacies M4b: Accretionary lapilli-bearing pebble breccia to sandstone

**Grain size**  1 mm to 30 mm; outsized clasts up to 10 cm
- sandstone to pebble breccia

**Components**  **Clasts:** 10 to 70%, sub-angular to sub-round
- polymictic, plagioclase-phyric andesite (M1a), pyroxene-phyric basalt (M2a), accretionary lapilli and variably altered clasts
- locally monomictic; plagioclase-phyric andesite (M1a) and accretionary lapilli
- accretionary lapilli, 2 to 8 mm; finer grained, darker rim (mud-sized) ~500 μm wide
- accretionary lapilli are concentrated along bedding planes and randomly distributed through massive beds

**Matrix:**  30 to 90%, <2 mm (sand-sized)
- plagioclase crystal fragments abundant

**Lithofacies**
- laminated to very thickly bedded
- massive to weakly normally graded, one reverse graded bed
- diffuse bed contacts
- chaotic clast organisation
- matrix-supported
- well- to poorly sorted

**Geometry**  **Contacts:** Upper and lower contacts are diffuse to sharp with polymictic, weakly graded breccia to sandstone (M4a).

**Thickness:**  10 to 30 m, interbedded with the 100- to 150-m-thick M4 facies association.

**Distribution:** Observed in the least-altered stratigraphy on the southern extent of section 9500 E, from 820 to 780 m RL.

**Alteration**  Weak to strong, pervasive adularia-quartz alteration. Disseminated pyrite and jarosite stain throughout. Patchy illite and chlorite alteration.

**Associated Facies**
- Interbedded with polymictic, weakly graded breccia to sandstone (M4a).

**Interpretation:** Pyroclastic facies
- In-situ pyroclastic surge deposits and resedimented accretionary lapilli bearing debris flow deposits ± pyroclastic flow deposits

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Figure 4.16 (caption on next page)
Figure 4.16 (continued) Accretionary lapilli-bearing pebble breccia to sandstone (M4b)

(A) Graphic log from DDHL1449 showing textural variations, location of accretionary lapilli and the interbedded M4b and M4a lithofacies. (B) Hand sample photograph of DDHL1449_95.83 m, the aligned accretionary lapilli are apparent in this strongly adularia-quartz altered sample. (C) Photomicrograph (PPL) of faint (altered) accretionary lapilli in sample DDHL1449_101.0 m. (D) Graphic log from DDHL1450, a well-preserved section of core, that shows zones of monomictic breccia and laminated to massive accretionary lapilli-rich beds, normal grading and one reverse graded bed. (E) Hand sample photograph of DDHL1450_114.8 m, showing the laminated bed forms, alignment of accretionary lapilli along beds and a plagioclase-phyric andesite clast (M1a) that has deformed the underlying beds. (F) Hand sample photograph of DDHL1450_115.0 m, showing the massive bed forms and random distribution of accretionary lapilli through the bed. (G) Photomicrograph (PPL) of sample DDHL1450_114.27 m showing the plagioclase-phyric andesite (M1a) clasts with abundant plagioclase crystal fragments in the matrix.
Lithofacies M4c: Strongly altered polymictic breccia to sandstone

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

Components
- Clasts: 10 to 80%, angular to round
  - polymictic, pyroxene-phyric basalt (M2a), plagioclase-phyric andesite (M1a) and rare mudstone clasts
  - strong alteration produces apparent clastic textures, compositions and pseudo clastic textures
- Matrix: 20 to 90%, <2 mm (sand-sized)
  - strong biotite-orthoclase-anhydrite alteration
- Cement / altered matrix: <5%
  - anhydrite-orthoclase-biotite

Lithofacies
- massive to weakly graded
- diffusely, thickly to very thickly bedded
- chaotic clast organisation
- matrix-supported, locally clast-supported
- moderately- to poorly-sorted

Geometry
- Contacts: Diffuse to gradational upper and lower contacts with M1a and M4 facies associations. Sharp contacts with pyroxene-phyric basalt (M2a) dyke. Sharp contacts with M5 facies association.
- Thickness: 100 to 150 m
- Distribution: Continuous throughout the stratigraphy and the most volumetrically abundant lithofacies in the Minifie open pit and section 9500 E.

Alteration
- Strong, pervasive biotite-orthoclase-anhydrite alteration of clasts and matrix component.
- Disseminated pyrite and jarosite stain throughout.
- Patchy illite and chlorite alteration.

Associated Facies
- Gradational to, with apparently similar composition and texture to, the polymictic, weakly-graded breccia to sandstone (M4a).

Interpretation: Volcanogenic sedimentary facies
- Volcaniclastic debris flow deposit

Figure 4.17 Strongly altered polymictic breccia to sandstone (M4c)
(A) Composite graphic log drawn from DDHL1408, 1415, 1446, 1448 and 1455 showing the apparent textures. Note: the dashed grain-size outline is from areas where the grain-size was apparent as well. (B) Hand sample photograph of DDHL1415_118.52 m and (C) DDHL1455_85.48 m showing the strong, pervasive biotite-orthoclase-anhydrite alteration throughout the matrix and clasts.
Interpretation: Distinctive characteristics of this facies association include diffuse bed forms, weak normal grading and poor sorting. The contacts between polymictic, weakly graded breccia to sandstone (M4a) and the strongly altered polymictic breccia to sandstone (M4c) are laterally and vertically gradational. The diffuse bed forms, presence of outsized clasts, poor sorting, abundant sand-sized matrix and very thick beds indicate deposition from high-particle-concentration cohesionless sediment gravity flows (Lowe, 1982). These two lithofacies (M4a and M4c) are interpreted as volcaniclastic debris flow deposits.

Accretionary lapilli of lithofacies (M4b) are interpreted to have been sourced from an explosive subaerial eruption. The dense plagioclase-phryic andesite (M1a) clasts, plagioclase crystal fragments and minor pyroxene-phryic basalt clasts cannot be established beyond doubt to be pyroclasts. However, the arrangement of accretionary lapilli in diffusely laminated to thin beds that are generally poorly sorted is characteristic of pyroclastic surge deposits (e.g. Carey, 1991). Pyroclastic surge deposits form in a subaerial depositional setting typically close to a volcanic vent (McPhie et al., 1993). Locally, the accretionary lapilli-bearing breccia to sandstone are thickly bedded and associated with volcaniclastic debris flow deposits. This implies that intervals are resedimented accretionary lapilli-bearing pyroclastic flow deposits or debris flow deposits derived from and accretionary lapilli-bearing source. These facies variations are not indicative of either a subaerial or subaqueous depositional environment.

4.2.5 Hydrothermally cemented breccia facies association (M5)

This facies association consists of four breccia facies defined on the basis of cement mineralogy, including: biotite-orthoclase-anhydrite-calcite-cemented breccia (M5a), quartz-calcite-adularia-anhydrite-cemented breccia (M5b), adularia-quartz-pyrite-cemented breccia (M5c) and pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia (M5d). These lithofacies cross cut and overprint the volcano-sedimentary stratigraphy and are associated with veins and gold mineralisation.
**Biotite-orthoclase-anhydrite-calcite-cemented breccia (M5a)**

The biotite-orthoclase-anhydrite-calcite-cemented breccia facies (Fig. 4.18) has a narrow, 3- to 5-m-wide, NE-elongated dyke-like geometry (Fig. 4.3) with a vertical extent in excess of 100 m (Fig. 4.4). The northeastern extension of the breccia has terminated near the centre of the Minifie open pit, adjacent to the central Minifie Shear (Fig. 4.3). The southwestern limits of this breccia remain undetermined. Clasts were derived from the local wall-rocks and the organisation ranges from monomictic and jigsaw-fit on the margins to polymictic and chaotic in the centre of the breccia. Clast shapes vary from sub-round to angular. The matrix is a very fine grained aggregate of biotite, orthoclase and anhydrite (Fig. 4.18c). Cement comprises up to 40% of the breccia and is composed of crystalline biotite, anhydrite (massive and bladed), calcite, adularia, orthoclase, pyrite, chalcopyrite and magnetite (Figs. 4.18g, 4.18h and 4.18i). The central region of the breccia contains a number of hydrothermally cemented “chimneys” that are composed of chalcedony, quartz, anhydrite, calcite, and sulfides (Fig. 4.18e). These chimneys are interpreted to have filled former cavities in the breccia.

**Interpretation:** The abundance of hydrothermal cement, the dyke-like geometry, near-vertical orientation, and a vertical extent of >100 m suggest fragmentation involved a subsurface hydrothermal fragmentation process. The central, chaotically organised zone has a fine grained matrix and round clasts implying significant clast abrasion during transport. Biotite and orthoclase cement mineralogy constrains the temperature and composition of the hydrothermal fluid to the porphyry environment, typically greater than 1 km (e.g. Seedorff et al., 2005). This lithofacies is interpreted to be a magmatic-hydrothermal breccia dyke (e.g. Sillitoe, 1985).

**Quartz-calcite-adularia-anhydrite-cemented breccia (M5b)**

The quartz-calcite-adularia-anhydrite-cemented breccia facies is associated with and gradational to veins of the same composition (Fig. 4.19). This lithofacies occupies a central region of section 9500 E (Fig. 4.4) but predominantly occurs below the current level of mining. The breccias and veins predominantly (although not ubiquitously) dip shallowly (5 to 20°) to the north. Veins range in width from several mm up to one metre. The breccia contains 5 to
70% cement, is monomictic, and ranges from jigsaw-fit to chaotic clast organisation. Clasts are angular, and have tabular to splintery shapes (Figs. 4.19b and 4.19c). Cement and vein mineral assemblages are typically coarsely crystalline, and display colloform and crustiform open-space-fill textures. The anhydrite cement commonly exhibits bladed textures. Open space is common, although some has been partially infilled by chalcedony. This facies has gold grades from 2 to 63 g/t (based on 2 m composite assays; Lihir Gold Limited unpublished data), and is the most voluminous significant gold-bearing facies in the Minifie drill holes logged during this study.

**Interpretation:** Abundance of hydrothermal cement, monomictic jigsaw-fit to clast-rotated organisation and association with veins are characteristics consistent with sub-surface hydraulic or hydrothermal fluid-assisted fragmentation (Jebrak, 1997). The cockade and crustiform infill textures in the coarsely crystalline cement indicate sustained hydrothermal fluid flow through open space. Little or no clast transport is inferred from the splintery, tabular and shard-like clast shapes and the jigsaw-fit to clast-rotated organisation.

The presence of adularia in the cement assemblage constrains the environment of mineral precipitation to a shallow (<1 km), epithermal setting (White and Hedenquist, 1990). The presence of bladed anhydrite may indicate that boiling was occurring at the time of deposition based on analogy with bladed calcite textures observed from boiling geothermal systems (e.g. Simmons and Christenson, 1994) and the observation of bladed anhydrite at other epithermal gold deposits (e.g. Acupan, Philippines; Cooke et al., 1996).

**Adularia-quartz-pyrite-cemented breccia (M5c)**

The adularia-quartz-pyrite-cemented breccia is characterised by very fine grained cement (grain size <200 μm) and a sooty black appearance (Fig. 4.20). The breccia is massive, shows jigsaw-fit to clast-rotated organisation and occurs in 0.5- to 3-m-thick zones above 860 m RL (Fig. 4.4). The M5c lithofacies is associated with assay values of ~4 to ~6 g/t Au, consistent with the grade of the bulk mineable ore in the Minifie open pit. Only a small amount of this facies was observed during the current study, because it has been predominantly mined out. Based on the observed occurrences, the contacts of these breccias are steep to near-vertical.
Lithofacies M5a: Biotite-orthoclase-anhydrite-calcite-cemented breccia

Grain size  
- predominately <8 cm  
- pebble to cobble breccia

Components  
Clasts: 60 to 80%, angular to sub-round  
- polimictic, pyroxene-phryic basalt (M2a), plagioclase-phryic andesite (M1a), apparent polimictic breccia to sandstone (M4c), vein clasts  
- tabular, splintery, equant and rounded clast shapes

Matrix: 0 to 20%, <2 mm (sand-sized)  
- aggregate of biotite-anhydrite-orthoclase (possibly altered components)  
- appears turbid in thin section

Cement: 20 to 40%  
- biotite, anhydrite (massive, crystalline and bladed), calcite, adularia, orthoclase  
- pyrite, chalcopyrite and magnetite

Lithofacies  
- massive to weakly graded  
- jigsaw-fit to chaotic organisation  
- cement-supported  
- moderately- to poorly sorted

Geometry  
Contacts: Sharp to gradational upper and lower contacts. Steep orientation (near vertical).  
Geometry: 3 to 5 m wide, >100 m vertical extent, elongate in the NE direction.  
Distribution: Cross-cuts the stratigraphy in the centre of the open pit and northern extent of section 9500 E.

Alteration  
Clasts and apparent matrix are pervasively altered by biotite, orthoclase, anhydrite and adularia. Disseminated pyrite, chalcopyrite and magnetite.

Associated Facies  
None.

Interpretation: Hydrothermal facies  
- Magmatic-hydrothermal breccia dyke

Figure 4.18 Biotite-orthoclase-anhydrite-calcite-cemented breccia (M5a)  
(A) Graphic log from DDHL1415 showing the sharp to gradational contacts between M5a and the host rocks. Note: In the centre of the lower interval, there is a polymictic zone that is not host rock controlled.
Figure 4.18 (continued)
(B) Hand sample photograph of sample DDHL1415_134.86 m showing the anhydrite and biotite cement. The box outline denotes the location of (C). (C) Photomicrograph (PPL) of sample DDHL1415_134.86 m showing the presence of biotite and anhydrite cement and a fine grained matrix component. (D) Hand sample photograph of sample M872_01 from bench 872 of the Minifie open pit. (E) Photograph of a “chimney” observed in the Minifie open pit on bench 872. The “chimneys” occur in the centre of the M5a lithofacies and are composed of chalcedony, quartz, anhydrite, calcite and sulfides. (F) Hand sample photograph of an anhydrite vein within a clast in sample DDHL1415_122.17 m. (G) Photomicrograph (PPL) of biotite and orthoclase cement in sample DDHL1415_134.86 m. (H) Photomicrograph (XPL) of orthoclase, anhydrite and biotite cement. (I) Photomicrograph (XPL) of a fluid inclusion with a daughter crystal within an anhydrite crystal.
Lithofacies M5b: Quartz-calcite-adularia-anhydrite-cemented breccia

**Grain size** 3 mm to 9 cm
- pebble to cobble breccia

**Components**
- **Clasts**: 30 to 95%, angular to sub-round
  - monomictic; variable compositions determined by host rock
  - splintery, tabular and equant clast shapes
  - locally irregular and jagged clast margins
  - locally alteration rinds (mm to several cm thick) on clasts

**Geometry**
- Contacts: Upper and lower contacts are gradational to sharp with host rock. Gradational contacts with veins of the same composition.
- Thickness: 50 cm to 20 m
- Distribution: Throughout the stratigraphy but most intensely developed in the centre of section 9500 E.

**Alteration**
- Clasts are variably biotite-orthoclase-anhydrite altered. Alteration rinds on clasts are illite dominant.

**Interpretation**: Hydrothermal facies
- Hydraulic breccia gradational to veins

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**Figure 4.19 Quartz-calcite-adularia-anhydrite-cemented breccia (M5b)**
(A) Composite graphic log drawn from DDHL1408, 1415, 1446 and 1455. (B) Hand sample photograph of DDHL1446_154.12 m showing the location of photomicrographs (E and F), the jagged and splintery clast shapes and the arrangement of cement; pyrite is the dominant cement next to clast margins, followed by quartz and then later calcite.
Figure 4.19 (continued)

(C) Jagged and splintery clasts of lithofacies M4c arranged in a jigsaw-fit to clast-rotated organisation in coarse-grained quartz-anhydrite-adularia-calcite cement in sample DDHL1408_90.61 m. (D) Quartz-anhydrite-calcite cement that grades into a vein with 1 to 2 mm wide chlorite-clay laminae developed oblique to the vein margins in sample DDHL1448_118.47 m. Photomicrographs (E, F, G) are all from sample DDHL1446_154.12 m. (F) Photomicrograph (XPL) showing the coarse colloform quartz cement. (F) Photomicrograph (XPL) of the pyrite + clay-rich contact with colloform quartz cement. (G) Photomicrograph (XPL) of the calcite-only zone.
Lithofacies M5c: Adularia-quartz-pyrite-cemented breccia

Grain size  
<10 cm predominantly; locally as fine as 1 mm
* pebble to cobble breccia

Components  
Clasts: 60 to 95%, angular to sub-angular
* monomictic
* pseudo-rounding; clast boundaries are obscured by pyrite alteration rinds
* tabular to splintery clast shapes
* adularia, quartz, pyrite and clay altered clasts

Cement: 5 to 35%
* adularia, quartz and pyrite
* very fine-grained, < 1/16 mm

Open Space: 2 to 5%

Lithofacies  
* massive
* jigsaw-fit to clast-rotated organisation
* clast- to cement-supported
* moderately- to poorly sorted
* associated with ~ 5 g/t Au

Geometry  
Contacts: Upper and lower contacts are gradational.

Thickness: 0.5 to 3 m

Distribution: Above 860 m RL and concentrated on the southern edge of section 9500 E. This lithofacies has been mostly mined out by the time of this study.

Alteration  
Strong, pervasive adularia, quartz, pyrite, calcite and clay alteration of clasts.

Associated Facies  
The cement components are the same as in pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia (M5d). Also spatially associated with the M5d lithofacies.

Interpretation: Hydrothermal facies
* Hydraulic breccia

Figure 4.20 Adularia-quartz-pyrite-cemented breccia (M5c)
(A) Composite graphic log drawn from DDHL1446, 1448, 1449 and 1450 showing the gradational contacts between this lithofacies and the host rocks. (B) Hand sample photograph of jigsaw-fit clast organisation with dark grey to black cement and open space in sample DDHL1446_10.36 m. (C) Hand sample photograph showing dark grey to black cement and alteration in sample M884_13Jul06_98 (3502N, 9850E, 884m RL).
Figure 4.20 (continued)

(D) Photomicrograph (XPL) of adularia cement in sample DDHL1446_10.36 m. (E) Photomicrograph (XPL) of quartz and adularia cement in sample DDHL1446_10.36 m. (F) Reflected light photomicrograph of colloform pyrite cement in sample 16521 (M884_29Jun06) from open pit bench 884. (G) Reflected light photomicrograph of colloform pyrite in sample 16521 (M884_29Jun06) from open pit bench 884, showing the alternating fibrous and dense pyrite zones after marcasite.

Clasts comprise 6 to 90% of the breccia and have angular to sub-angular, blocky, tabular and splintery shapes. Many clast shapes appear sub-round because they have alteration rinds that obscure the original clast margins. The cement assemblage of adularia, quartz, pyrite, calcite and anhydrite accounts for 5 to 35% of the breccia, and open space accounts for 2 to 5%. Two samples of adularia associated with this assemblage were dated by Carman (1994) using $^{40}$Ar-$^{39}$Ar, providing ages of gold mineralisation of $0.61 \pm 0.25$ to $0.52 \pm 0.11$ Ma. This breccia facies is associated with, and transitional to, veins of the same composition. The veins range from 1 mm to 1 cm in width.
**Interpretation:** The jigsaw-fit to clast-rotated organisation of the adularia-quartz-pyrite-cemented breccias, the hydrothermal cement, lack of matrix and the intense alteration rinds and pseudo-rounding of clasts are all characteristic of hydraulic or hydrothermal fluid-assisted fragmentation (Jebrak, 1997). The adularia-quartz-pyrite-calcite-anhydrite cement assemblage is consistent with deposition in the epithermal or shallow-level hydrothermal environment (White and Hedenquist, 1990; Corbett and Leach, 1998).

**Pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia (M5d)**

This hydrothermally cemented lithofacies (Fig. 4.21) has the same cement mineralogy as M5c, but occurs as an isolated 50-cm-wide dyke. It has a near-vertical, sharp-sided, discordant aspect (Fig. 4.4). The pyrite clast-bearing breccia is chaotically organised, cement-supported and moderately sorted. Angular to round clasts comprise 30 to 50% of the breccia and include pyrite clasts, quartz-calcite vein clasts, illite-altered clasts and adularia-quartz-pyrite-altered clasts (Fig. 4.21b and 4.21d). Colloform pyrite clasts are up to 4 cm in length and locally occur in jigsaw-fit groups (Fig. 4.21d). This breccia has grades of up to 6.6 g/t Au but it is unclear whether gold occurs in the clasts, in the pyritic cement, or in the pyrite clasts.

**Interpretation:** The pyrite clasts, quartz-calcite veins clasts and illite-altered clasts were produced during a hydrothermal event that preceded brecciation. The colloform pyrite clasts are interpreted to have formed contemporaneous with the M5c cemented breccia and related veins. The steeply dipping orientation of this facies suggests a structural control on its formation. Like the M5c lithofacies, the abundance of adularia-quartz-pyrite-cement is characteristic of hydraulic or hydrothermal fluid-assisted fragmentation (Jebrak, 1997) and is consistent with deposition in the epithermal or shallow-level hydrothermal environment (White and Hedenquist, 1990; Corbett and Leach, 1998). The pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia is interpreted to be a hydraulic breccia dyke and could be occupying a steeply dipping fault.
Lithofacies M5d: Pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia

**Grain size**
- <8 mm
- Granule to pebble breccia

**Components**
- Clasts: 30 to 50%, angular to round
  - polymictic, pyrite clasts, quartz-calcite vein clasts, wispy clay (illite) altered clasts, variably altered clasts
  - lithic clasts pervasively adularia, quartz, pyrite altered
  - pyrite clasts have colloform textures and are locally jigsaw-fit fractured

**Cement:**
- 50%
  - adularia, quartz, calcite, anhydrite, illite, pyrite
  - <1/16 mm grain size

**Lithofacies**
- massive
- chaotic clast organisation
- cement-supported
- moderately sorted

**Geometry**
- **Contacts:** Sharp upper and lower contacts, both steeply dipping.
- **Width:** 50 cm
- **Distribution:** Observed as one unit at 840 m RL, ~3350 N.

**Alteration**
- Lithic clasts are pervasively adularia, quartz, pyrite altered.

**Associated Facies**
- Cement composition is the same as the adularia-quartz-pyrite-cemented breccia (M5c).

**Interpretation:** Hydrothermal facies
- Hydraulic breccia dyke / vein

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**Figure 4.21 Pyrite clast-bearing, adularia-quartz-pyrite-cemented breccia (M5d)**
(A) Graphic log from DDHL1446 showing the sharp, discordant upper and lower contacts and the thickness of this lithofacies. (B) Hand sample photograph of sample DDHL1446_64.10 m showing a colloform pyrite clast and an illite clast. (C) Photomicrograph (XPL) of adularia, quartz and anhydrite cement from sample DDHL1446_64.10 m. (D) Reflected light photomicrograph of a fragmented pyrite clast from sample DDHL1446_64.10 m.
4.3 Volcanic and hydrothermal evolution of the Minifie ore zone

Carman’s (1994) detailed alteration and ore mineral paragenesis (Table 2.2 and 2.3), was generated in part from studies of the shallow parts of section 9500 E and is integrated below with a new geologic framework and evolution of the Minifie ore zone. Lithofacies are categorised into three temporally distinctive groups; development of the volcano-sedimentary stratigraphy, overprinting porphyry-style alteration and mineralisation, and later epithermal-style alteration and mineralisation.

Volcano-sedimentary stratigraphy

The oldest parts of the succession are dominated by polymictic breccia to sandstone lithofacies (M4; Fig. 4.22b). This facies association is interpreted to comprise volcaniclastic debris flow deposits (M4a and c) and subaerial pyroclastic surge deposits (M4b). This style of sedimentation was interrupted by the deposition of autoclastic facies associated with lavas and shallow intrusions, the plagioclase-phyric autobreccia (M1c) and pyroxene-phyric autobreccia (M2b).

The pyroxene-phyric autobreccia (M2b) is associated with a pyroxene-phyric basalt dyke (M2a) and a volcanioclasti c debris flow deposit (M2c). This association is interpreted as a feeder-dyke and autoclastic breccia complex. The lensoid deposit of volcanioclastic debris flow breccia (M2c) records mass wasting that affected the unstable parts of contemporaneous pyroxene-phyric basalt autoclastic facies.

At least locally, the supply of coarse detritus ceased and suspension-settled mud accumulated in a quiet subaqueous setting (M3; Fig. 4.22b). This change may have been the result of cessation of subaerial volcanism or a change in basin geometry. A plagioclase-phyric lava or shallow intrusion (M1a) with a peperitic basal contact was emplaced on (or within) the succession (Fig. 4.22b). Associated with the plagioclase-phyric coherent facies are intrusive peperite (M1b) along the base, autobreccia (M1d) along the top and margins, and a lense of globular (fluidal) peperite (M3c). The plagioclase-phyric coherent and clastic facies association (M1) is interpreted to be a partly extrusive cryptodome erupted into a subaqueous depositional environment represented by the mudstone facies association.
The volcano-sedimentary succession resulting from these processes was ~200 m thick (Fig. 4.22b). Vent proximal volcanic facies record the evolution of the depositional environment from subaerial at the base of section 9500 E, to subaqueous throughout the remainder of the succession. Subaerial volcanic facies (M4b) resulted from explosive eruptions. Subaqueous volcanic facies, (e.g. M1c, M1b and M1d) are interpreted as autoclastic deposits resulting from effusive eruptions and intrusions. The thick accumulation of coarse volcaniclastic debris flow facies (M4) deposited throughout the succession does not constrain the position of the depositional environment but reflects a continual and abundant source of detritus, driven by gravity transportation. In contrast to the high sediment supply of the M4 facies association, the overlying mudstone (M3) was deposited in a quiet subaqueous environment. Accumulation of the coarse thick units (M4) probably occurred over a much shorter time than the mudstone (M3). The subaqueous environment throughout the succession is likely to have been submarine, based simply on the uplift rates determined in Chapter 3. Ongoing volcanic activity is presumed to have constructed the Luise volcanic edifice above the level of the Minifie ore zone (Fig. 4.22a). All of these overlying deposits have been removed from the Minifie area by the later volcanic sector collapse event.

**Porphyry-style alteration and mineralisation**

Porphyry-style biotite + orthoclase alteration associated with stage 1A phlogopitic biotite + orthoclase veins (Carman, 1994) has obscured primary textures within the central portion of the Minifie stratigraphy (Fig. 4.22c). The inherent permeability of the host volcano-sedimentary stratigraphy and activation of the Minifie shear appear to have focused porphyry-stage alteration (Carman, 1994).

The last porphyry-related event was the emplacement of a 3- to 5-m-wide, near-vertical magmatic-hydrothermal breccia “dyke” (M5a; Fig. 4.22c). The magmatic-hydrothermal breccia dyke was focused along a northeast-oriented structure and may be related to the Minifie shear.

Epithermal-like temperatures (200° to 300°C) in the late, transitional porphyry-stages of hydrothermal activity (i.e. orthoclase alteration and stage 1B and 2 veins; Carman,
Chapter 4 - Lithofacies associations in the Minifie ore zone

Stage 1 A veins and biotite alteration
Stage 1 A veins and chlorite alteration

Study area

A

B

C

3250 N 3550 N

M1a
M2b
M2c
M3a
M3b
M3c
M4a
M4b
M4c
M5a

C

900 m RL 700 m RL

900 m RL 700 m RL

3550 N

3250 N

Stage 1 A veins and biotite alteration
Stage 1 A veins and chlorite alteration

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Figure 4.22 Schematic evolution of the Minifie ore zone from volcano-sedimentary stratigraphy (A and B) to porphyry-style alteration and associated magmatic hydrothermal fragmentation (C) to sector collapse (D) and subsequent epithermal-style alteration and mineralisation and associated hydrothermal fragmentation (E). (A) Simplified geomorphology of the Luise volcano prior to the sector collapse event, with the outline of the study area. (B) Development of the volcano-sedimentary stratigraphy. (C) Tilting of the stratigraphy (30° S), and formation of the porphyry-style alteration features documented by Carman (1994, 2003; Table 2.2), together with the newly recognized biotite – orthoclase – anhydrite – calcite – cemented breccia dyke (M5a). (D) 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 show in the current near-surface configuration. (E) Epithermal-style alteration from Carman (1994, 2003; Table 2.2), quartz – calcite – adularia – anhydrite – cemented breccia facies (M5b) and adularia – quartz – pyrite – calcite – anhydrite – cemented breccia facies (M5c).

1994) at Lihir could be accounted for by gradual unroofing of the deeper porphyry system by erosion of the Luise volcanic edifice (Carman, 1994).

The biotite and orthoclase alteration assemblages, their associated veins, and the magmatic-hydrothermal breccia dyke do not contain economic copper grades (<0.1% chalcopyrite by visual estimate). Despite extensive drilling, core logging and mapping, the causative intrusion for the porphyry-style features at Minifie remains undiscovered.
Epithermal-style alteration and gold mineralisation

Epithermal breccias and veins disrupted and overprinted earlier porphyry-related alteration and mineralisation features (Fig. 12e; Carman, 1994). Bulk mineable gold formed at this time (Carman, 1994). The gold occurs mostly in refractory pyrite, which precipitated from low temperature fluids (T <250°C) and salinities <7 weight % NaCl (Carman, 1994, 2003) possibly in a submarine environment (Reich et al., 2006).

The shallow-level refractory sulfide ore zone at Miniifie occurs in the adularia-quartz-pyrite-cemented breccia facies (M5c) and associated veins and forms a concave blanket covering an area of 200 m by 300 m centered on, and slightly drawn down into, the Miniifie shear (Rutter et al., 2008). Refractory-pyrite-hosted gold ore typically has homogeneous grades (>4 g/t), and has been predominantly mined out.

Deep-level quartz-calcite-adularia-anhydrite-cemented breccias (M5b) and veins are predominantly shallowly north-dipping to sub-horizontal. The sub-horizontal veins imply a near-vertical minimum principal stress (σ₃) orientation at the time of emplacement or a rotation of a more steeply emplaced vein network to the currently observed orientation. The structural controls on sub-horizontal vein formation at the Ladolam ore deposit remain poorly understood and further research is necessary.

4.4 Conclusions

The host rocks to Miniifie are variably altered, south-dipping volcano-sedimentary rocks that were overprinted by three stages of hydrothermal breccias and veins. The volcano-sedimentary lithofacies record the transition from a subaerial environment close to an explosive vent to a subaqueous, quiet depositional environment into which a partially extrusive cryptodome was emplaced.

The hydrothermal breccia facies reflect the evolution from porphyry to epithermal conditions, as reported by Carman (1994). Gold mineralisation is hosted predominantly in hydraulic breccias and veins that are characterised by epithermal-style quartz-calcite-adularia and adularia-quartz-pyrite mineral assemblages.
The regional south to southwest tilting of Lihir Island, as evidenced by the uplifted limestone, is reflected in the southward dip of the strata in the Minifie open pit. Tilting is therefore interpreted to have occurred post-limestone and post-development of the volcanic stratigraphy, the porphyry-environment and potentially the epithermal environment as well.