CHAPTER 1
Introduction: Thesis aims and contents

1.1 Introduction

The Ladolam gold deposit, on Lihir Island, Papua New Guinea (Figs. 1.1, 1.2 and 1.3) has been classified by previous workers as a giant, low-sulfidation epithermal gold deposit (Carman, 1994). Mineralisation is associated with diverse breccia facies that include the products of hydrothermal, volcanic and sedimentary processes. The central aim of this thesis is to unravel the complexity of the breccias at Ladolam. This chapter introduces the field site, presents the thesis aims and their significance, and provides a background discussion on breccia terminology and approach used in this study.

This research project has focused on the character and origin of the host succession to the Ladolam gold deposit, based on exposures and drill core from the Minifie and Lienetz ore zones. The lithofacies identified in this study record the evolution of a host volcano-sedimentary stratigraphy overprinted by hydrothermal facies. Hydrothermal facies record the progression from porphyry to epithermal environments, as previously reported by Carman (1994), and contain gold deposited in at least three distinct stages (Carman, 1994, 2003).

Figure 1.1 Aerial view of mining of the Ladolam gold deposit (view looking south). The Lienetz open pit is in the centre of the photo and the Minifie open pit is in the background.

1.2 Thesis aims and significance

The principal aims of this thesis are to:

1) characterise the breccia facies at Ladolam, specifically, their textures, components, geometries, contact relationships and spatial context, and to interpret their origins;
2) evaluate the spatial and temporal relationships between breccia facies and gold mineralisation;
3) define the architecture of the host succession to the Ladolam gold deposit in the Minifie and Lienetz ore zones;
4) reconstruct the geologic history of the host succession and the ore forming events of the Ladolam gold deposit based on the Minifie and Lienetz ore zones, and outline potential exploration implications.

In terms of contained gold, the Ladolam gold deposit is the world's largest low-sulfidation epithermal deposit (Carman, 2003), but the controls on mineralisation remain poorly understood. This research contributes to that understanding by characterising the geologic setting and resolving relationships amongst various facies that host the gold deposit. The host succession of the Ladolam gold deposit is geologically young and therefore provides an analogue for older, less well preserved alkalic mineralised successions. As well, the current tectonic configuration of Lihir Island as part of the New Ireland Basin can be linked to ore formation, and this information could be useful for alkalic epithermal ore deposit exploration strategies.

Another significant goal of this research has been to develop a systematic approach to breccia description and classification in volcanic-hydrothermal environments. Such breccias have been widely documented by previous workers (e.g. Sillitoe, 1985; Taylor and Pollard, 1993; Corbett and Leach, 1998; Browne and Lawless, 2001), but a standard approach to description and interpretation has not been universally established. Careful systematic description is a pre-requisite for further understanding of the processes of fragmentation, transportation and deposition in volcanic-hydrothermal environments, as well as understanding the relationships between breccias and mineralisation events.

This research was conducted as part of a broader research project entitled "Shallow- and deep-level alkalic mineral deposits: an integrated exploration model". The 'alkalic' project was a joint study between the Mineral Deposit Research Unit (MDRU) at the University of British Columbia and CODES. This PhD study has helped to develop a holistic alkalic mineral deposit model by unravelling both the deposit-scale and regional-scale geologic setting of the Ladolam gold deposit.

1.3 Field site

The Lihir Island group is located ~900 km north-east of Port Moresby, (3°08"S, 152°38"E) in the New Ireland Province of Papua New Guinea (Figs. 1.2 and 1.3). Niolam Island is commonly referred to as Lihir and is the largest of five islands that make up the Lihir Island group (Mali, Mahur, Masehet, Sanambiet and Niolam). Lihir Island rises to 660 m above sea level from more than 2000 m water depth. The temperature ranges from 19 to 35°C and the

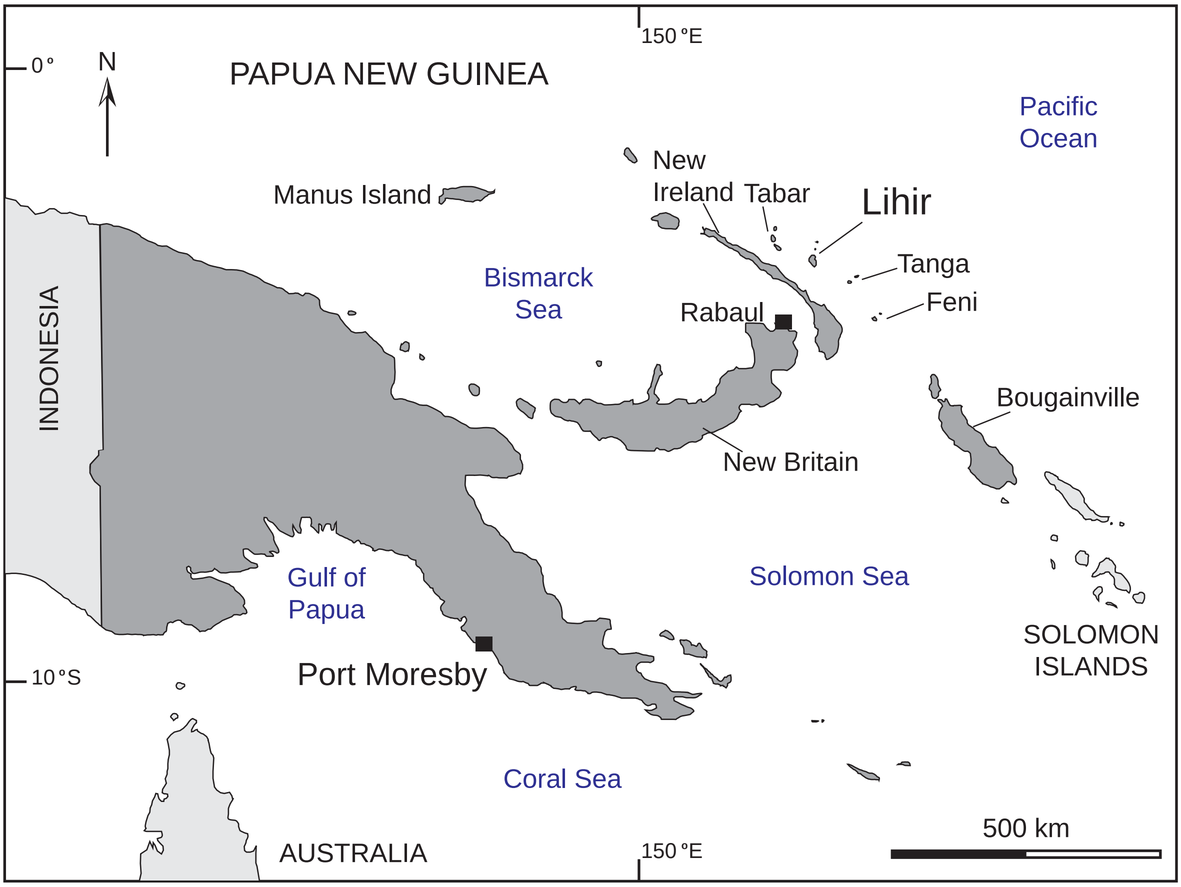


Figure 1.2 Map of Papua New Guinea and surrounding countries, showing the location of the Lihir Island group.

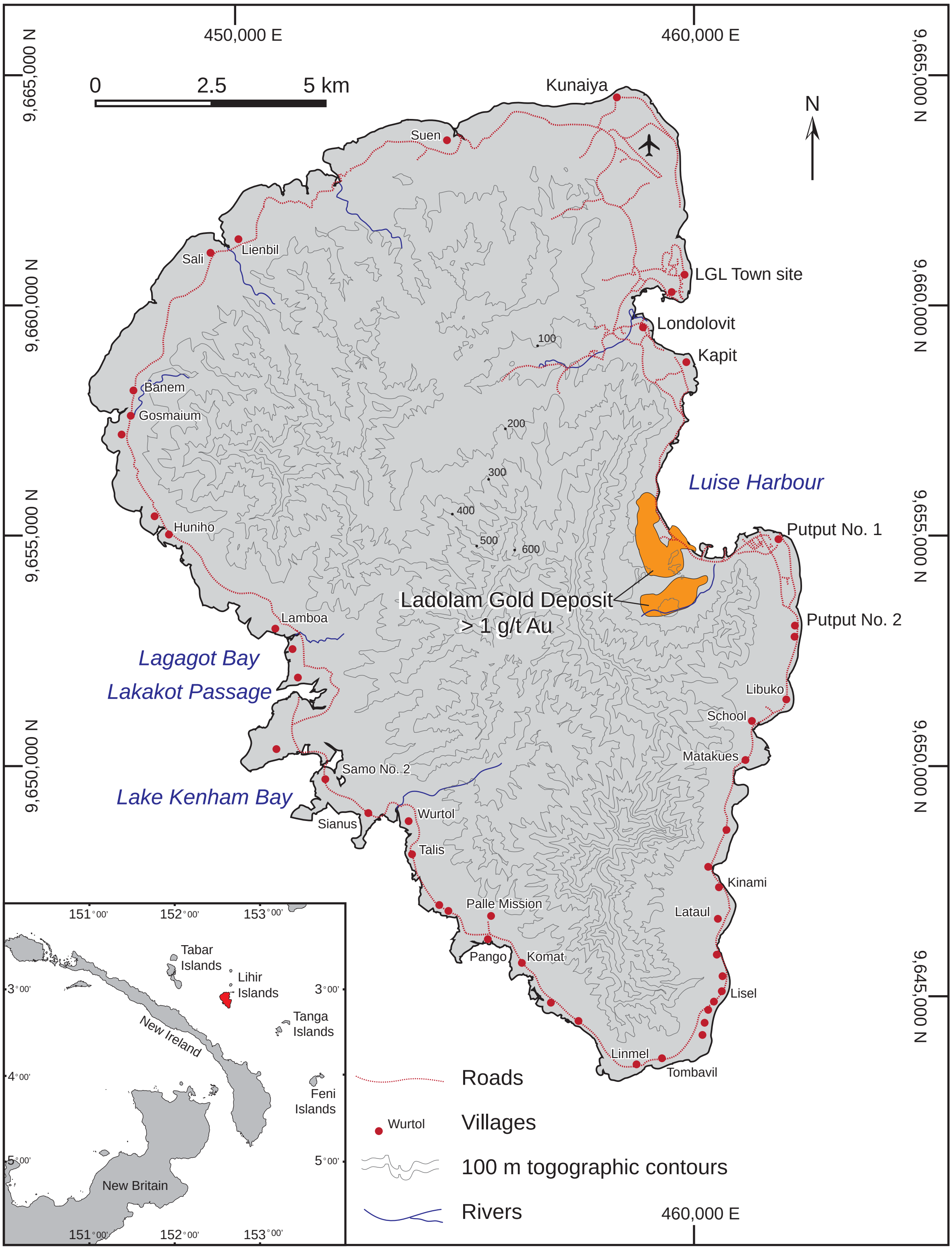


Figure 1.3 Location of the Ladolam gold deposit on Lihir Island, in the New Ireland Province of Papua New Guinea. Map Projection: Austalian UTM map grid, zone 56S. Contours, streams, roads and ore shells (> 1.5 g/t Au) from LGL database. Villages and geographic locations from the Lihir Sheet 9491, Papua New Guinea - Australian National Mapping Bureau, 1983.

annual rainfall averages ~4800 mm per year (Lihir Gold Limited website).

The Ladolam gold deposit is located on the eastern coast in an area of significant geothermal activity centred on the Luise volcanic edifice and Luise harbour. The deposit is mined by Lihir Gold Limited (LGL) in a joint venture between the Lihir land holders, the Papua New Guinea government and Australian share holders. The current resource is 39 Moz (LGL Resources Reserves Update, Lihir Gold Limited, 2008); an additional 6.5 Moz was mined since 1997. Gold is primarily hosted in refractory pyrite ores and the average grade of the deposit is 2.42 g/t Au (Updates reserves and resources, Lihir Gold Limited, 2008).

Access to Lihir Island is through the Niolam airport located ~7 km north of the Ladolam gold mine and ~3 km north of the Londolovit town site. Daily travel to the mine from the town site is by road on company buses or by company vehicles.

1.4 Methods of investigation

This project was field-based and involved systematic core logging and open-pit mapping over 5½ months from June 2006 to November 2008. Four field seasons were completed: June-July, 2006, July-August, 2007, April-May, 2008, November, 2008. Fieldwork focussed on the Minifie and Lienetz ore zones. Fieldwork was divided between two main tasks, drill core logging and open pit mapping. The descriptive nomenclature for coherent and clastic facies follows the methods of McPhie et al. (1993) and Davies (2002). Mineral abbreviations and symbols used in this thesis are provided in Table 1.1.

The characterisation of the lithofacies at Ladolam concentrated on three main field tasks:

1) Construction of the host stratigraphy of the Luise volcanic block by logging six geothermal well holes (GW29, GW30, GW31, GW32, GW33 and GW34), totalling ~4430 m logged.
2) Characterisation of lithofacies of the Minifie ore zone by logging eight drill holes (DDHL1408, DDHL1415, DDHL1446, DDHL1448, DDHL1449, DDHL1450, DDHl1455, DDHL1456; 1144 m logged) along section 9500, and Minifie open pit mapping of ~3020 m along benches 980, 968, 884 and 872.

Table 1.1 Mineral abbreviations and symbols used in this thesis

Mineral	Mineral Abbreviation (from IUGS)	Map / log symbol	
		Cement / alteration	Mineral
Actinolite	Act		
Adularia	Ad	▬	
Albite	Ab		
Amphibole	Am		∨
Anhydrite	Anh	▬	
Apatite	Ap		
Arsenopyrite	Apy		
Barite	Brt		
Biotite	Bt	▬	╲
Calcite	Cal	▬	
Chalcopyrite	Ccp	▬	
Chalcedony	Cdny	▬	
Chlorite	Chl	▬	
Clinopyroxene	Cpx		
Dolomite	Dol		
Epidote	Ep		
Feldspar	Fsp		⌐
Ferromagnesian			∧
Galena	Gn		
Hornblende	Hbl		∨
Illite	Ill	▬	
Kaolinite	Kln	▬	
K-feldspar	Kfs	▬	⌐
Magnetite	Mag	⊕	⊕
Marcasite	Mrc	▬	
Molybdenite	Mo		
Olivine	Ol		□
Orthoclase	Or		
Orthopyroxene	Opx		∧
Phlogopite	Phl		
Plagioclase	Pl		
Pyrite	Py	▬	
Pyroxene	Px		∧
Pyrrhotite	Po		
Quartz	Qtz	▬	+
Realgar	Rea		
Rutile	Rt		
Sanidine	Sa		⌐
Sphalerite	Sp		
Sulfide (fine grained - black)		▬	
Vermiculite	Vrm		

3) Characterisation of lithofacies of the Lienetz ore zone by logging eight drill holes (DDHL712, DDHL757, DDHL791, DDHL1160, DDHL1476, DDHL1703, DDHL1704 and DDHL1709; 1585 m logged), and Lienetz open pit mapping of ~3750 m from bench 992 down to bench 824.

1.4.1 Drill core logging methods

Over 2070 drill holes have been drilled into and surrounding the Ladolam ore body. Because much of the archived core has been discarded or is too degraded to recognise lithology, recently drilled core was selected for this study. Core was logged in detail at a 1:10 to 1:20 scale. The graphic logging method (Fig. 1.4; described in detail in McPhie et al., 1993; Gifkins et al., 2005) was used for drill core, supplemented with an additional column for cement mineralogy and texture. Drill holes logged as part of this study are provided digitally in Appendix A.

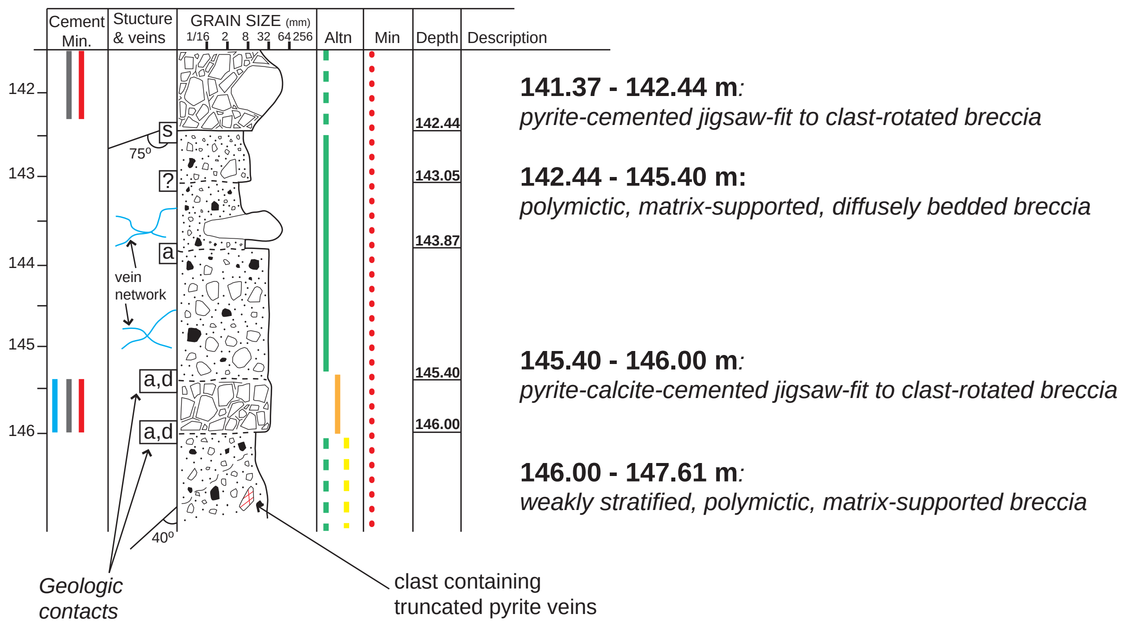
1.4.2 Open pit mapping methods

The Lihir open pits have a unique set of obstacles presented by the active geothermal system. Benches are mined at 12 m heights to allow the rocks to cool enough for safe mining practices. Many areas, especially within the Lienetz pit, are classified as "Potential Geothermal Outburst Areas; PGOA's" and entry is not permitted. Within these geothermal areas, the rocks are hot (> 50°C) and there are geysers, fumaroles, unstable ground and pools of boiling water. The areas of active mining provide the best exposure for pit mapping as the newly exposed rock reacts quickly with rainfall and air to form a coating of jarosite that obscures primary textures. Despite these complications, the pits offer excellent three dimensional exposures of lithofacies that has aided tremendously in geologic interpretation. The pits were mapped at 1:1000 scale using the "Anaconda" method (Einaudi, 1997) to produce a plan map. The Anaconda method was adapted to record descriptive data (Fig. 1.4).

At the time of this study, the Minifie ore zone had been mined to 872 m RL and since 2007, the area has been reclaimed as a low grade stockpile. Systematic mapping of Minifie benches throughout the 2006 field season was permitted. Active mining of the Lienetz pit has been ongoing throughout this PhD study. Opportunistic mapping (dictated by safety issues)

Graphic drill core log

e.g. DDHL1160 Collar: 5400 E, 9400 N, 968 m RL Azimuth 180°, Inclination -65°



1. Descriptive data recorded for clastic lithofacies

A. Components

Clasts: grain size (drawn to scale)
mode %
types
morphologies

Matrix: grain size (< 2 mm)
mode %
components
textures

Cement: mineralogy (refer to Table 1.1)
mode %
grain size
textures

Open space: mode %

Clastic grain size symbols
- mud / mudstone (< 1 / 16 mm)
- sand / sandstone (1/16 to 2 mm)
- gravel / conlgomerate or breccia (> 2 mm)

Clasts
(drawn to scale on pit mapping logs)
- granule (2 to 4 mm)
- pebble (4 to 64 mm)
- cobble (64 to 356 mm)
- boulder (> 256 mm)

10 mm

- monomictic / polymictic
- mudstone clasts
- clasts containing veins
- mineralised / altered clasts
- accretionary lapilli
- organics

Cement textures
- bladed
- crystalline
- colloform
- disseminated
- drusy
- massive
- zoned

B. Lithofacies

Massive (non-bedded) or stratified

Bedding

laminated	< 1 cm
very thinly bedded	1 - 3 cm
thinly bedded	3 - 10 cm
medium bedded	10 - 30 cm
thickly bedded	30 - 100 cm
thickly bedded	> 100

equal or unequal thickness
laterally even or uneven thickness
laterally continuous or discontinuous
cross-bedded, cross laminated

Massive (non-graded) or graded
normally graded
reversely graded

clast (internal) organisation
jigsaw fit / clast-rotated / chaotic

Fabric
clast, matrix, cement-supported
sorting
very well sorted / well sorted / moderately sorted / poorly sorted / very poorly sorted

Figure 1.4 Logging legend and examples of descriptive data recorded on drill core logs and open pit mapping logs

Open pit mapping log (plan view)

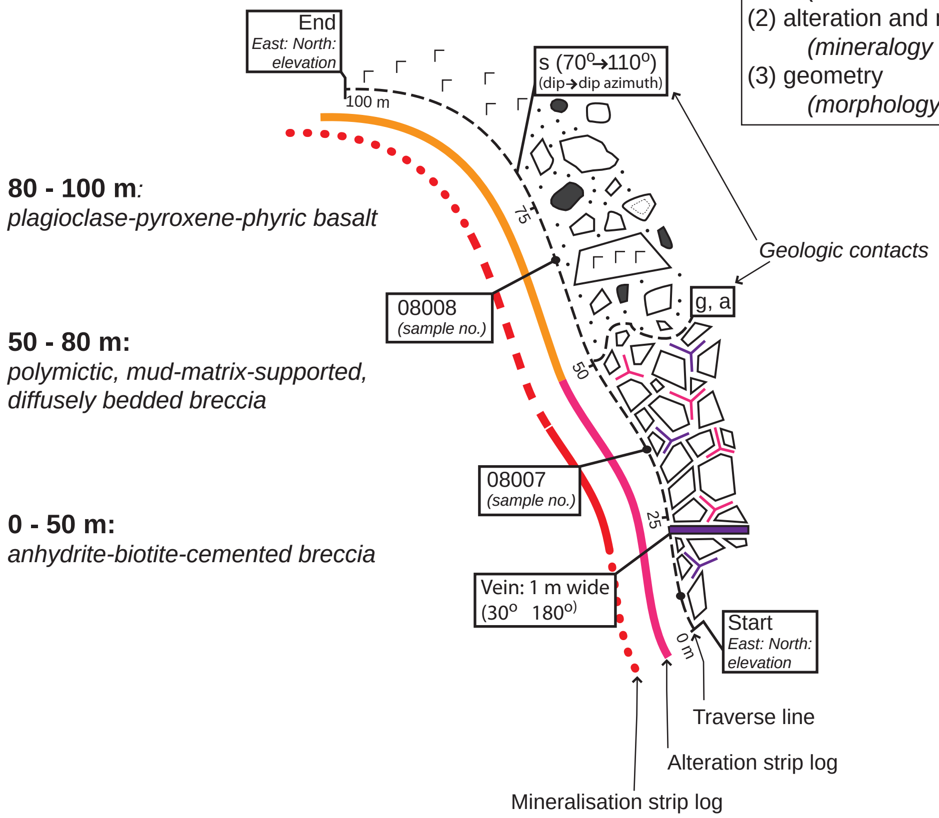
e.g. Bench 968, Date: 07 July 2007

Information recorded on graphic drill core & open pit mapping logs

(1) descriptive data
(coherent / clastic lithofacies)

(2) alteration and mineralisation
(mineralogy and intensity)

(3) geometry
(morphology and contacts)



1. Descriptive data recorded for coherent lithofacies

A. Texture:
(e.g. porphyritic, equigranular, aphanitic, glassy, vesicular, spherulitic, trachytic)

B. Mineralogy: (refer to Table 1.1)
mode %
grain size

C. Lithofacies: (e.g. jointing, massive or flow-foliated, pillows, pseudo-pillows)

Coherent grain size
(drawn to scale on pit mapping logs)

- > 8 mm, mega
- 5 to 8 mm, coarse
- 1 to 5 mm, medium
- < 1 mm, fine

Jointing

blocky joints
columnar joints
concentric joints
prismatic joints
platy joints
radial columnar joints
tortoise shell joints

2. Alteration and mineralisation: recorded for clastic and coherent lithofacies

Mineralogy (for a complete list refer to Table 1.1)

Adularia	Chalcedony	Kaolinite	Quartz
Anhydrite	Chalcopyrite	K-feldspar	Sulfide (black)
Biotite	Chlorite	⊕ Magnetite	
Calcite	Illite	Pyrite	

Intensity
weak (< 5 %)
moderate (5 to 15 %)
strong (> 15 %)

3. Geometry: recorded for clastic and coherent lithofacies

Morphology

concodant	stratabound
discordant	tabular
irregular	unknown

Contacts

a, altered	d, diffuse	g, gradtional	p, planar	v, vein
b, broken	fg, fine grained	irr, irregular	s, sharp	w, wavy
def, deformed	*(i, intrusive)*	ob, obscure	un, unknown	

Figure 1.4 (continued) The graphic core logging method was modified after McPhie (1993) and Davies (2002). The open pit mapping method was modified after the "Anaconda method" (Einaudi, 1997).

of the Lienetz pit occurred throughout the 2007 and 2008 field seasons. Pit mapping data are provided digitally in Appendix B.

1.4.3 XRF analyses

Major and trace element compositions of seven lavas and intrusions (Appendix C; Table C.1) from the Luise volcano were analysed by X-ray fluorescence (XRF) at the University of Tasmania. The aim of this study was to assign geochemical nomenclature to supplement each of the coherent facies descriptions in Chapter 4 and 5, and a detailed lithogeochemical study was not attempted. Analyses have been interpreted with caution due to the absence of fresh samples, the proximity to the Ladolam ore deposit and the presence of hydrothermal alteration minerals.

Rocks were first crushed in a hydraulic crusher. Fragments were hand-picked to exclude chips with oxidised or weathered rinds, veins or amygdales, and were powdered in a tungsten carbide disc mill. Major element and trace element concentrations were determined on a Phillips automated XRF spectrometer at the University of Tasmania using standard analyses and have been recalculated to 100% anhydrous to remove variations caused by differing loss on ignition values. An expanded discussion on element mobility and compositions is provided in Appendix C.

1.4.4 Ar-Ar geochronology

^{40}Ar / ^{39}Ar geochronology was used to constrain the age and/or cooling history of coherent volcanic units in the Minifie and Lienetz ore zones. Only one unit in the study area contained the appropriate mineralogy for the study – a plagioclase-phyric andesite (L7) in the Lienetz ore zone. Amphibole selected for ^{40}Ar / ^{39}Ar analysis contains glassy melt inclusions and the sample does not contain secondary biotite, chalcopyrite or other alteration minerals that may reset the isochrons. Analyses were done at the Noble Gas Laboratory of the Pacific Centre for Isotopic and Geochemical Research (PCIGR) in the Department of Earth and Ocean Sciences at the University of British Columbia. An expanded discussion on the methods and results is provided in Appendix D.

1.5 Thesis organisation

In total, this thesis comprises six chapters. Chapters 3 to 6 address one or more of the principal aims of the project.

Chapter 1 introduces the field area, outlines the main aims of the research project and their significance. Relevant background information on breccias is provided, including terminology used in this thesis. The motivation behind the approach and methods is discussed, followed by a summary of the thesis layout.

Chapter 2 introduces the Ladolam gold deposit and reviews the tectonic setting, geology and alkalic affinity of the region and Lihir Island. The geothermal system, and alteration and mineralisation assemblages of the Ladolam gold deposit are also discussed.

Chapter 3 introduces three important aspects of the setting of the Ladolam gold deposit: the facies architecture of the Luise volcanic edifice, geomorphology of the Luise volcanic edifice and relationships to the fringing limestone unit. These data set the regional geological scene, and are followed by more detailed lithofacies analyses in Chapters 4 and 5.

Chapters 4 and 5 present detailed descriptions and interpretations of the lithofacies of the Minifie and Lienetz ore zones respectively. The lithofacies architecture forms the basis of the geological history. These chapters address the first and second aims of the thesis by characterising the various volcanic and hydrothermal breccias and evaluating the spatial and temporal relationships among different host lithofacies and gold ore.

Chapter 6 synthesises data from preceding chapters and reconstructs the geologic history of the host volcanic succession including the main hydrothermal and mineralising events, and comments on future research avenues and potential exploration implications.

1.6 Breccia terminology

The focus of this thesis is the surface and shallow subsurface epithermal environment, which is generally considered to be the upper 1 km of the Earth's crust (White and Hedenquist, 1990; Cooke and Simmons, 2000). In this environment a variety of volcanic, sedimentary, hydrothermal and hybrid processes produce breccias.

A discussion of terminology and criteria used for identifying various genetic classes are provided in this section. Lithofacies described in this thesis are not restricted to breccias. The multidisciplinary scope (e.g. volcanology and economic geology) and an inconsistent use of nomenclature across these fields, requires a discussion of how “breccia” and other potentially ambiguous terms have been used in this thesis.

1.6.1 Breccias in mineralised environments

Breccias in mineralised environments provide significant challenges for interpretation and classification. Particularly where the host rocks are volcanic (as they often are in the epithermal environment), there are many options for interpretation. Several generations of fragmentation, transportation and deposition can produce complex overprinting relationships (e.g. Wau, Papua New Guinea, Sillitoe et al., 1984; Cripple Creek, U.S.A., Thompson et al., 1985; El Teniente, Chile, Cannell et al., 2005; Rosia Montana, Romania, Wallier et al., 2006). Hydrothermal alteration further complicates overprinting relationships and may modify genuine clastic textures, as well as producing pseudo-breccias with apparent matrix (*cf.* McPhie et al., 1993).

Breccia-dominated areas in altered and mineralised terranes are often termed ‘breccia complexes’ (e.g. Kelian, Indonesia, Davies et al., 2008; Agua Rica Argentina, Landtwing et al., 2002; Rio Blanco, Chile, Warnaars et al., 1985; Fig. 1.5). The breccia-dominated host rocks of the Ladolam gold deposit have been termed a breccia complex by previous workers (e.g. Davies and Ballantyne, 1987; Moyle et al., 1990; Carman, 1994). Single breccia facies within a breccia complex may host or disrupt ore (e.g. the Braden breccia pipe disrupts ore at El Teniente, Chile, Cannell et al., 2005; tourmaline breccias host ore at Rio Blanco-Los Bronces, Chile, Warnaars et al., 1985; Vargas et al., 1999). It can be difficult to identify new mineralised zones due to the complex interplay of facies relationships, grade distributions and structural disruptions. Some breccia facies may behave as barriers to fluid flow (e.g., carbonaceous mud-matrix breccia at Kelian, Davies, 2002), whereas others may focus mineralising hydrothermal fluids (e.g. adularia-quartz-pyrite-cemented breccias at Kelian, Davies, 2002). The breccia composition (clast, matrix and cement) and any syn- or post-brecciation hydrothermal alteration may affect the physical properties of the breccia. Routine logging of breccias in drill core can also prove challenging, particularly with regard

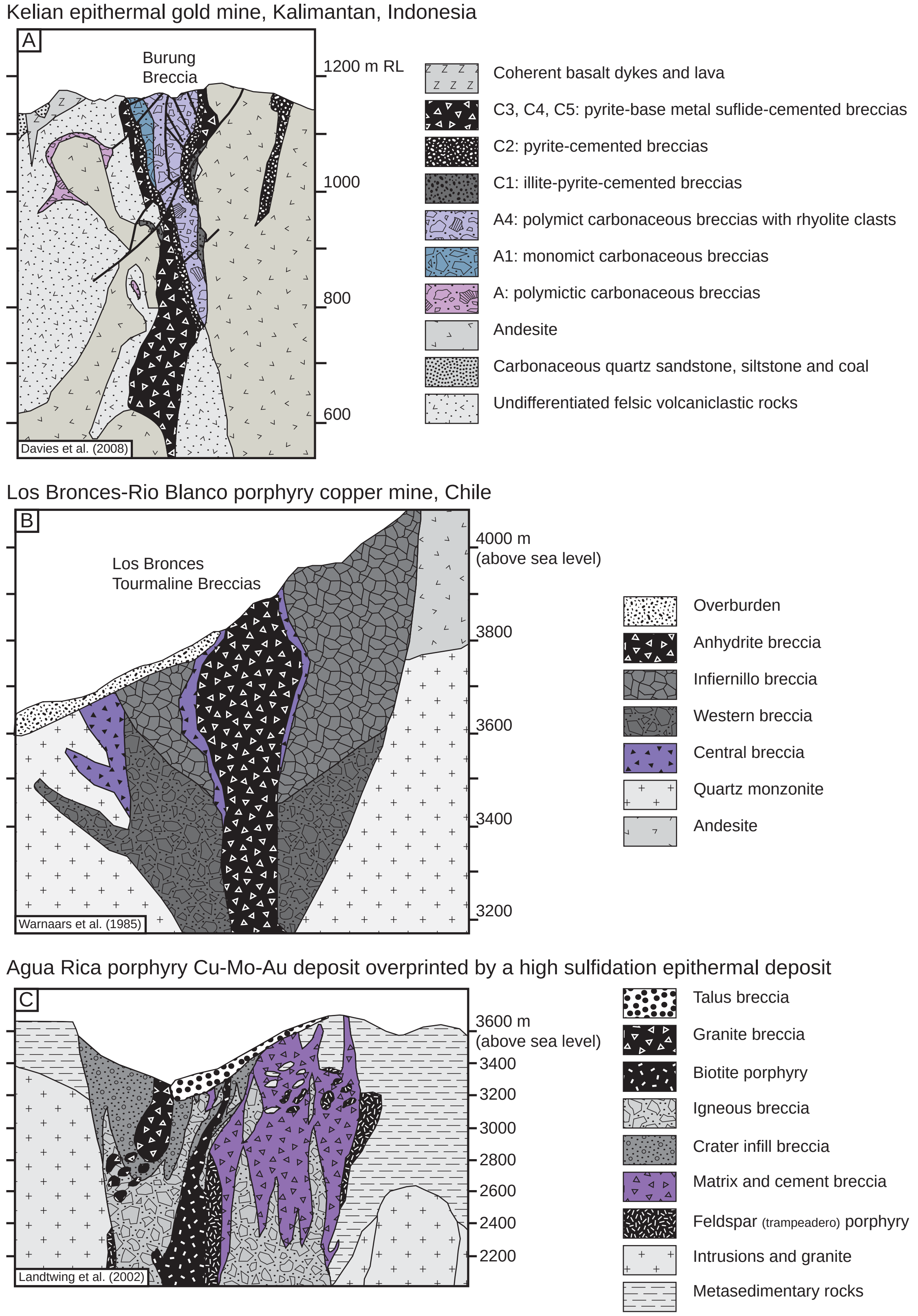


Figure 1.5 Examples of breccia complexes in mineralised and altered terranes. All three breccia complexes: (A) Kelian from Davies et al. (2008), (B) Los Bronces-Rio Blanco from Warnaars et al. (1985) and (C) Agua Rica from Landtwing et al. (2002), are characterised by predominantly near vertical breccias.

to recording sufficient data to enable an understanding of their controls on the distribution of mineralisation.

This study uses a descriptive logging scheme, adapted from McPhie et al., (1993), which focuses on the compositional and textural variations at a variety of scales in order to identify discrete breccia facies within a complex. Facies associations are then used to unravel the relationships between the host lithofacies, grade distribution and hydrothermal alteration.

1.6.2 Descriptive terminology

Breccia: A coarse-grained (>2 mm) clastic aggregate of angular rock fragments (after Wentworth, 1935; Krynine, 1948). Conglomerate is the equivalent of breccia, except that it is composed of round rock fragments. The components of breccia (and conglomerate) may include clasts, matrix, cement and open space.

Clast: A single grain or particle in a clastic aggregate (Krynine, 1948). In this study, clasts are defined as >2 mm diameter particles in a breccia or conglomerate.

Matrix: The grains or particles of a clastic aggregate that are smaller than, are in the presence of, and fill the interstices between the clasts (Krynine, 1948). In this study, matrix is defined as particles that are <2 mm diameter in a breccia or conglomerate.

Cement: Crystalline precipitate that infiltrates around clasts and/or matrix (after Krynine, 1948). Cement may precipitate from an aqueous fluid and may include ore and gangue minerals (Davies et al., 2008a). Cement precipitated from aqueous fluids is a diagnostic component of most hydrothermal breccias (Davies et al., 2008a).

1.6.3 Volcanic, sedimentary and hydrothermal breccias: genetic terminology and distinguishing criteria

The literature on classification of volcanic and sedimentary breccias is well established and voluminous (e.g. Cas and Wright, 1987; McPhie et al., 1993). The literature on hydrothermal breccias is not extensive or well established, in contrast to volcanic breccias. To simplify this review, only breccia facies that are relevant to the geological setting of Lihir Island are considered. The approach of this study has been to attempt to identify end-member facies whilst considering that overlaps in volcanic, sedimentary and hydrothermal processes may occur.

Volcanic breccias: Volcanic breccias, distinguished primarily by their clast components, internal organisation, and facies associations, are generated by both effusive and explosive eruptions and are deposited at or near the Earth's surface. Many pyroclastic facies are breccias and most autoclastic facies (autobreccia and hyaloclastite) are breccias. Autoclastic deposits are characteristically monomictic (McPhie et al., 1993). Monomictic clasts may be dense or vesicular, porphyritic or aphanitic and have slabby, ragged or blocky shapes (McPhie et al., 1993). Autoclastic breccias are often distinguished by their jigsaw-fit or clast-rotated internal organisation and association with coherent facies. Pyroclastic deposits are composed of crystals, pumice or scoria, less vesicular juvenile clasts and lithic fragments (McPhie et al., 1993). Pyroclasts are transported away from the vent or eruption column as a flow, fall or surge (Cas and Wright, 1987). Flow deposits are massive, poorly sorted and have valley-fill geometries (Branney and Kokelaar, 2002). Fall deposits are well sorted and bedded, and mantle topography (Carey, 1991). Surge deposits are poorly sorted with lenticular thin beds or laminations (Carey, 1991). Pyroclastic breccias are distinguished by not only components, but by their conformable bed morphologies and chaotic internal organisation. In this thesis, breccias that have volcanic components but whose facies association or geometries are ambiguous, are modified by the prefix "volcanogenic".

Sedimentary breccias: Sedimentary breccias form by processes such as weathering, erosion and mass wasting and are composed of particles of pre-existing rocks, crystals, and/or organics. Detrital sedimentary deposits are characterised by sedimentary structures that reflect the mechanisms that physically transport particles from the source area to the place of deposition. In volcanic terranes, important transport processes include grain flow, slide or slump, debris flows, debris avalanche, rock fall, and particulate traction, suspension and flotation transport in water or air (Cas and Wright, 1987; McPhie et al., 1993). Grain flow

HYDROTHERMAL BRECCIAS: Subsurface

Hydrothermal facies
- discordant geometry (highly variable)
- altered clasts common (alteration rinds on clasts = syn-breccia alteration)
- hydrothermal cement (e.g. quartz, adularia, biotite, tourmaline)
- mineralised clasts and clasts containing veins and / or fragments of veins
- clasts of cemented breccias

a) In-situ
- monomictic (non-juvenille clasts)
- angular to splintery clast shapes
- variably altered clasts (including syn-breccia alteration rinds on clasts)
- variable open space
- jigsaw-fit to clast-rotated organisation
- massive, poorly sorted
- may be associated with veins

e.g. hydraulic breccias

b) Polymictic (minor matrix)
- lithic (non-juvenille) clasts
- irregular, embayed margins on highly altered clasts (typically clay altered)
- tabular, angular, subround, blocky or ragged clast shapes
- “snow on roof” texture (cement preferentially on one side of clasts)
- variable open space
- jigsaw-fit to chaotic organisation
- massive, poorly sorted
- clasts may be aligned or imbricated
- highly variable geometry

e.g. chemical dissolution breccia, magmatic-hydrothermal breccia

c) Polymictic (abundant matrix)
- juvenile and non-juvenile clasts
- angular to round clast shapes
- juvenile clasts may be globular, blocky, ragged or splintery shaped
- tabular clasts
- accretionary lapilli may be present
- plant debris may be present
- variable open space
- chaotic to clast-rotated internal organisation
- massive, poorly sorted
- may be stratified or diffusely bedded
- variably geometry (locally pipe-like geometry that can exceed 2 km in depth and diameters up to 3 km)

e.g. magmatic-hydrothermal breccia

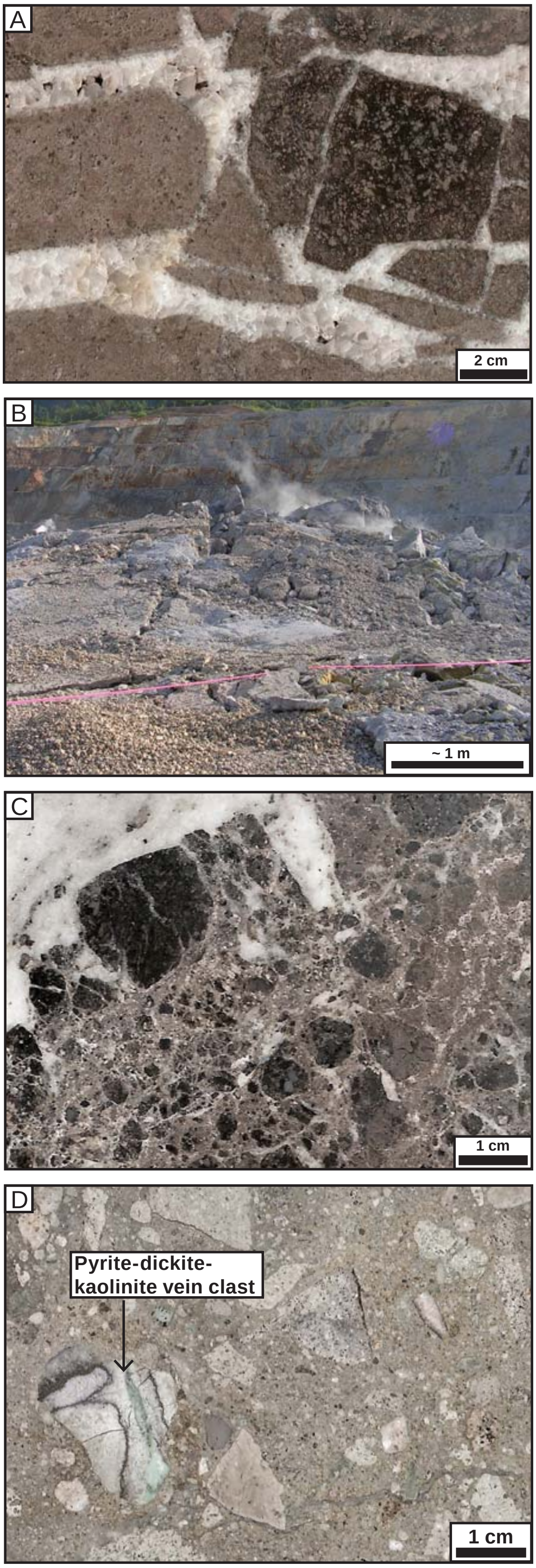


Figure 1.6 Characteristics of hydrothermal deposits. Deposit characteristics from Muffler (1971), Nairn et al. (1980), McPhie et al. (1993), Browne et al. (2001), Sillitoe (1985), Cooke et al. (1996), Cooke and Davies (2007), Cooke (2007), and Davies et al. (2008b). (A) Quartz-cemented hydraulic breccia from Ladolam, Lihir Island, PNG.
(B) Recent phreatic eruption crater in the Lienetz open pit, Ladolam gold deposit, Lihir Island, PNG. (C) Anhydrite-biotite-orthoclase-cemented magmatic-hydrothermal breccia from Ladolam, Lihir Island, PNG. (D) Polymictic, matrix-supported hydrothermal breccia from Ladolam, Lihir Island, PNG.

deposits are distinguished by reversely graded beds with steep primary dips. Slide or slump and debris avalanche deposits are characterised by a large blocks of intact stratigraphy within a massive, very poorly sorted breccia (Glicken, 1991). The presence of large blocks produces distinctive hummocky topography. Debris flow deposits are very poorly sorted and though typically non-graded, reverse graded beds do occur (Lowe, 1982). Turbidites are characterised by normally graded beds and commonly occur as thick sequences where normally graded beds are of uniform thickness (Lowe, 1982). Turbidity currents suspend sediment in water and thus deposits are indicative of a subaqueous environment, below wave base.

Hydrothermal breccias: Hydrothermal breccias are generated by the interaction of hydrothermal fluid with wall rock and/or magma, irrespective of the source of the hydrothermal fluid or nature of the wall rock (Burnham and Ohmoto, 1980). Diagnostic properties of hydrothermal deposits (although not always present) are discordant geometries, hydrothermal cement (e.g. quartz, adularia, and tourmaline) and wall rock clasts that have evidence of pre-existing hydrothermal conditions (altered or mineralised clast or clasts containing veins and fragments of veins; Sillitoe, 1985). The components and characteristics of in-situ jigsaw fit and polymictic hydrothermal deposits are summarised in Figure 1.6.

Hydrothermal processes that can fragment rock include hydraulic or fluid over-pressurisation (e.g. Jebrak, 1997), chemical dissolution (e.g. Wenrich, 1985), magmatic volatile exsolution during second boiling in the magmatic-hydrothermal environment (Burnham and Ohmoto, 1980; Burnham, 1985), steam expansion (e.g. Muffler et al., 1971; Nelson and Giles, 1985) and quench fragmentation resulting from the interaction of external hydrothermal fluid with magma (e.g. Lorenz and Kurszlaukis, 2007). Transportation processes include gravitational collapse and fluidisation or flow (McCallum, 1985; Sillitoe, 1985). Often, the main difference between in-situ and polymictic hydrothermal deposits is whether or not processes are repeated; i.e. multiple fragmentation and transportation events; a hydraulic breccia may end up polymictic and bedded and matrix-rich if the processes go on long enough.

Although surficial deposits do occur (e.g. phreatic eruption deposits), hydrothermal facies are best preserved in the subsurface where they have discordant pipe, dyke or vein geometries and cut basement rock lithologies. Distinctions between deeper and shallower subsurface depositional environments may be determined by the associated cement mineral assemblage (e.g. biotite versus halloysite) or from temperature and pressure conditions determined by fluid inclusion studies.

Complications that can arise in an active hydrothermal system in a geologically young volcanic centre include the overlap of volcanic and hydrothermal fragmentation processes and products. Careful documentation of breccia geometries and contact relationships are therefore critical for correct genetic interpretations (e.g. Sillitoe et al., 1984; Landtwing et al., 2002; Cannell et al., 2005). In the case of the Ladolam deposit, the shallow-level breccia-rich volcanic environment has complicated the recognition of hydrothermal facies that lack obvious cement and / or diagnostic clast components. The geometry of breccia facies is resolved in the following chapters by careful description of the components and textures.