

**GOLD-BEARING VOLCANIC BRECCIA
COMPLEXES RELATED TO
CARBONIFEROUS-PERMIAN MAGMATISM,
NORTH QUEENSLAND, AUSTRALIA.**

By

Stefan Mujdrlica

This dissertation is submitted as an integral part of the Exploration Geology Course for the degree of Master of Science at Rhodes University, Grahamstown, South Africa.

January, 1994

This research was prepared in accordance with specifications laid down by Rhodes University and was completed within a period of ten weeks full-time study.

Abstract

Gold-bearing volcanic breccia complexes are the major sources of gold in the Tasman Fold Belt System in north Queensland. The Tasman Fold Belt System represents the site of continental accretion as a series of island-arcs and intra-arc basins with accompanying thick sedimentation, volcanism, plutonism, tectonism and mineralisation. In north Queensland, the fold belt system comprises the Hodgkinson-Broken River Fold Belt, Thomson Fold Belt, New England Fold Belt and the Georgetown Inlier. The most numerous ore deposits are associated with calc-alkaline volcanics and granitoid intrusives of the transitional tectonic stage of the fold belt system.

The formation and subsequent gold mineralisation of volcanic breccia complexes are related to Permo-Carboniferous magmatism within the Thomson Fold Belt and Georgetown Inlier. The two most important producing areas are at Mount Leyshon and Kidston mines, which are high tonnage, low-grade gold deposits.

The Mount Leyshon breccia complex was emplaced along the contact between Cambro-Ordovician metasedimentary and metavolcanic rocks, and Ordovician-Devonian I-type granitoids of the Lolworth-Ravenswood Block. The Kidston breccia complex is located on a major lithological contact between the Early to Middle Proterozoic Einasleigh Metamorphics and the Silurian-Devonian Oak River Granodiorite.

The principal hosts to the gold mineralisation at the Mount Leyshon and Kidston deposits, are breccia pipes associated with several episodes of porphyry intrusives. The gold-bearing magmatic-hydrothermal and phreatomagmatic breccias post-date the development of a porphyry-type protore. The magmatic-hydrothermal breccias were initially emplaced without the involvement of meteoric-hydrothermal fluids, within a closed system. Later magma impulses reached higher levels in the cooled upper magma chamber, where meteoric water invaded the fracture system. This produced an explosive emplacement of phreatomagmatic breccias, as seen at Mount Leyshon. Widespread sericitisation and pyrite mineralisation are common, with cavity fill, disseminated and fracture/vein-controlled gold and base metal sulphides.

Abstract

The Kidston and Mount Leyshon breccia complexes have hydrothermal alteration and mineralisation characteristics of the 'Lowell-Guilbert Model'. However, the argillic zone is generally not well defined. The gold travelled as chloride complexes with the hydrothermal fluids before being deposited into cavities and fractures of the breccias. Later stage epithermal deposits formed at the top of the breccia complexes that were dominantly quartz-adularia-sericite-type. The erosion, collapse and further intrusion of later porphyry phases allowed the upper parts of the breccia complexes to mix with the lower hydrothermal systems.

Exploration for gold-related volcanic breccia complexes is directed at identifying hydrothermal alteration. This is followed by detailed ground studies including geological, mineralogical, petrological and geochemical work, with the idea of constructing a 'model' that can be tested with subsequent subsurface work (e.g. drilling).

Geomorphology, remote sensing, geochemistry, geophysics, petrology, isotopes and fluid inclusions are recommended exploration techniques for the search of gold-bearing volcanic breccia complexes. Spectral remote sensing has especially become an important tool for the detection of hydrothermal alteration. Clay and iron minerals of the altered rock, within the breccia complexes, have distinctive spectral characteristics that can be recognisable in multispectral images from the Landsat thematic mapper. The best combination of bands, when using TM remote sensing for hydrothermally altered rock, are 3/5/7 or 4/5/7. The breccia complexes have exploration signatures represented as topographic highs, emplaced within major structural weaknesses, associated I-type granitic batholiths, early potassic alteration with overprint of sericitic alteration, and an associated radiometric high and magnetic low.

The exploration for gold-bearing volcanic breccia complex deposits cannot be disregarded, because of the numerous occurrences that are now the major gold producers in north Queensland.

Contents

	Page
1.0 Introduction	1
2.0 The Tasman Fold Belt System in North Queensland	3
2.1 Regional Geology	3
2.1.1 Introduction	3
2.1.2 Thomson Fold Belt	5
2.1.3 Georgetown Inlier	7
2.1.4 Hodgkinson-Broken River Fold Belt	9
2.1.5 New England Fold Belt	12
2.2 Tectonic Setting	16
2.3 Metallogenic Classification of Deposits	20
3.0 The Thomson Fold Belt and Georgetown Inlier	27
3.1 Introduction	27
3.2 The Thomson Fold Belt	27
3.2.1 Anakie Inlier	27
3.2.2 Lolworth-Ravenswood Block	30
3.2.3 Burdekin Basin	32
3.2.4 Drummond Basin	34
3.2.5 Tectonic Environment	35
3.2.6 Economic Geology	37
3.3 Georgetown Inlier	39
3.3.1 General	39
3.3.2 Proterozoic Stratigraphy	40
3.3.3 Deformation	45
3.3.4 Metamorphism	46
3.3.5 Proterozoic Granitoids	48
3.3.6 Tectonic Environment	48
3.3.7 Economic Geology	51

4.0	Gold Related Volcanogenic Breccia Complexes	56
4.1	Introduction	56
4.2	Mount Leyshon Gold Mine	58
	4.2.1 Introduction	58
	4.2.2 Exploration and Production History	58
	4.2.3 Regional Geology	60
	4.2.4 The Mount Leyshon Breccia Complex	62
	4.2.5 Structural Framework	69
	4.2.6 Mineralisation	70
	4.2.7 Alteration	74
	4.2.8 Isotope and Fluid Inclusion Studies	75
	4.2.9 Ore Genesis	76
4.3	Kidston Gold Mine	76
	4.3.1 Introduction	76
	4.3.2 Exploration and Production History	77
	4.3.3 Regional Geology	79
	4.3.4 The Kidston Breccia Pipe	79
	4.3.5 Mineralisation and Alteration	83
	4.3.6 Isotope and Fluid Inclusion Studies	86
	4.3.7 Ore Genesis	91
4.4	Mount Wright Breccia Pipe	94
	4.4.1 Introduction	94
	4.4.2 Exploration and Production History	94
	4.4.3 The Mount Wright Breccia Pipe	95
	4.4.4 Ore Genesis	96
4.5	General Discussion	96
5.0	Exploration for Gold-Related Volcanic Breccia Complexes	100
5.1	Introduction	100
5.2	Model for Volcanic Breccia Complexes in North Queensland	100
	5.2.1 Volcanism and Tectonic Setting	100
	5.2.2 Classification of Volcanic Breccia Complexes	102
	5.2.3 Hydrothermal Chemistry of Gold	107
	5.2.4 Hydrothermal Alteration and Fluids	109

5.2.5	The Volcanic-Hosted Epithermal System	112
5.2.6	Model for Volcanic Breccia Complexes	115
5.3	Exploration in the Thomson Fold Belt and Georgetown Inlier	116
5.3.1	Geomorphology and Structure	116
5.3.2	Remote Sensing	117
5.3.3	Geophysics	119
5.3.4	Geochemistry	120
5.3.5	Isotopes and Fluid Inclusions	124
5.3.6	Petrology	126
6.0	Conclusions	128
	Acknowledgments	130
	References	131

List of Figures

	Page
Figure 2.1 : Major structural units of the Tasman Fold Belt System in Queensland (Murray, 1986).	4
Figure 2.2 : Simplified geological and structural map of the Hodgkinson-Broken River Orogen (or Fold Belt) (Day <i>et al.</i> , 1978).	11
Figure 2.3 : Simplified geological map of the New England Fold Belt (Day <i>et al.</i> , 1978).	13
Figure 2.4 : Simplified geological map of the northern part of the Tasman Fold Belt System in Queensland (Murray, 1990).	22
Figure 3.1 : Major structural elements of the eastern part of the Tasman Orogenic Zone (Day <i>et al.</i> , 1978).	28
Figure 3.2 : Simplified geological map of the Lolworth-Ravenswood Block (Murray and Kirkegaard, 1978).	31
Figure 3.3 : Simplified geological map of the Georgetown Inlier (Bain <i>et al.</i> , 1990).	39
Figure 3.4 : Proterozoic stratigraphic relationships in the Georgetown Inlier (Withnall <i>et al.</i> , 1988a).	40
Figure 3.5 : Summary of sedimentary features, Early to Middle Proterozoic rocks of the Georgetown Inlier (Withnall <i>et al.</i> , 1988a).	42
Figure 3.6 : Metamorphic map of the Georgetown Inlier (Withnall <i>et al.</i> , 1988a).	47
Figure 4.1 : Distribution of the major gold deposits with respect to structural-tectonic provinces of north-east Queensland. The provinces are : G = Georgetown, GR = Greenvale, CT = Charters Towers, H = Hodgkinson, BR = Broken River, DR = Drummond, CRIP = Coast Range Igneous Province (Morrison, 1988).	57

- Figure 4.2 :** Location and regional geological setting of the Mount Leyshon gold deposit. Note the concentration of gold occurrences in the north-east trending corridors, which also contain many of the Permo-Carboniferous subvolcanic complexes (Paull *et al.*, 1990). 61
- Figure 4.3 :** Detailed geological map of the breccia complex based on outcrop mapping at 1 : 2000 scale. The majority of the basement rhyolite and dolerite dykes have been omitted for clarity (Wormald, *et al.*, 1991). 63
- Figure 4.4 :** The evolution of the Mount Leyshon gold mine breccia complex (Hodkinson, 1990). 64
- Figure 4.5 :** Schematic cross-section. Note : (1) The steeply dipping, chaotic antler-like geometry of the Main Pipe breccia, (2) complex variation and gradation between the Main Pipe breccia sub-facies, (3) steeply dipping, inter-fingering porphyry contacts, (4) spatial relationship between Mount Hope breccia and porphyry phase III, (5) gross textural differences between Mount Leyshon and Mount Hope breccias compared to the Main Pipe breccia, (6) inter-fingering and intrusive nature of the tuffisite dykes, and (7) the largely in situ basement blocks (Wormald *et al.*, 1991). 66
- Figure 4.6 :** This specimen of Mount Leyshon breccia is composed mainly of fine grained metasediments which form the framework of the breccia. The fragment interstices are occupied by pyrite, smaller fragments and dark resin which has impregnated during polishing. The fragments are mostly angular, but significant rounding can be seen on many of the small, interstitial fragments. Cavity fill mineralisation is very dominant (Taylor, 1992). 73
- Figure 4.7 :** Regional geology of the Kidston breccia pipe showing the relationship to the Lochaber Ring Complex, north-west trending rhyolite dyke swarm and coincident gravity low, interpreted as reflecting an underlying batholith (Baker, 1988). 80
- Figure 4.8 :** Surface geology of the Kidston breccia pipe showing the distribution of breccia types and relation between intrusives and brecciation (Baker and Tullemans, 1990). 82
- Figure 4.9 :** Distribution of post-breccia early stage and late stage mineralisation and associated alteration (Baker and Tullemans, 1990). 85

- Figure 4.10 :** Cross section C-D-E through the breccia pipe showing the distribution and relation between mineralisation and the late stage alteration (refer to Figure 4.9). Note that the actual dips of the zonations in the centre of the section are steeper than suggested. The apparent shallowing results from the section being offset from the centre of the mineralised zone (Baker and Tullemans, 1990). 87
- Figure 4.11 :** Model for the formation of the Kidston breccia pipe.
A., Development of pre-main stage stockwork veins and tourmaline breccia associated with the build up of hydrothermal fluid during crystallisation of the underlying batholith. B., Formation of main stage 'outer zone' breccia, resulting from the collapse of the overlying rocks into the space produced during the escape of hydrothermal fluid. C., Emplacement of the main stage 'inner zone' breccia associated with the emplacement of post-breccia rhyolite. D., Formation of radial and concentric fractures filled by post-breccia rhyolite and sheeted veins respectively, associated with the emplacement of post-breccia rhyolite (Baker, 1988). 92
- Figure 5.1 :** Essential elements of an active back-arc-inter-arc-marginal basin and its associated arc-subduction complex (Karig, 1974). 102
- Figure 5.2 :** Grade-tonnage plot for some representative gold deposits (Sillitoe, 1991). Numbers : (1) Lepanto, (2) Santo Tomas II, (3) Dizon, (4) Ok Tedi, (5) Cuervo, (6) Marte, (7) Boddington, (8) Zortman-Landusky, (9) Salave, (10) Gilt Edge, (11) Kori Kollo, (12) Fortitude, (13) McCoy, (14) Nickel Plate, (15) Red Dome, (16) Thanksgiving, (17) Barney's Canyon, (18) Tai Parit, (19) Star Pointer, (20) Ketz River, (21) Cove, (22) Beal, (23) Quesnel River, (24) Equity Silver, (25) Mount Morgan, (26a) Porgera (Waruwari), (26b) Porgera (Zone VII), (27) Montana Tunnels, (28) Golden Sunlight, (29) Colosseum, (30) Ortiz, (31) Kidston, (32) Mount Leyshon, (33) Chadbourne, (34) Charters Towers, (35) Los Mantos de Punitaqui, (36) Masara. 103
- Figure 5.3 :** Stages A and B in the development of a magmatic-hydrothermal system in a porphyry system, with later input of meteoric water and associated alteration patterns. Drawing not to scale (McMillan and Panteleyev, 1980). 105

- Figure 5.4 :** ACF ($\text{Al}_2\text{O}_3\text{-CaO-FeO}$) AKF ($\text{Al}_2\text{O}_3\text{-Na}_2\text{O+K}_2\text{O-FeO}$) diagrams showing alteration types and related dominant mineral assemblages. **a.** Potassium silicate; **b.** propylitic; **c.** phyllic or sericitic; **d.** intermediate argillic; **e.** advanced argillic (Pirajno, 1992). 110
- Figure 5.5 :** Idealised representation of the main types and nature of geothermal fluids. Note that the upper sector is expanded with respect to the lower one. The types of geothermal fluids are: (1) chloride-rich fluids, (1') near-neutral chloride boiling spring; (2) acid-sulphate fluids, (2') acid-sulphate springs, fumaroles and mud pools; (3) CO_2 -rich fluids, (3') bicarbonate hot springs; (4) chloride-rich fluids, (4') dilute chloride warm springs. Chloride-rich fluids are usually associated with quartz-adularia-sericite systems and with siliceous sinters; acid-sulphate fluids are associated with varying degrees of acid leaching (argillic alteration); bicarbonate waters are commonly responsible for the precipitation of extensive deposits of carbonate material such as travertine. In this case the CO_2 may have been acquired from the surrounding lithologies. The magmatic fluids component is assumed, but the actual measure of its input is not known and is isotopically difficult to detect once the incursion of large quantities of meteoric waters has taken place (Pirajno, 1992). 114
- Figure 5.6 :** Spectral bands for TM and MSS systems. Reflectance curves for vegetation, unaltered rocks, and hydrothermally altered rocks (Sabins, 1983). 118
- Figure 5.7 :** Schematic representation of chemical and physical remobilisation of gold with increasing aridity (Lawrance, 1988). 123
- Figure 5.8 :** Schematic Y-Zr plot used for the determination of magmatic affinity (MacLean and Barrett, 1993). 123
- Figure 5.9 :** Classification of fluid inclusions observed at room temperature (Shepherd *et al.*, 1985). 125

List of Tables

	Page
Table 2.1 : Mineral deposits of the northern part of the Tasman Fold Belt System in Queensland (Murray, 1990).	23
Table 4.1 : The geological evolution of the Mount Leyshon breccia complex.	59
Table 4.2 : Observed sulphide and gangue phases from the primary zone, Mount Leyshon gold mine (Paull <i>et al.</i> , 1990).	71
Table 4.3 : The geological evolution of the Kidston breccia complex.	78
Table 4.4 : Summary of homogenisation and salinity data for primary inclusions. The inclusion types are listed in order of abundance (Baker and Andrew, 1988).	90
Table 5.1 : Characteristics of selected breccia-hosted gold deposits (Sillitoe, 1991).	104
Table 5.2 : Thematic-mapper spectral bands (Sabins, 1987).	119
Table 5.3 : Geochemical exploration for gold: summary of different sampling media and intervals, size fractions retained for analysis, Au geochemical responses obtained, and significant pathfinder elements, in relation to various climatic and morphological environments (Zeegers and Leduc, 1991).	121

intruded into, and/or extruded onto, host rocks from a deep-seated magma source. The most common features of these deposits, are the relationship with a porphyry-type episode of intrusion and mineralisation, and their localised formation within the Thomson Fold Belt and Georgetown Inlier.

Chapter 2 describes the regional geological setting and mineralisation of the Tasman Fold Belt System in north Queensland. The regional tectonic environment and associated mineral deposits, are important in order to understand the relationship of the Thomson Fold Belt and Georgetown Inlier, with the surrounding Tasman Fold Belt System.

The Thomson Fold Belt and Georgetown Inlier are the host areas for gold-related volcanic breccia complexes. Chapter 3 describes the geology of the Thomson Fold Belt and Georgetown Inlier. The rocks in these areas contributed to the mineralising fluids within each volcanic breccia complex. Therefore, their geology and associated mineral deposits are important events in the eventual formation of these breccia complexes, especially when most other deposits in the Thomson Fold Belt and Georgetown Inlier are earlier than Permian-Carboniferous mineralisation.

Chapter 4 has detailed descriptions of the Mount Leyshon, Kidston and Mount Wright deposits. The study of these individual deposits contributes to the understanding of the tectonic and metallogenic framework of the Thomson Fold Belt and Georgetown Inlier. It is the final stage in determining an exploration model for gold-related volcanic breccia complexes.

The development of an exploration ore genesis model, importance of hydrothermal fluids and related alteration, and the exploration techniques of gold-related volcanic breccia complexes in the Thomson Fold Belt and Georgetown Inlier, are compiled into Chapter 5.

The goal of this dissertation is to provide an exploration ore genesis model and to discuss the type of exploration techniques that can be used to search for gold-bearing volcanic breccia complexes in north Queensland. This can only be achieved by understanding the tectonic, regional, and local geological settings for these type of deposits.

1.0 Introduction

In the southern portions of Pangea (e.g. Gondwana), orogenic events that had started in the Late Proterozoic continued into the Early Phanerozoic. An active continental margin was present from the western side of the South American craton, around the southwestern part of Africa, the southern margin of East Antarctica, and eastern Australia. In eastern Australia, the Tasman Fold Belt System is a major orogenic province at the eastern end of a global system of orogens along the western and southern continental margin of Gondwana, portions of which are still active today. The northern extent of the fold belt system comprises, from north to south, the Hodgkinson-Broken River Fold Belt, the Georgetown Inlier, the Thomson Fold Belt, and the New England Fold Belt. The complex history of each of these areas can be divided into three basic tectonic regimes that represent stages of progressive cratonisation:

1. a pre-cratonic (or orogenic) regime characterised by a Pacific-type mobile zone composed of volcanic arcs, rifts and marginal, inter-arc, and back-arc basins;
2. a transitional (or mountain building) regime associated with the emplacement of late- to post-orogenic volcanic and plutonic rocks. This phase is generally separated in time from the pre-cratonic regime by a major orogeny; and
3. a cratonic (or continental platform) regime.

The Tasman Fold Belt is very important from the metallogenic point of view, because of the numerous and various contained mineral deposits, most of which are of hydrothermal origin. Second only to the Archean Yilgarn craton, the Tasman orogens are Australia's richest gold province. In Queensland, important recent discoveries or re-evaluations of low- and high-grade porphyry-epithermal-type gold mineralisation have been made. Some of these include the gold deposits of Kidston, Mount Leyshon, Mount Wright, and Pajingo. The eastern Australian mineral deposits are linked to a complex interplay of subduction-related environments, and generation of crustal melts in collision and rift-related settings.

The Mount Leyshon, Kidston and Mount Wright deposits in north Queensland represent gold-related volcanic breccia complexes of Permian-Carboniferous age. The term 'volcanic breccia complex' is referred to as a sequence of volcanic events that have

2.0 The Tasman Fold Belt System in North Queensland

2.1 Regional Geology

2.1.1 Introduction

The Tasman Fold Belt System (or Tasman Orogenic Zone) represents the site of continental accretion as a series of island-arcs and intra-arc basins with accompanying thick sedimentation, volcanism, plutonism, tectonism and mineralisation (Lacy, 1980). In north Queensland the fold belt system comprises the Hodgkinson-Broken River Fold Belt in the north, the Thomson Fold Belt in the west, and the New England Fold Belt in the east (Figure 2.1). Boundaries between these three segments are concealed by younger strata and granite intrusives. Only along the western margin of the Hodgkinson-Broken River Fold Belt is the contact with the Precambrian Georgetown Inlier craton exposed. The contact to the southwest can be interpreted to be beneath sedimentary cover from the existence of very prominent linear gravity and aeromagnetic gradients, broadly coincident with the Diamantina River Lineament (Murray, 1990).

In general, the age of orogenesis becomes younger to the east, possibly reflecting successive stages of accretion to the Australian continent. The three fold belts appear to have had differing tectonic histories until the end of Middle Devonian time. It is only in the Upper Devonian and younger rocks, that connecting links can be recognised between them. These different tectonic boundaries in some cases gave rise to different crustal structures.

The Tasman Fold Belt System was an active orogenic region from Cambrian to Cretaceous time. Cambrian shelves extending across northeastern Queensland underwent thermal and volcanic disturbances which culminated in Lower Ordovician volcanicity and infrastructure mobilisation associated with extensive mid-Ordovician plutonism. Gneissic zones developed under these mobile conditions and thermal disturbances contracted, and activity focused on west-northwesterly zones intruded by mantle derived hydrous tholeiitic magmas. By Silurian times deep-seated sources of heat and magma were exhausted, leaving a metastable crust. Gross instabilities were eliminated by Upper Silurian to Lower Devonian post-orogenic plutonism, followed by subsidence on extensive low-angle faults.

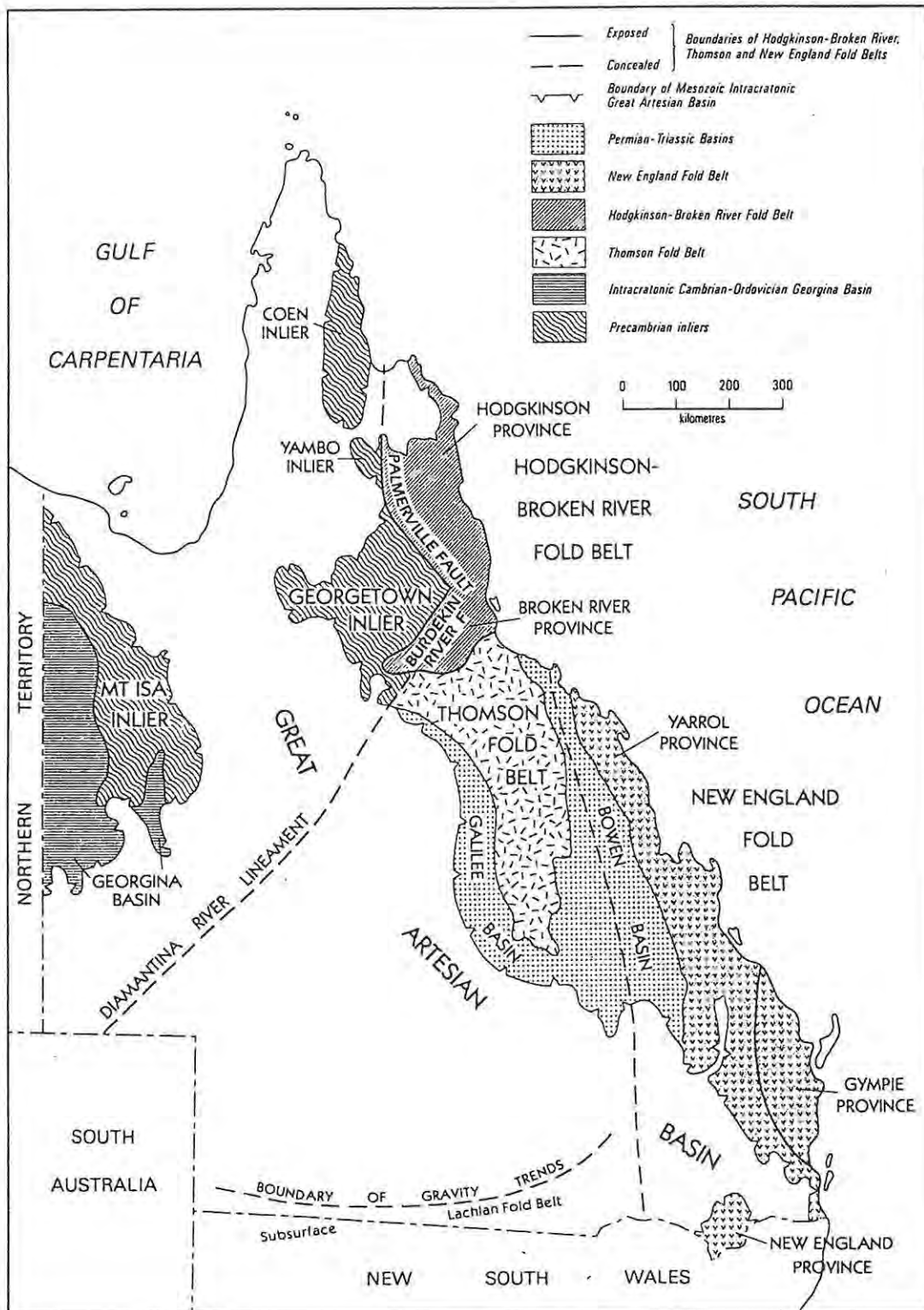


Figure 2.1 : Major structural units of the Tasman Fold Belt System in Queensland (Murray, 1986).

2.0 The Tasman Fold Belt System in North Queensland

Roots of subsiding, recrystallising mafic zones are likely to have been the source of high temperature (garnet and pyrophyllite) vein minerals, followed by large quantities of auriferous quartz.

Episodes of failure accompanied igneous cycles in Upper Devonian and Carboniferous times. Each cycle commenced with andesite issuing from depressed relict early Palaeozoic zones. Metalliferous solutions released late in the andesitic phase of each cycle, produced widespread hydrothermal effects in the volcano-sedimentary sequences. Extensive explosive silicic volcanicity accompanied ensuing phases of folding and faulting. Stanniferous granites were emplaced in tensional structures which assumed importance late in each cycle.

The following sections describe the belts and blocks associated with the Tasman Fold Belt System in north Queensland.

2.1.2 Thomson Fold Belt

The name Thomson Fold Belt (or Orogen) was introduced by Kirkegaard (1974) to refer to the early and middle Palaeozoic rocks of the northwestern part of the Tasman Fold Belt System. It was a tectonically active area with several episodes of deposition, deformation and plutonism from Cambrian to Carboniferous time.

Only the northeastern part of the fold belt is exposed, the remainder is covered by gently folded Permian and Mesozoic sediments of the Galilee, Cooper and Great Artesian Basins.

The boundaries of the Thomson Fold Belt with other tectonic units are concealed, but discordant trends suggest that they are abrupt. To the west, the fold belt is bordered by Proterozoic structural blocks which form basement west of the northeast-trending Diamantina River Lineament. The most appropriate boundary with the Lachlan and Kanmantoo Orogens to the south is an arcuate line marking a distinct change in the direction of gravity trends. The north-northwest orientation of the northern part of the New England Fold Belt to the east, cuts strongly across the dominant northeast trend of the Thomson Fold Belt.

Early Palaeozoic rocks considered to belong to the fold belt stage, crop out as two structural blocks in the northeast, the Lolworth-Ravenswood Block and the Anakie Inlier.

These form a basement beneath the Drummond and Galilee Basins. Two Devonian to Carboniferous transitional basins are exposed in the northeast; the Burdekin Basin lies within the Lolworth-Ravenswood Block, and the Drummond Basin surrounds the Anakie Inlier.

The geology of the Lolworth-Ravenswood Block differs markedly from that of the Broken River Province. Although its overall trend is not the same as that of the remainder of the Thomson Fold Belt, the Lolworth-Ravenswood Block is best regarded as part of the fold belt because of its similar early Palaeozoic tectonic history. The northern limit of the Thomson Fold Belt is the Clarke River Fault (White, 1965), along the northern margin of the Lolworth-Ravenswood Block. The boundary between the Lolworth-Ravenswood Block and the southern end of the Precambrian Georgetown Inlier is concealed by thin Cainozoic volcanics, but probably trends southwest in line with a major fault to the north. No definite Precambrian rocks have been identified to the east of this line, although blocks of amphibolite-grade metamorphics in the northern and western parts of the Lolworth-Ravenswood Block have been tentatively mapped as Precambrian because of their metamorphic grade (Wyatt *et al.*, 1970) and structural complexity.

The north-northwest trend of the northern part of the New England Fold Belt is strongly discordant to that of the Thomson Fold Belt, but the contact between the two fold belts is concealed by the Permo-Triassic Bowen Basin. This basin can be divided into contrasting eastern and western areas showing different tectonic styles. The eastern part was a tectonically active area throughout the Permian and Triassic, as evidenced by a thick sequence of folded sediments and volcanics. These appear to have developed within the framework of the New England Fold Belt. By contrast, strata in the western part of the basin are gently folded shallow-marine and fluviatile clastics and minor volcanics which were deposited on a relatively stable platform, assumed to be the Thomson Fold Belt craton. However, there is no clearly defined structural feature marking the eastern limit of cratonic basement (Murray and Kirkegaard, 1978).

The Thomson Fold Belt developed as a tectonic entity in the Late Proterozoic or Early Cambrian time, when the former northern extension of the Adelaide Fold Belt (or Adelaide Geosyncline) was truncated along the Muloorinna Ridge. Early Palaeozoic deposition was dominated by fine-grained, quartz-rich clastic sediments. Cambrian carbonates accumulated in the southwest and a Cambro-Ordovician island-arc was active in the north. Along the western margin of the fold belt, sediments were probably laid

down on downfaulted blocks of deformed Proterozoic rocks, with oceanic crust further to the east.

A mid- to Late Ordovician orogeny, which affected the whole of the Thomson Fold Belt, marked the climax of its pre-cratonic (orogenic) stage. The northeast structural trend of the fold belt (parallel to its western boundary with the Precambrian craton) was imposed at this time, and has controlled the orientation of later folding and faulting. Up to three generations of folding have been recognised. Metamorphism was to the greenschist and amphibolite facies, the highest grade rocks being associated with syn-orogenic granodiorite batholiths in the north. Following deposition of Late Ordovician marine sediments at the eastern margin, emplacement of post-tectonic Late Silurian or Early Devonian batholiths ended the pre-cratonic history of the Thomson Fold Belt.

The Subsequent transitional tectonic regime was characterised by deposition of Devonian to Early Carboniferous shallow marine and continental sediments, including widespread red-beds, and andesitic volcanics. The maximum marine transgression occurred in the early Middle Devonian. Localised folding affected the easternmost part of the Thomson Fold Belt at the end of Middle Devonian time, and was followed by intrusion of Devonian-Carboniferous granitic plutons. However, the terminal orogeny which deformed all Devonian to Early Carboniferous rocks of the fold belt was of mid-Carboniferous age. It produced northeast-trending open folds and normal and high-angle reverse faults which are considered to reflect basement structures. The cratonisation of the Thomson Fold Belt was completed with the emplacement of Late Carboniferous granites and the eruption of comagmatic volcanics in the northeast, Permian and Mesozoic sediments accumulated in broad, relatively shallow downwarps which covered most of the former fold belt (Murray and Kirkegaard, 1978).

2.1.3 Georgetown Inlier

The Georgetown Inlier is approximately 25000 km² in area. It is the largest and best studied of the several Precambrian Inliers of northeastern Queensland (Figure 2.1). The inliers are probably all part of one province, termed the Georgetown-Coen Province by Henderson (1980). The Georgetown Inlier has been divided from west to east into the Croydon, Forsayth and Greenvale Subprovinces (Withnall *et al.*, 1980). The Georgetown inlier consists largely of variably metamorphosed and deformed sedimentary and volcanic rocks of Early to Middle Proterozoic age, intruded by Proterozoic to late Palaeozoic

granitoids. The Proterozoic sequence in the central part of the inlier (Forsayth Subprovince) is divided into two groups, the Etheridge Group and Langlovale Group. The Croydon Subprovince in the west contains the Croydon Volcanic Group and Inorunie Group. Late Palaeozoic felsic volcanic rocks overlie the inlier which is surrounded to the north, west, and south by Mesozoic and Cainozoic, largely fluviatile, sedimentary rocks of the Carpentaria and Eromanga Basins, and in the east by Pliocene to Holocene flood basalt. The eastern quarter of the inlier (Greenvale Subprovince) contains some Proterozoic rocks, but most of the rocks there, although previously regarded as Precambrian, are now thought to be early Palaeozoic, allochthonous sheets thrust under Proterozoic rocks from the east. The following regional geology of the Georgetown Inlier will be based around the Forsayth and Greenvale Subprovinces.

The Precambrian rocks of the Georgetown Inlier consists of the Etheridge Group (lower metamorphosed dolomitic psammitic rocks and upper siltstones and mudstones) the Langlovale Group (predominantly micaceous feldspathic sandstone), the Croydon Volcanic Group (subaerial rhyolitic to dacitic ignimbrite) and the Inorunie Group (sandstone, siltstone and mudstone).

Although the Etheridge Group locally shows evidence of rapid deposition, individual formations are relatively uniform in thickness, and members within them can be traced for more than 100 km, indicating relatively uniform subsidence over the entire outcrop area. The shallow water environment of deposition of the Etheridge Group indicates that it was deposited on continental crust. However, this continental crust is not exposed and its age is unknown (Bain *et al.*, 1990). Withnall (1985) suggests that the mafic rocks in the Etheridge Group may have resulted from convective mantle upwelling during crustal extension and the formation of a shallow epicontinental sea. The Etheridge Group was affected by regional metamorphism during D₁ and D₂, at grades ranging from lower greenschist facies (chlorite zone) in the southwest to granulite facies in the northeast.

The oldest granitic rocks are small trondhjemite bodies dated about 1550 million years. Most of the Proterozoic granitoids are S-type and intrude into amphibolite facies rocks.

Cambrian and Ordovician rocks, and associated mineralisation of the Mount Windsor Igneous Province, have overprinted the southeastern part of the Georgetown Inlier. They are generally difficult to distinguish with confidence from the Precambrian rocks and

mineral deposits because of the degree of metamorphism, their structural complexity and the general paucity of isotopic age determinations.

Siluro-Devonian I-type plutons and batholiths in the Georgetown Inlier, including the Charters Towers Province, constitute the Cape York Plutonic Belt which is 100 to 150 km wide and 1000 km long. The plutonic belt is especially well defined in the Georgetown region. The most common rock type is biotite (\pm hornblende) granodiorite. Plutons are generally large and composite, but not zoned. They are locally foliated or sheared, and strongly discordant. Most intrude high grade metamorphics, and lack obvious contact aureoles (Bain *et al.*, 1990).

Carboniferous igneous bodies exposed in the Georgetown district and concealed beneath the Carpentaria Basin to the northwest define wide and rather irregular north trending belts. These belts are interpreted to reflect axes of fracture systems developed under the influence of east-west directed extensional stresses. A maximum repeat distance of 45 ± 5 km between major belts may reflect Carboniferous crustal thickness (Vogt, 1974). East to southeast-trending structures within the belts appear analogous in part to the accommodation zones and transfer faults of extensional rifts and basins (Bosworth, 1985). Lateral continuity of some of these structures with apparently older faults and fractures in basement rocks suggests a degree of control by these earlier structures. Some of the east-southeast trending structures both within and outside late Palaeozoic belts coincide with diffuse mineralised lines identified by Bain and Withnall (1980). Separation distances between these 'lines' are irregular, from about 25 to 60 km.

The Early Permian igneous rocks are more widely distributed than their Carboniferous counterparts. The extrusive sequences are characteristically thinner, much less extensive, and more heterogeneous than the Carboniferous sequences. Early Permian intermediate and basic rocks are relatively more voluminous (Bain *et al.*, 1990).

2.1.4 Hodgkinson-Broken River Fold Belt

The Hodgkinson-Broken River Fold Belt appears to represent a mobile belt whose development commenced after the Middle Ordovician orogeny in the Thomson Fold Belt. It is characterised by a north to north-northwest trend and transects the northeast trend of the Thomson Fold Belt.

In the Hodgkinson-Broken River Fold Belt, Ordovician to Early Carboniferous sequences of volcanoclastic flysch with subordinate shelf facies were deposited. This sedimentation occurred immediately east of, and partly on, Precambrian crust. Major fault zones formed a hinge line between the Precambrian craton to the west and the subsiding depositional area to the east and southeast. Seismic evidence from the Hodgkinson Province suggests that the Precambrian basement may underlie parts of the province as far as the present coastline (Pelham, 1983).

The Broken River Province can be divided into two distinct subprovinces, with different histories of sedimentation and deformation. These are the Graveyard Creek Subprovince to the west and the Camel Creek Subprovince to the east, which are separated by a major fault zone (Figure 2.2). The earliest rocks within the province are quartzose flysch and spilite of probable Ordovician age, best known from the Graveyard Creek Subprovince but possibly also occurring to the east. These sediments appear to overlie deformed ultramafic complexes of Proterozoic age and show recumbent folding and slaty cleavage.

Ordovician rocks are known from the Broken River Province in the area south of Greenvale. A thin belt of andesitic volcanics, volcanoclastic sediments and limestone lenses of Middle to Late Ordovician age, has been interpreted as a volcanic arc behind which an extensional back-arc basin developed near the edge of the Precambrian craton. In this back-arc basin, Ordovician quartzose turbidites overlie a Proterozoic ophiolite complex. The quartz rich flysch was folded and melange or broken formation developed before erosion prior to the late Early Silurian.

The Barnard Metamorphics in the extreme east of the Hodgkinson Province are early Palaeozoic or older. Conodonts of Late Ordovician age have been recovered from quartzose turbidites of the Mulgrave Formation along the western margin of the province, suggesting a similar history to that of the Broken River Province (Murray, 1990).

Two main tectonic models have been proposed for the Hodgkinson-Broken River Fold Belt. Arnold and Fawckner (1980) and Henderson (1987) proposed that the fold belt represents an arc-trench gap assemblage associated with an Andean-type continental margin volcanic arc on the Precambrian craton to the west. They interpreted the southwestern part of the Broken River Province as a fore-arc basin, and the remainder of the fold belt as an accretionary prism formed above a west dipping subduction zone.

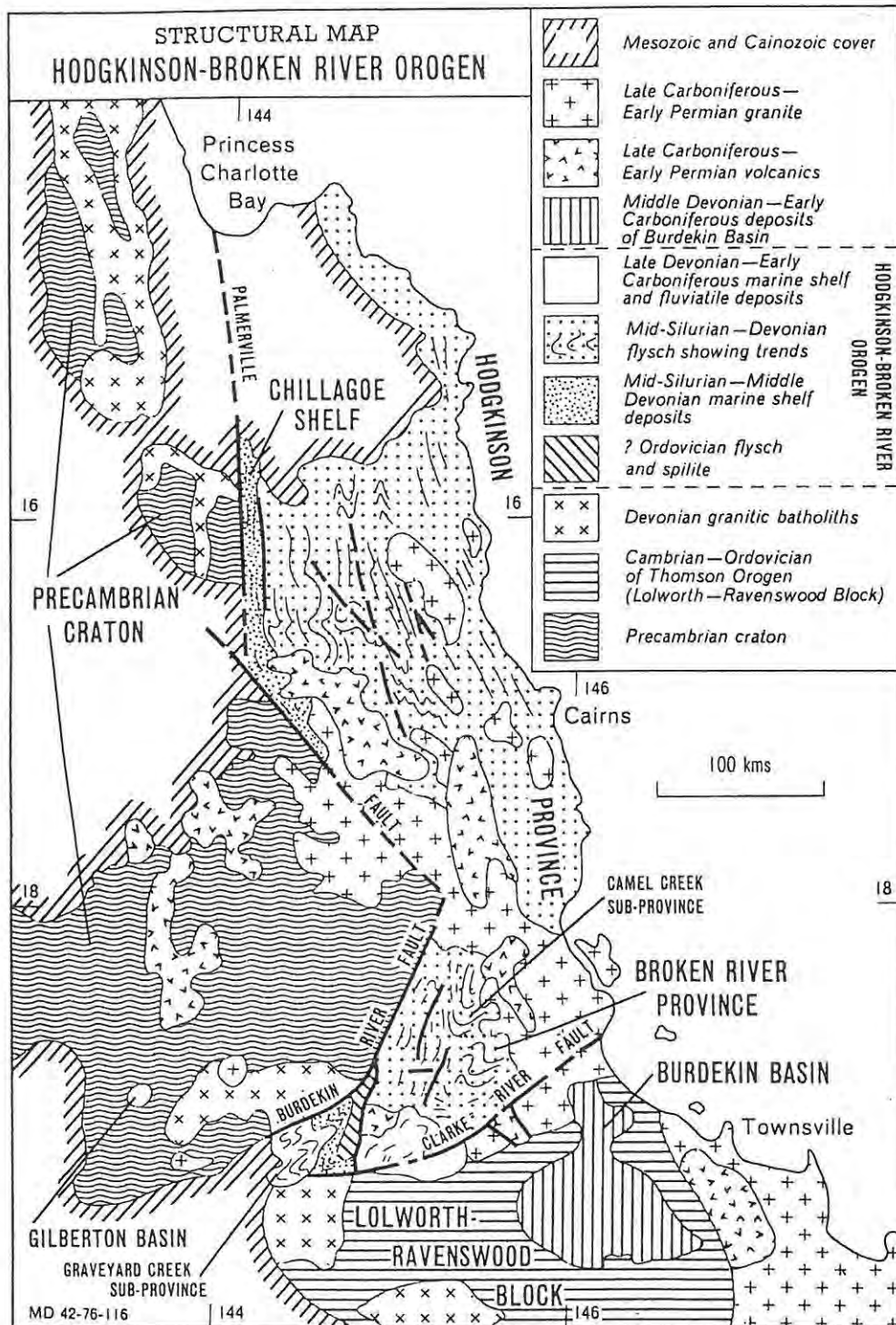


Figure 2.2 : Simplified geological and structural map of the Hodgkinson-Broken River Orogen (or Fold Belt) (Day *et al.*, 1978).

The belt of Silurian-Devonian granitoids extending from the Coen Inlier to Charters Towers was assumed to be the unroofed remnants of the magmatic arc. The main problem with this model is the lack of volcanic detritus, particularly in the Hodgkinson Province.

An alternative tectonic model, put forward by Arnold and Fawcner (1980) and favoured by most workers (Withnall *et al.*, 1988b), envisaged the Hodgkinson-Broken River Fold Belt as a marginal basin formed by rifting and crustal extension of the Precambrian craton, behind a continental margin magmatic arc. The typical imbricate structure developed by compression in the Devonian, which formed a west dipping thrust duplex as the Coen and Georgetown Inliers, were thrust over the Palaeozoic rocks (Murray, 1990).

All of north Queensland, outside the New England Fold Belt, was the site of post-orogenic acid volcanism and plutonism, with block faulting in the Late Carboniferous and Early Permian. The volcanics are mainly ash flow tuffs and lavas preserved in large cauldron subsidence depressions and ring complexes; comagmatic plutonic rocks consist dominantly of adamellite with subordinate granite and granodiorite (Day *et al.*, 1978).

2.1.5 New England Fold Belt

The New England Fold Belt forms the easternmost, youngest part of the Tasman Fold Belt System. For much of late Palaeozoic time, it was a convergent plate margin at the edge of the Australian continent (Murray *et al.*, 1987). It can be conveniently divided into three parts or provinces, the Yarrol Province in the north, the New England Province in the south, and the Gympie Province in the east (Figure 2.3). The Yarrol and New England Provinces are separated by Mesozoic platform cover of the Great Artesian and Moreton-Clarence Basins, which makes direct correlation of their structures and tectonic elements difficult. However, they had similar geological histories from Late Silurian to Triassic time, and both may be divided into contrasting western (volcanic-arc and unstable marine-shelf deposits) and eastern zones (submarine basic volcanics, pelagic sediments and thick flysch sequences) which are separated by major ultramafic belts. The Gympie Province lies to the east of the Yarrol Province, and unlike the eastern zones of the Yarrol and New England Provinces, comprises Permian and Early Triassic shallow marine and fluvial sediments (including the only marine Triassic rocks known from eastern Australia) and basic to intermediate volcanics. A discontinuous serpentinite belt separates the Gympie Province from the Yarrol Province (Day *et al.*, 1978).

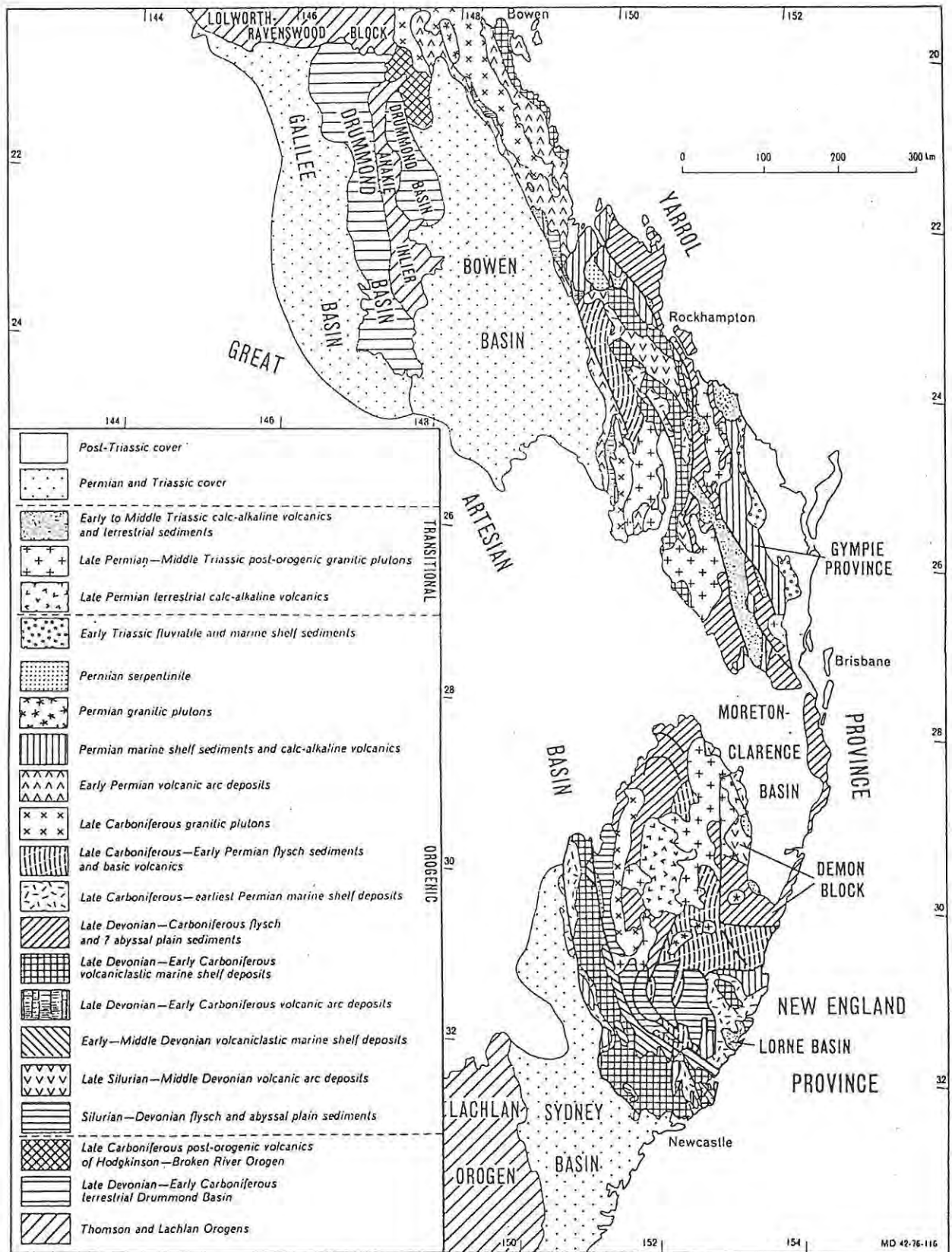


Figure 2.3 : Simplified geological map of the New England Fold Belt (Day *et al.*, 1978).

The New England Fold Belt is a very extensive system extending from north Queensland to northern New South Wales. This section will be based on the northern section of the New England Fold Belt, the Yarrol Province. The other provinces of the fold belt are not relevant to this dissertation.

The western margin of the Yarrol Province is marked by a linear Bouger anomaly, a north-northwest-trending positive ridge which corresponds to the Connors and Auburn Arches.

The eastern section is in approximate isostatic equilibrium except for a strong north-trending positive anomaly west of Rockhampton. The northern part of this anomaly coincides with large outcrops of ultramafic rocks; the southern part reflects the presence of several gabbroic plutons.

Widespread deposition in the New England Fold Belt commenced in Late Silurian time. In the Yarrol Province, Late Silurian to Middle Devonian calc-alkaline volcanics, volcanoclastic sediments and limestones are preserved in isolated fault blocks (Marsden, 1972). Volcanics range from basalt to rhyolite; andesitic flows and pyroclastics are probably dominant, with widespread dacitic and rhyolitic pyroclastics and local tholeiitic basalt flows. Associated sediments are medium and fine-grained clastics of volcanic provenance, coralline limestone, and minor radiolarian chert and conglomerate (Whitaker *et al.*, 1974). The rock types are typical of island-arc environments, with both submarine and subaerial deposits, and it is postulated that an island-arc (Calliope Island Arc) extended from north of Rockhampton to southwest of Brisbane in Late Silurian to Middle Devonian time. The arc developed either on oceanic crust or on unexposed early Palaeozoic basement, and may have been separated from the Australian continent by a marginal sea (Marsden, 1972). Shallow marine deposition continued as far west as the Anakie Inlier and an Early and Middle Devonian shoreline extended southwesterly across the Adavale Basin, the western half of which was terrestrial.

In the Late Devonian and Early Carboniferous, calc-alkaline volcanic arcs appear to have occupied the entire western margin of the New England Fold Belt. All evidence suggests that these volcanic arcs were of Andean-type. In the Yarrol Province, thick terrestrial volcanics formed the Connors-Auburn Volcanic Arc. Massive andesite flows are the main rock type in the northern part of the arc between Bowen and Rockhampton, with subordinate dacitic and rhyolitic lavas and pyroclastics, and locally abundant basalt flows (Malone *et al.*, 1969).

Changes to the Late Devonian to Early Carboniferous tectonic pattern began in mid-Carboniferous time, particularly in the Yarrol Province. These changes may be related to the tectonic events which deformed the Drummond Basin and the Hodgkinson-Broken River Fold Belt at the end of the Early Carboniferous. However, no significant deformation occurred in the New England Fold Belt in mid-Carboniferous time.

Volcanism waned in the Connors-Auburn Volcanic Arc at the end of the Early Carboniferous, which suggests that the pattern of subduction changed as a result of changes in relative plate motions. Granite batholiths were intruded in the Late Carboniferous and their emplacement may have coincided with uplift which restricted mid- and Late Carboniferous sedimentation on the Yarrol Shelf (Day *et al.*, 1978).

The sea retreated from the Yarrol Shelf at the end of the Early Carboniferous. There is no record of Late Carboniferous sedimentation from the northern part of the Yarrol Shelf, between Bowen and Rockhampton, but Late Carboniferous deposition took place further to the south. These deposits contain moderate amounts of acid to intermediate volcanic detritus, clasts derived from granitic rocks, and more quartz than the Late Devonian to Early Carboniferous sediments, and lack oolites (Kirkegaard *et al.*, 1970). There is little evidence of contemporary volcanism.

Major changes occurred in the Yarrol Province in the Early Permian. A calc-alkaline volcanic chain (Camboon Volcanic Arc) developed largely on the site of the earlier Connors-Auburn Volcanic Arc. The Early Permian arc was relatively short-lived but of major proportions. A thick sequence of dominantly andesitic volcanics is exposed along the western side of the Connors Arch and forms the basal sequence of the Bowen Basin. Rock types range from basalt to rhyolite, with only minor interbedded sediments. The various lithologies are evenly distributed throughout the succession except in the Bowen area, where basalt is overlain by andesite and minor acid volcanics (Paine *et al.*, 1974). East of the Connors Arch is a dominantly freshwater sequence of volcanics and volcanoclastic sediments. Acid volcanics are dominant with widespread andesitic lavas and pyroclastics and rare basalt (Paine *et al.*, 1974).

Calc-alkaline volcanism and shallow-marine sedimentation were widespread over much of the Yarrol Shelf and possibly parts of the deformed and uplifted Wandilla Slope and Basin to the east. The volcanics range from andesite and basalt in the south to dominantly acid with subordinate andesite in the north (Whitaker *et al.*, 1974).

The major deformation of the New England Fold Belt is traditionally considered to have been of mid-Permian age, and has been referred to as the Hunter-Bowen Orogeny. Folding of shelf areas, such as the Yarrol Shelf, were apparently of mid- to Late Permian age. It is possible that the orogenesis was essentially continuous from Permo-Carboniferous to mid- to Late Permian time, and that its effects were experienced earliest in the easternmost flysch sequences, and latest in the shelf deposits to the west.

Deformation on the Yarrol Shelf was characterised by open folding along north-northwest axes and high-angle reverse and minor transcurrent faulting. The intensity of folding increases towards the eastern boundary of the shelf. A large thrust sheet of ultramafic rocks, which appears to overlie the central part of the Yarrol Shelf and Permian sediments of the Grantleigh Trough, may have been emplaced in the early Late Permian. Its root zone lies to the east within an extension of the Yarrol fault system (Murray, 1974).

Folding of the Yarrol Shelf was probably accompanied by renewed thrusting and remobilisation of serpentinite along the Yarrol and Peel fault zones (Murray, 1974).

The eastern part of the Yarrol Province, and probably also the New England Province, were extensively affected by normal faulting during much of the Triassic, and volcanic fault troughs or rift zones were developed in the area from Rockhampton to south of Brisbane (Day *et al.*, 1978).

2.2 Tectonic Setting

The tectonic history of the northern part of the Tasman Fold Belt System began in the Cambrian, when deposition occurred in a northeast-trending mobile zone, marginal to the Precambrian craton of the Georgetown and Mount Isa areas. Oceanic crust, indicated by basic volcanics and ultramafic rocks, is recognised furthest from the craton, with a belt of volcanic rocks developed near the craton. These rocks were folded, metamorphosed and intruded by granites in the Upper Ordovician during tectonism which can be equated with the Benambran Orogeny in the Lachlan Fold Belt. Fold axes trend northeast, parallel to the craton margin.

Following the Upper Ordovician tectonism, a new mobile belt developed east of the Thomson Fold Belt having a north to north-northwest trend transecting the northeast

trend of the Cambrian-Lower Ordovician mobile belt. The earliest sediments deposited in this mobile zone, which later became the New England Fold Belt, are thick quartzose flysch during the Late Ordovician and Silurian. At the same time, similar quartzose flysch was deposited in the Broken River Embayment. This embayment was formed by the rifting of folded, metamorphosed and intruded Cambrian and Lower Ordovician rocks from the Precambrian craton.

In the Upper Silurian and Lower Devonian, a belt of rhyolitic-andesitic volcanics developed in the New England Mobile Belt, but quartzose flysch continued to be deposited in the Broken River Embayment. At the same time sedimentation extended north into the area of the Hodgkinson Basin for the first time.

The history of the Thomson Fold Belt from the Upper Ordovician to the Middle Devonian is obscure, but the occurrence of Middle Devonian marine volcanics around the Anakie High suggest that sedimentation and volcanism continued in this area following the Upper Ordovician tectonism.

In the late Middle Devonian, rocks within both the Thomson Fold Belt and the New England Fold Belt were folded and intruded by granites. This marked the end of the Thomson Fold Belt as an orogenic domain. Following this tectonism, Upper Devonian and Lower Carboniferous sedimentation and volcanism within the Thomson Fold Belt was dominantly continental. Marine deposition continued in the New England Fold Belt. The Hodgkinson Basin appeared to have been shielded from this mid-Devonian tectonism, and deposition of flysch-like sediments continued.

The mid-Devonian tectonism resulted in the development of the north-south-trending Drummond Basin in the eastern part of the Thomson Fold Belt. This tectonism produced a strong unconformity, but further west where the effects of the tectonism are mild, the Upper Devonian-Lower Carboniferous sedimentation occurred in a northeast-trending area, influenced by existing structural trends (Kirkegaard, 1974).

Mid-Carboniferous tectonism is recognised in all divisions, but intensity varies in each area. Folding is most intense in the Hodgkinson Basin where it appears to mark the end of the area as a significant basin. Formation of the Broken River Province can be rationalised in terms of oblique subduction and strike-slip faulting. Its two broad-scale terranes, the smaller southwestern Graveyard Creek Subprovince and larger Camel Creek Subprovince,

are regarded as Silurian-Devonian fore-arc basinal, and subduction complex assemblages, respectively. They are divided by the Gray Creek Fault, interpreted as a dextral strike-slip structure of Siluro-Devonian age. Part of the multiphase structural history of the Camel Creek Subprovince is ascribed to the partitioning of shortening and shear stress regimes known to characterise continental margins experiencing oblique-slip subduction. Late Devonian crustal shortening is ascribed to a change in the direction of plate motion and an increase in its rate. A sheet basement is thought to have been thrust eastwards to cover most of the fore-arc basinal assemblage with the southwestern part of the Burdekin River Fault Zone, regarded as a transform offsetting the continental margin in a sinistral sense, is also inferred for Late Devonian. Northeasterly trending folds characteristic of the Graveyard Creek Subprovince and recognised as a discrete fold phase in the southern Camel Creek Subprovince, are considered to have been induced by shearing adjacent to the Clarke River Fault Zone and to wedging of the continental margin sedimentary assemblage between basement blocks. Oblique subduction appears to have resumed in Early Carboniferous time. Two previously separate structures, the southwestern Burdekin River Fault and part of the older Gray Creek Fault, united to form a single dextral strike-slip structure. Movement on this composite fault, the Burdekin River Fault, sponsored the development of a deeply Early Carboniferous pull-apart molasse basin which retained stratigraphic and structural continuity with the preceding fore-arc basin. Extensive shallow Early Carboniferous molasse basins developed in response to vertical movements on the Gray Creek and Clarke River Fault Zones. With subsequent vertical movement coupled with erosion, the Burdekin River Fault has come to mark the eastern limit of overthrust basement.

Gentle folding about north-northwest-trending axes is recognised in the intracratonic Drummond Basin within the Thomson Fold Belt. The only recognisable effect of this tectonism, in the New England Fold Belt, is the intrusion of granites into the Connors and Auburn Arches, and the recognition of a slight disconformity between the Lower and Upper Carboniferous in the Yarrol Basin.

The New England Fold Belt is separated into the Yarrol Province in the north, and the New England Province in the south, by Mesozoic sediments of the Moreton-Clarence Basin near the Queensland-New South Wales border. In both provinces, parallel belts can be equated with volcanic arc, fore-arc basin and subduction complex assemblages, and were originally continuous over the entire length of the fold belt. Formulation of a

variable tectonic model for the Carboniferous history of the New England Fold Belt has been hampered by the following complicating factors :

1. All pre-Permian tectonic elements of the Yarrol Province are displaced at least 200 km eastwards relative to their equivalents in the New England Province.
2. Fore-arc basin and subduction complex assemblages are repeated across the northern part of the New England Province.
3. The Carboniferous subduction complex in the New England Province is folded into a large double orocline or megafold with a dextral sense with hinge zones near Texas in southern Queensland and Coffs Harbour in northeastern New South Wales.
4. Continental margin arc volcanism was continuous in the New England Province throughout Carboniferous time, but appears to have ceased in the Yarrol Province in the mid-Carboniferous.

A plate tectonic model, presented by Murray *et al.* (1987), explains all four of these features by large-scale dextral transform faulting of the eastern part of the New England Fold Belt in Middle and Late Carboniferous time. The model is based on the Late Cainozoic evolution of western North America and the formation of the San Andreas Fault.

The New England Fold Belt persisted as a mobile area in the Permian, and Lower Permian volcanics and sediments were deposited in the Yarrol Basin and in the area which became the Cracow-Eungella Mobile Belt. Sedimentation in the western part of the Bowen Basin occurred over the now cratonic Thomson Fold Belt. Tectonism in the Upper Permian caused (Hunter-Bowen Orogeny) strongly folded rocks in the Yarrol Basin and the Cracow-Eungella Mobile Belt. Elsewhere its effects are only mild. Following this tectonism, the history of the northern part of the Tasman Fold Belt System was that of a cratonic area (Kirkegaard, 1974).

2.3 Metallogenic Classification of Deposits

A great variety of mineral deposits, ranging in age from Late Cambrian to Early Ordovician, and possibly even Precambrian to Early Cretaceous, is present in the exposed rocks of the Tasman Fold Belt System in northern Queensland. These mineral deposits are shown in Figure 2.4 with the accompanying Table 2.1.

Volcanogenic massive sulphides and Slate Belt-type gold-bearing quartz veins are the most important deposits formed in the pre-cratonic (orogenic) stage of all three fold belts. The volcanogenic massive sulphides include classic Kuroko-type orebodies associated with silicic volcanics, such as those at Thalanga (Late Cambrian-Early Ordovician, Thomson Fold Belt) and at Mount Chalmers (Early Permian, New England Fold Belt), and Kieslager or Besshi-type deposits related to submarine mafic volcanics, such as Peak Downs (Precambrian or early Palaeozoic, Thomson Fold Belt) and Dianne, OK and Mount Molloy (Silurian-Devonian, Hodgkinson-Broken River Fold Belt).

The most numerous ore deposits are associated with calc-alkaline volcanics and granitoid intrusives of the transitional tectonic stage of the three fold belts, particularly the Late Carboniferous-Early Permian of the Hodgkinson-Broken River Fold Belt, and the Late Permian-Middle Triassic of the southeast Queensland part of the New England Fold Belt. In general, these deposits are small but rich. They include tin, tungsten, molybdenum and bismuth in granites and adjacent metasediments, base metals in contact metasomatic skarns, gold in volcanic breccia pipes, gold-bearing quartz veins within granitoid intrusives and in volcanic contact rocks, and low-grade disseminated porphyry-type copper and molybdenum deposits. The porphyry-type deposits occur in distinct belts related to intrusives of different age: Devonian (Thomson Fold Belt), Late Carboniferous-Early Permian (Hodgkinson-Broken River and Thomson Fold Belts), Late Permian-Middle Triassic (southeast Queensland part of the New England Fold Belt), and Early Cretaceous (northern New England Fold Belt).

Tertiary deep weathering events were responsible for the formation of lateritic nickel deposits on ultramafic and surficial manganese concentrations from disseminated mineralisation in cherts and jaspers (Murray, 1986).

The following styles of gold deposits in north Queensland have been recognised as :

1. Deep Vein (e.g. Charters Towers)
2. Metamorphic Vein (e.g. Hodgkinson)
3. Shallow Vein (e.g. Ravenswood)
4. Volcanogenic Massive Sulphide (e.g. Liontown)
5. Breccia Complexes (e.g. Mount Leyshon)
6. Stockwork/Skarn (e.g. Mungana)

Historical production has been almost entirely from the 'Deep Vein' group of deposits. The deep veins are base-metal rich fissures and shear zones related to syn- or post-tectonic Late Devonian (?) granitoids and hosted in older Palaeozoic or Precambrian granitoids or metamorphics. Bulk tonnage potential in these deposits depends on disseminated or stockwork mineralisation in sheared wall rocks adjacent to the fissures.

Minor gold has been produced from the Liontown and Highway volcanogenic massive stockwork/skarn deposits which are hosted in the Cambrian Mount Windsor Volcanics.

The discovery of the Kidston and Mount Leyshon breccia deposits and the Mungana stockwork/skarn deposit have led to extensive exploration of Permo-Carboniferous rhyolites using epithermal models. These occurrences are in linear belts adjacent to major calderas and associated with subvolcanic rhyolite-granite bodies (Morrison, 1987).

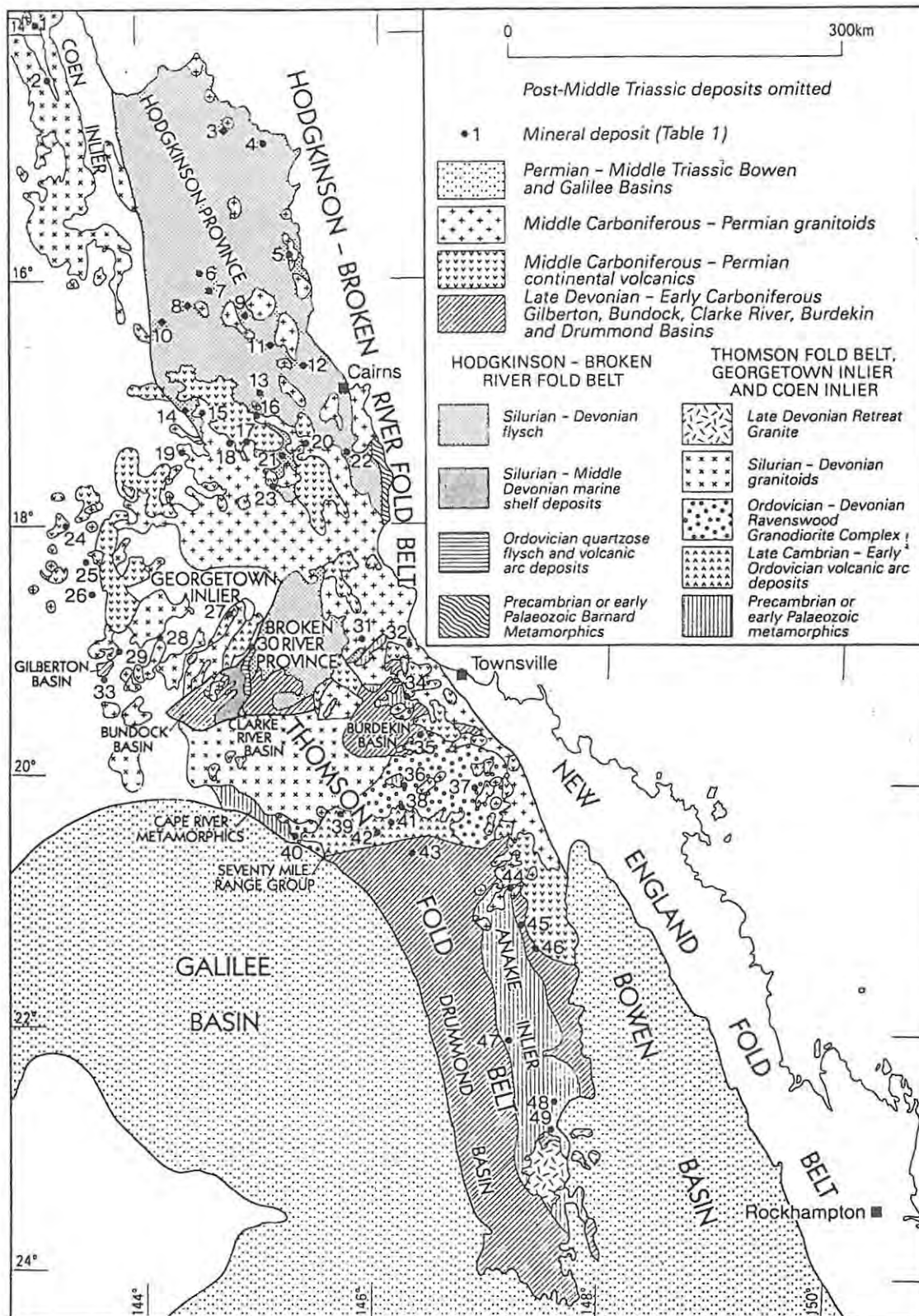


Figure 2.4 : Simplified geological map of the northern part of the Tasman Fold Belt System in Queensland (Murray, 1990).

Deposit number in Fig. 1	Name	Type and age of deposit	Recorded production and years of main production	Resources and reserves	References
1	Coen gold field	Quartz reefs in shear zones in Devonian granite; alluvial placers	About 2300 kg gold bullion, 1876-1910		Willmott et al., 1973; Whitaker, 1975
2	Hamilton gold field	Quartz reefs in Devonian granodiorite and along granite - metamorphic contact; alluvial placers	About 2300 kg gold bullion, 1900-1921		Willmott et al., 1973; Whitaker, 1975
3	Jeannie River prospect	Complex tin-sulphide lodes in Devonian metasediments intruded by Permian granite			Lord and Fabray, this publication
4	Starcke gold field	Syntectonic and synmetamorphic quartz veins in flysch, formed during Devonian deformation; alluvial placers	About 440 kg gold, 1890-1908		de Keyser and Lucas, 1968
5	Annan River tin field	Quartz-tourmaline-cassiterite veins in Permian granite; disseminated cassiterite in argillised granite; alluvial placers	About 14 000 t cassiterite concentrates, 1885-1922		Department of Mines, Queensland, 1953a; de Keyser and Lucas, 1968; Gregory, Taylor and White, 1980; Krosch, 1985
5	Collingwood prospect	Cassiterite in siliceous sheeted veins, albite veins and greisen associated with Permo-Carboniferous intrusives		4 Mt of 0.7 % tin	Krosch, 1985; Jones, Moeller and Truelove, this publication
6	Palmer River gold field	Alluvial placers; syntectonic and synmetamorphic quartz veins in flysch, formed during Devonian deformation	More than 40 000 kg gold, 1873-1891		de Keyser and Lucas, 1968
7	Dianne	Besshi-Kieslager type volcanogenic massive sulphides of Silurian-Devonian age	About 15 500 t copper and 1000 kg silver, 1980-1983		Gregory, Taylor and White, 1980; Gregory and Robinson, 1984
8	Cannibal Creek	Alluvial placers; quartz-cassiterite greisen veins in metasediments at Permian granite contact	About 2400 t cassiterite concentrates, 1879-1884		de Keyser and Lucas, 1968; Bateman, 1985
9	Watershed prospect	Calc-silicate hosted skarn type scheelite deposit, probably related to Permian plutonism			Krosch, 1985
10	O.K.	Besshi-Kieslager type volcanogenic massive sulphides of Silurian-Devonian age	About 7800 t copper, 1902-1912		de Keyser and Lucas, 1968; Fawckner, 1978; Gregory, Taylor and White, 1980; Gregory and Robinson, 1984
11	Mount Carbine	Sheeted quartz-wolframite-scheelite veins in metasediments near Permian granite contact	About 16 400 t wolframite concentrates, 1894-1921, 1972-1986		Department of Mines, Queensland, 1953b; de Keyser and Lucas, 1968; Plumridge, 1975; Higgins et al., 1987; de Roo, 1988; Forsythe and Higgins, this publication
12	Mount Molloy	Besshi-Kieslager type volcanogenic massive sulphides of Silurian-Devonian age	More than 3870 t copper, 1903-1910		de Keyser and Lucas, 1968; Gregory, Taylor and White, 1980; Gregory and Robinson, 1984
13	Hodgkinson gold field	Syntectonic and synmetamorphic quartz veins in flysch, formed during Devonian deformation	About 9000 kg gold and 3150 t antimony, 1875-1882		de Keyser and Lucas, 1968; Peters, 1987a
14	Mungana-Chillagoe-Almaden	Contact metasomatic (skarn) deposits in calcareous rocks at contacts with Carboniferous-Permian granite; brecciated zones or pipes in some deposits	About 12 225 t copper, 42 340 t lead, and 129 600 kg silver, 1894-1927		Broadhurst, 1952, 1953a; de Keyser and Wolff, 1964; de Keyser and Lucas, 1968; Verwoerd and Harvey, 1975; Gregory, Taylor and White, 1980

Table 2.1 : Mineral deposits of the northern part of the Tasman Fold Belt System in Queensland (Murray, 1990).

Deposit number in Fig. 1	Name	Type and age of deposit	Recorded production and years of main production	Resources and reserves	References
14	Red Dome	Calc-silicate skarn, breccia and quartz vein stockwork related to Carboniferous-Permian rhyolite dykes	5754 kg gold and 499 kg silver, 1987-present*	17.5 Mt of 2 g/t gold, 0.46% copper, 1.8% zinc and 4.6 g/t silver	Mathews and Timms, 1984; Karjalainen, Erceg and Joyce, 1987; Ewers and Sun, 1988; Torrey et al., 1988; Ewers, Torrey and Erceg, this publication
15	Ruddygore	Porphyry type copper deposit in Carboniferous-Permian granitoid	About 1475 t copper and 1865 kg silver, 1903-1909	Grade about 0.1% copper	Broadhurst, 1949; de Keyser and Wolff, 1964; de Keyser and Lucas, 1968; Horton, 1978, 1982
16	Wolfram Camp	Irregular quartz pipes along contact of greisenised Carboniferous-Permian granite with metasediments	About 7100 t wolframite concentrates, 1625 t molybdenite concentrates, 165 t bismuthinite concentrates, and 1480 t mixed wolframite-bismuthinite concentrates, 1894-1921, 1938-1945, 1969-present*		Morton and Ridgway, 1944; Department of Mines, Queensland, 1953c; de Keyser and Wolff, 1964; de Keyser and Lucas, 1968; Plimer, 1975
17	Bamford Hill	Quartz pipes at contact of greisenised Carboniferous-Permian granite with volcanics	About 2250 t wolframite concentrates, 180 t molybdenite concentrates, 20 t bismuthinite concentrates, and 100 t mixed wolframite-bismuthinite concentrates, 1893-1921, 1938-1945		de Keyser and Wolff, 1964; Connah, 1965a; de Keyser and Lucas, 1968; Gregory, Taylor and White, 1980
18	Koorboora-Sunnymount	Irregular, pipe-like lodes along joint intersections in metasediments above Carboniferous-Permian granite; alluvial placers	About 14 630 t cassiterite concentrates, 700 t scheelite concentrates, and 670 t wolframite concentrates, 1900-1920, 1959-1985		de Keyser and Wolff, 1964; de Keyser and Lucas, 1968; Gregory, Taylor and White, 1980
19	Tate River	Alluvial placer deposits derived from small lodes associated with Carboniferous granitoids	About 5365 t cassiterite concentrates, 1883-1903, 1972-1985		de Keyser and Lucas, 1968
20	Herberton-	Fracture controlled pipes and veins and greisen zones and veins in roof zones of Carboniferous-Permian granitic intrusives and in metasedimentary contact rocks; alluvial placers	About 140 000 t cassiterite concentrates, 3950 t wolframite concentrates, 8165 t copper, 11 830 t lead, and 101 330 kg silver, 1881-present*		Broadhurst, 1951, 1953b; Connah and McIver, 1965; Blake, 1972; Olatunji et al., 1978; Gregory, Taylor and White, 1980; Pollard and Taylor, 1983
21	Irvinebank-				
23	Mount Garnet tin field				
22	Russell gold field	Alluvial placers; syntectonic and synmetamorphic quartz veins in metasediments, formed during Devonian deformation	About 835 kg gold, 1887-1905		de Keyser and Lucas, 1968
23	Mount Garnet	Lenses and pipes in calc-silicate skarn at contact with Carboniferous granitoid	About 4600 t copper and 29 500 kg silver, 1901-1903		de Keyser and Lucas, 1968; Whitcher, 1975a
24	Maureen prospect	Stratabound replacement deposit in sediments at base of Carboniferous volcanics		1.65 Mt of 0.153% and 0.73 Mt of 0.056% uranium	O'Rourke, 1975; Bain, 1977; Bain and Withnall, 1980; Battey, Miezitis and McKay, 1987

Table 2.1 - Continued

Deposit number in Fig. 1	Name	Type and age of deposit	Recorded production and years of main production	Resources and reserves	References
25	Georgetown	Hydrothermal quartz veins in Devonian granites and metamorphic contact rocks	About 7175 kg gold bullion, 485 kg gold, 2460 kg silver and 1370 t lead, 1870-1920		Withnall, 1978; Bain and Withnall, 1980; Bain, Withnall and Black, 1984; Bain et al., 1988
26	Forsayth	Hydrothermal quartz veins in Devonian granites and metamorphic contact rocks	3460 kg gold bullion, 1070 kg gold, 1790 kg silver, 120 t copper and 710 t lead, 1871-1913		Withnall, 1976; Bain and Withnall, 1980; Bain, Withnall and Black, 1984; Bain et al., 1988
27	Balcooma, Dry River South and Surveyor 1 prospects	Kuroko type volcanogenic massive sulphides of probable Late Cambrian-Early Ordovician age		3.5 Mt of 3% copper (Balcooma); 1.8 Mt of 12.6% zinc, 5.0% lead, 1.0% copper, 112 g/t silver and 0.9 g/t gold (Dry River South and Surveyor 1)	Harvey, 1984; Louthean, 1988; Huston and Taylor, this publication
28	Kidston	Breccia pipe related to Carboniferous-Permian magmatism	30 274 kg gold and 18 029 kg silver, 1985-present*	36.2 Mt of 1.74 g/t gold and 2.11 g/t silver	Bain and Withnall, 1980; Mustard, 1984; Andrew and Baker, 1987; Baker, 1987, 1988; Baker and Andrew, 1988; Baker and Tullemans, this publication
29	Percyville	Hydrothermal quartz veins in Devonian granites and metamorphic contact rocks	About 590 kg gold bullion and 60 t copper, 1890-1899		Withnall, 1976, 1981; Bain and Withnall, 1980; Bain, Withnall and Black, 1984; Bain et al., 1988
30	Greenvale	Lateritic profile on ultramafic rocks, formed by Tertiary deep weathering	382 523 t nickel and 32 165 t cobalt, 1974-present*	About 8 Mt of 1.35% nickel and 0.11% cobalt	Fletcher and Couper, 1975; Burger, 1979, 1982; Louthean, 1988
31	Kangaroo Hills-Ewan	Alluvial placers; irregular pipes and veins at contact of Carboniferous granite and metasediments	About 7100 t cassiterite concentrates and 420 t stannite concentrates, 1900-1930, 1967-1985		Connah and McIver, 1965; Levingston, 1971; Gregory, Taylor and White, 1980; Krosch, 1985
32	Ollera	Irregular quartz pipes controlled by joints in greisenised and silicified Carboniferous granite	About 240 t wolframite concentrates, 1903-1906		Connah, 1965a; Levingston, 1971
33	Gilberton	Alluvial placers; hydrothermal quartz veins in metamorphics, related to Devonian granites	About 4900 kg gold bullion, 1869-1893		Bain and Withnall, 1980; Withnall, 1981; Bain, Withnall and Black, 1984; Bain et al., 1988
34	Ben Lomond prospect	Fractures, veins and stockwork zones in Carboniferous-Permian rhyolitic tuff		1.93 Mt of 2 kg/t uranium and 1.5 kg/t molybdenum	Valsardieu, Cocquio and Bauchau, 1980; Battey, Miezius and McKay, 1987
35	Far Fanning	Quartz veins in a major shear zone in Late Devonian sediments	About 414 kg gold, 1986-1988	1.6 Mt of 2.86 g/t gold	Elliott and Houtgraaf, 1986; Dunham and Skrzeczynski, this publication
36	Charters Towers	Hydrothermal quartz veins in granitoids, probably related to Devonian granodiorite	206 845 kg gold, 35 450 kg silver and 4395 t lead, 1871-1918		Blatchford, 1953; Levingston, 1972; Peters and Golding, 1987; Peters, 1987b
37	Ravenswood	Hydrothermal quartz-sulphide veins in granitoids, possibly related to Carboniferous-Permian intrusives	29 363 kg gold and 6534 kg silver, 1868-1918, 1987-present*	About 1 Mt of 2.5 g/t gold	Clarke, 1971; Levingston, 1972; Morrison, 1987, 1988; Louthean, 1988; Neindorf et al., 1989

Table 2.1 - Continued

Deposit number in Fig. 1	Name	Type and age of deposit	Recorded production and years of main production	Resources and reserves	References
37	Mount Wright	Breccia pipe related to Carboniferous-Permian magmatism	35 kg gold bullion, 35 kg gold and 20 kg silver, 1917-1942	79 000 t of 10 g/t gold	Clarke, 1971; Levingston, 1972; Watters, 1984
38	Mount Leyshon	Breccia pipe related to Carboniferous-Permian magmatism	6968 kg gold and 8050 kg silver, 1987-present*	10.4 Mt of 2.2 g/t gold and 4.8 g/t silver	Levingston, 1972; Morrison, Teale and Hodgkinson, 1987, 1988; Morrison, Andrew and Teale, 1988; Paul et al., this publication
38	Disraeli	Multiple quartz vein systems in broad, moderately dipping fracture zones within hornblende granodiorite of Ordovician-Devonian age		4.25 Mt of 3.0 g/t gold	Louthean, 1988; Morrison, 1988
39	Thalanga prospect	Kuroko type volcanogenic massive sulphides of Late Cambrian-Early Ordovician age		7.4 Mt of 15.5% combined copper-lead-zinc, 83 g/t silver and 0.52 g/t gold	Gregory and Hartley, 1982; Gregory, Hartley and Wills, 1987, this publication
40	Cape River	Alluvial placers; hydrothermal quartz veins associated with ? Carboniferous-Permian dykes in metamorphics	About 1400 kg gold bullion, 1867-1938, 1984-present*		Paine, Harding and Clarke, 1971
41	Highway	Volcanogenic gold-barite stringer mineralisation of Late Cambrian-Early Ordovician age	About 22 kg gold, 1979-1983	171 000 t of 4.4 g/t gold and 5.0 g/t silver	Russell, 1986; Kay, 1987
41	Reward prospect	Kuroko type pyrite-copper-lead-zinc-gold-barite in Late Cambrian-Early Ordovician volcanics		630 000 t of 6.8% copper (including 287 000 t of 1.3 g/t gold), 309 000 t oxide ore of 5.0 g/t gold and 27 g/t silver	Beams, Laing and O'Neill, 1989; Beams, Laurie and O'Neill, this publication
42	Liontown	Kuroko type volcanogenic massive sulphides of Late Cambrian-Early Ordovician age	About 500 kg gold, 2150 kg silver, 530 t lead and some copper, 1905-1911 (copper), 1951-1961 (lead)		Levingston, 1972; Lacy, 1980
43	Pajingo	Epithermal mineralisation possibly related to Carboniferous-Permian subvolcanic intrusives	3092 kg gold and 7859 kg silver 1987-present*	1.15 Mt of 10.0 g/t gold and 38 g/t silver	Porter, 1988; Porter, this publication
44	Sellheim-Ukalunda	Hydrothermal veins related to Carboniferous granitoids; alluvial placers	About 12 000 kg silver, 30 kg gold, 30 t lead, 10 t copper and 1 t bismuth, 1883-1934		Malone et al., 1966; Golding et al., 1987
45	Wirralie	Epithermal mineralisation possibly related to Carboniferous-Permian magmatism	2943 kg gold and 257 kg silver 1988-present*	3.65 Mt of 2.75 g/t gold (oxidised ore)	Fellows and Hammond, 1988, this publication
46	Mount Coolon	Altered and silicified andesite adjacent to narrow joint or fissure, possibly of Carboniferous age	4395 kg gold and more than 1865 kg silver, 1914-1939	500 000 t of 10 g/t gold	Coldham, 1953; Louthean, 1988; Wells, Murray and Cunneen, 1989
47	Lucky Break	Syntectonic and synmetamorphic quartz vein in metamorphics, probably of early Palaeozoic age	48 kg gold to September 1987	88 000 t of 2.3 g/t gold	Ishaq, 1985; Louthean, 1988
48	Clermont	Placers in Permian and Cainozoic sediments	About 8200 kg gold, 1862-1901		Olgers, 1972; l'Ons, 1983
49	Peak Downs	Besshi-Kieslager type volcanogenic massive sulphides of probable early Palaeozoic age	More than 17 000 t copper, 1863-1877		Department of Mines, Queensland, 1953d; Cox, 1975

Table 2.1 - Continued

3.0 The Thomson Fold Belt and Georgetown Inlier

3.1 Introduction

The Thomson Fold Belt and the Georgetown Inlier are described in detail within this chapter. Figure 3.1 shows the two areas and their structural elements. The geology, tectonic setting and economic geology of the areas will be discussed.

The Permo-Carboniferous gold-related volcanic breccia complexes in northern Queensland, were emplaced into Precambrian sedimentary rocks and Ordovician to Devonian granitoids. It is important to describe these older rocks in detail to visualise the type of wall rocks, and their associated mineralisation, that may of contributed to the formation of the volcanic breccia complexes.

3.2 The Thomson Fold Belt

3.2.1 Anakie Inlier

The Anakie Inlier is a north-northwest-trending block which comprises poorly known, strongly folded metasediments and metavolcanics of Precambrian or early Palaeozoic age. A basal sequence of metamorphosed mafic volcanics, calc-silicates, recrystallised limestones and small serpentinite lenses is overlain by clastic metasediments, with at least one possible unconformity in the succession (Murray, 1990).

In the south, the inlier comprises generally low-grade regional metamorphics (Anakie Metamorphics), intruded by Late Devonian granodiorite. The Anakie Metamorphics consists dominantly of albite-muscovite-quartz schist with quartz-albite-chlorite-actinolite-epidote schist, which appears to be metamorphosed basic volcanics associated with small lenses of serpentinitised harzburgite. Structurally the metamorphics are complex, and have been deformed by more than one generation of folding. A Middle or Late Ordovician age for the folding and metamorphism is indicated by a K-Ar date of 458 million years from mica schist (Webb and McDougall, 1968).

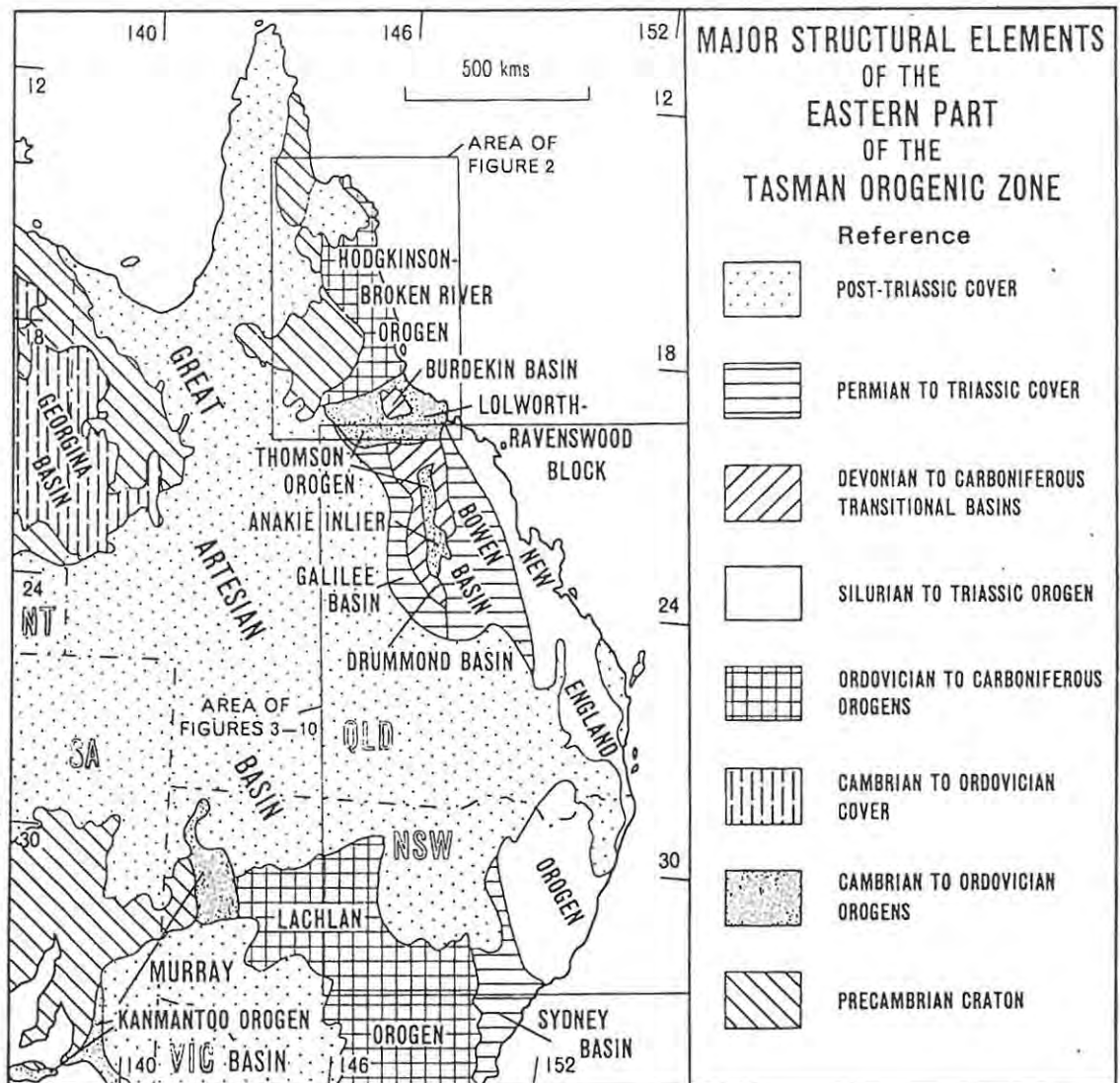


Figure 3.1 : Major structural elements of the eastern part of the Tasman Orogenic Zone (Day et al., 1978).

Within the metamorphosed rocks are belts of unmetamorphosed quartz arenite and mudstone with lenses of crystalline limestone. These sediments appear to be unconformable on the schists.

Fold axes, bedding and schistosity within the Anakie Metamorphics commonly have a northeast trend (Kirkegaard, 1974). Thus the mid-Ordovician folding was about northeast

axes, parallel to the overall trend of the Thomson Fold Belt. The north-northeast orientation of the Anakie Inlier must have been due to later tectonism.

The Middle Devonian volcanics and sediments of the Anakie Inlier are considered to belong to the transitional tectonic stage of the Thomson Fold Belt. The transitional tectonic regime is represented by two Devonian to Carboniferous basins, the Burdekin and Drummond Basins, which overlie early Palaeozoic metamorphics and intrusives of the fold belt. Early to Middle Devonian volcanics and sediments crop out along the eastern side of the Anakie Inlier and in the core of the Nogoia Anticline at the southern margin of the Drummond Basin (Fordham, 1976). Andesitic volcanics are dominant, with minor rhyolite, shale and limestone lenses. These rocks appear to overlie the Anakie Metamorphics unconformably. The restriction of Early to Middle Devonian outcrops to the eastern margin of the Anakie Inlier, suggests that the inlier was emergent at this time, and that the Devonian rocks were deposited close to the shoreline. The small size and poor exposure of most outcrops prevents determination of structure, except in the Nogoia Anticline, where andesitic volcanics strike northeast and dip almost vertically (Fordham, 1976).

The northern part of the Anakie Metamorphics consists of weakly metamorphosed quartz-rich clastic sediments. Schistosity appears to be parallel to bedding, fold axes trend north, and dips are steep (Malone *et al.*, 1964). The presence of crenulation cleavage in some rocks suggest more than one generation of folding. These rocks can be traced northwards with no apparent break into sediments of the Ukalunda Beds (Malone *et al.*, 1966), which contain limestones with Early to Middle Devonian corals (Jell and Hill, 1969). The Ukalunda Beds and Late Carboniferous granites constitute the northern end of the Anakie Inlier.

The Early to Middle Devonian rocks of the Anakie Inlier were deformed in late Middle Devonian and are unconformably overlain by Late Devonian strata of the Drummond Basin (Malone, 1967; Olgers, 1972; Fordham, 1976). The Anakie Inlier probably developed as a distinct north-trending tectonic unit at this time, since it controlled stream directions in the Late Devonian to Early Carboniferous Drummond Basin (Murray and Kirkegaard, 1978).

3.2.2 Lolworth-Ravenswood Block

The Lolworth-Ravenswood Block consists of early Palaeozoic sediments and volcanics intruded by two large composite batholiths of Ordovician to Devonian age (Figure 3.2). It is separated from the Broken River Province to the north, by the Clarke River Fault (White, 1965). This fault is largely concealed by Permo-Carboniferous volcanic and intrusive complexes which also border the Lolworth-Ravenswood Block to the east. Rocks of the Lolworth-Ravenswood Block pass beneath Late Devonian to Early Carboniferous strata of the Drummond Basin to the south, and Permian and Triassic sediments of the Galilee Basin to the west. The block forms basement rocks of the Burdekin Basin, and much of its western half is covered by a veneer of Cainozoic sediments and basalt.

A thick east to east-northeast-trending sequence of tuffaceous arenite, siltstone, black shale (Cape River Beds) and calc-alkaline volcanics occurs along the southern margin of the Lolworth-Ravenswood Block, south of Charters Towers. The proportion of interbedded volcanics increases from west to east, and the thickest sections have been mapped separately as the Mount Windsor Volcanics (Wyatt *et al.*, 1971). Acid volcanics are dominant, but the sequence is characterised by rapid variations in lithology along strike, and andesite and basalt are locally abundant.

A belt of metasediments, which trends west-northwest along the south-western margin of the Lolworth-Ravenswood Block, has been correlated with the fossiliferous sediments south of Charters Towers. Rock types include phyllite, quartzite, mica schist, amphibolite and garnet-biotite gneiss of greenschist to amphibolite facies. Up to three generations of folding have been recognised in these rocks (Baker, 1974), which appear to have had a much more complex history of deformation than the unmetamorphosed sediments.

A Rb-Sr isochron on four samples of metamorphics yielded an Early to Middle Ordovician age, which represents the final episode of metamorphism and deformation.

The metamorphosed Cape River Beds are similar in structure and metamorphic grade to the Running River Metamorphics, at the northern edge of the Lolworth-Ravenswood Block, and to the Argentine Metamorphics, which occur as basement to the Burdekin Basin. The Running River Metamorphics, Argentine Metamorphics and Cape River Beds have been assigned a tentative Precambrian age (Murray and Kirkegaard, 1978).

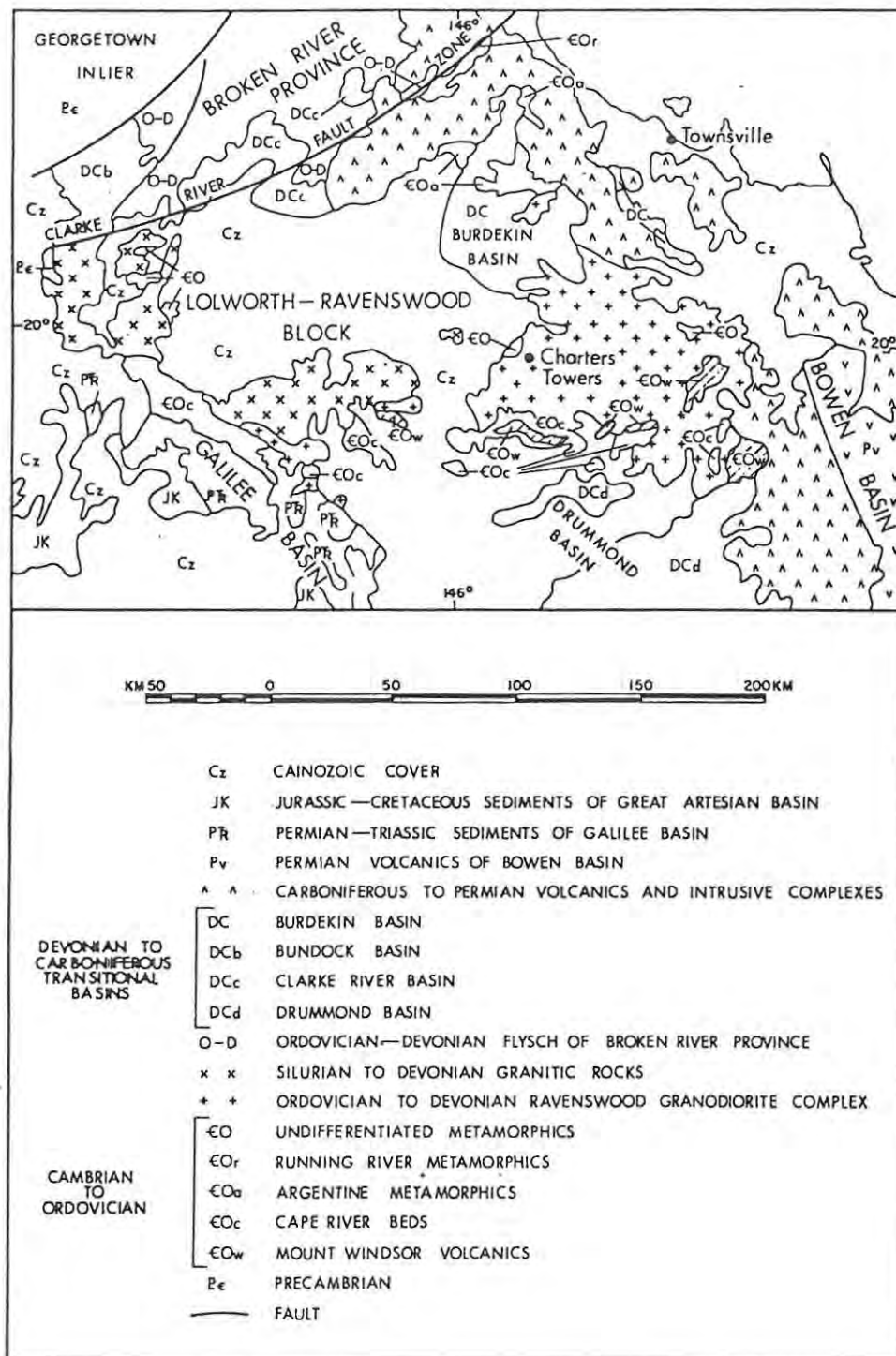


Figure 3.2 : Simplified geological map of the Lolworth-Ravenswood Block (Murray and Kirkegaard, 1978).

The Mount Windsor Volcanics and unmetamorphosed Cape River Beds are readily interpreted as remnants of a Cambro-Ordovician volcanic island-arc, and their associated sediments were separated from the Precambrian Georgetown Inlier by a marginal sea.

Two main episodes of granite emplacement are recognised in the Lolworth-Ravenswood Block. The Ravenswood Granodiorite Complex is a large composite batholith which crops out mainly east of Charters Towers. Rb-Sr isotopic dating has yielded Middle or Late Ordovician and Late Silurian or Early Devonian ages. Both intrusive epochs appear to have commenced with emplacement of a main granodiorite phase followed by intrusion of later, more acid phases (Wyatt *et al.*, 1971). Diorite and gabbro are widespread but not abundant. All rock types of the Ravenswood Granodiorite Complex locally are strongly foliated. Gneissic granodiorite which intrudes the metamorphosed Cape River Beds is foliated parallel to the schistosity. This suggests that the initial intrusions of the Ravenswood Granodiorite Complex, were synorogenic with the final mid-Ordovician phase of metamorphism and deformation of the Cape River Beds (and possibly of the Running River and Argentine Metamorphics).

The Lolworth Igneous Complex, which crops out west of Charters Towers, is the same age as the younger intrusions of the Ravenswood Granodiorite Complex (Late Silurian or Early Devonian). It consists chiefly of biotite adamellite and granodiorite, with banded pegmatitic and garnetiferous muscovite granite.

The Late Silurian to Early Devonian post-orogenic intrusions stabilised the Lolworth-Ravenswood Block. From Late Devonian to early Carboniferous time, the emergent block was a source area separating the largely marine Burdekin Basin on its northeastern margin from the continental Drummond Basin to the south.

3.2.3 Burdekin Basin

The Burdekin Basin formed as a shallow but subsiding marine basin on a basement of early Palaeozoic intrusives and metamorphics of the Lolworth-Ravenswood Block. This occurred when the sea transgressed southwards from the Broken River Province in Middle Devonian time. Remnants of strata indicate that the Burdekin Basin gradually expanded to cover 4000-5000 km² (Levingston, 1981).

The neritic, transitional, and continental sediments of the basin, were deposited in a tectonic environment ranging from a mildly unstable shelf to a yoked intra-cratonic basin. The strata is thickest in the southern and central portions of the basin.

The basin appears to have been of roughly constant size during the Middle Devonian (Fanning River Group). The change in environment displayed by the overlying Dotswood Formation, was probably related to changes in the hinterland rather than in the basin itself. The Dotswood Formation is markedly continental red-bed type, suggestive of a subtropical upland, supplying sediment to an environment ranging from piedmont, to flood plain and shallow lacustrine.

The lower boundary of the Dotswood Formation is marked in places by a conglomerate, which at one point contains pebbles of limestone, indicating that the Fanning River Group has been exposed to erosion by marine regression. However, there is no angular unconformity between the Fanning River Group and the Dotswood Formation, so any differential uplift must have lain beyond the basin.

Fluctuating shallow marine to continental sedimentation continued into the Early Carboniferous (Wyatt and Jell, 1967). Periodic, mild tectonism during deposition, accompanied the extrusion of calc-alkaline lavas and generated growth faults which caused abrupt changes of facies and thicknesses (Heidecker, 1974).

The basin was uplifted and gently warped in the mid-Carboniferous, so that the succeeding Late Carboniferous calc-alkaline volcanics and terrestrial sediments overlie the older rocks, unconformably and disconformably. Following deposition of the Late Carboniferous strata, the rocks of the Burdekin Basin were folded into irregular open basins and domes, with axial trends controlled by the proximity of the early Palaeozoic basement rocks or by basement faults. Dips are shallow to moderate. Two prominent sets of faults strike northwest to west and southwest; the former set shows considerable strike-slip movement, whereas, the latter are mainly normal faults (Wyatt *et al.*, 1970).

Intrusion of Carboniferous to Permian granite and adamellite plutons in the Burdekin Basin completed the cratonisation of the Lolworth-Ravenswood Block (Murray and Kirkegaard, 1978).

3.2.4 Drummond Basin

The Drummond Basin contains Late Devonian to Early Carboniferous strata which were deposited mainly west, but also east of the Anakie Inlier, on a basement of early Palaeozoic metamorphics and granite. The western, southern and eastern limits of the basin are concealed beneath Permian and Triassic sediments of the Galilee and Bowen Basins. Vine (1972) considered that the Drummond Basin did not extend west or southwest of the existing outcrops, and that its western margin coincided with the fault-generated Belyando Feature. Interpretations of seismic traverses, show the Drummond Basin strata thinning to the west and pinching out 20 km west of the Belyando Feature (Harrison *et al.*, 1975).

Sedimentation in the Drummond Basin was continental, except for a brief marine incursion in the north during Late Devonian time. Fluvial clastics were deposited in a narrow, subsiding basin, west of the emergent Anakie Inlier, by a north-flowing river system. Olgers (1972) recognised three distinct cycles of sedimentation separated by minor epeirogenic events associated with volcanism. These three cycles of sedimentation are described as follows :

1. Deposition was in a shallow sea, with sediment derived from the Lolworth-Ravenswood Block. This cycle came to an end with the deposition of acid flows and pyroclastics, both on land and in water.
2. Locus of deposition was a long, narrow basin along the western flank of the geanticline. Much of the sediment was derived from the geanticline, but later in the cycle the southern margin of the basin became the dominant provenance. Transport was by a strongly-flowing river which ran north-ward through the basin, swinging to the east to the sea around the northern end of the geanticline. In the later stages of this cycle, the Lolworth-Ravenswood Block was eroded to a sufficiently low level for the river to flow northeastward across it.
3. This cycle was inaugurated by renewed epeirogeny and volcanism in the areas bordering the basin. Originally deposition was over roughly the same area as that of the previous cycle, but as the landscape matured, deposition extended to practically the limits of the basin (Levingston, 1981).

Folding by compression from the east in the mid-Carboniferous produced open folds. The overall orientation of the fold axes is north to north-northwest, parallel to the boundary with the Anakie Inlier. Variations from this trend are common, particularly in the southern and northern parts of the basin. Anticlinal crests are cut by normal or high-angle reverse faults with a zone of thrusting immediately west of the inlier. Post-orogenic Late Carboniferous granitic plutons were emplaced in the area between the Lolworth-Ravenswood Block and the Anakie Inlier, accompanied by extrusion of genetically related acid volcanics (Murray and Kirkegaard, 1978).

3.2.5 Tectonic Environment

The tectonic framework of the Thomson Fold Belt developed in Early Cambrian time, when the former northern extension of the Adelaide Fold Belt was truncated along the Muloorinna Ridge. The initial sediments of the fold belt were deposited in a deep marine basin bordered to the west, southwest and northwest by Precambrian crustal blocks.

Late Cambrian calc-alkaline volcanics of the Lolworth-Ravenswood Block were probably deposited in an island-arc separated from the Precambrian Georgetown Inlier by a marginal sea.

Ordovician deposition was widespread in the Thomson Fold Belt. Metasediments and metavolcanics of possible Ordovician age occur in the Anakie Inlier. The association of basic metavolcanics with serpentinite lenses in the Anakie Inlier, suggests that deposition took place on an oceanic crust. In the Lolworth-Ravenswood Block, Early Ordovician tuffaceous sediments overlie the Late Cambrian volcanics.

On the basis of observed structures in the Anakie Inlier, and correlation with basement related structures in strata overlying early Palaeozoic rocks of the Thomson Fold Belt, it is suggested that the dominant northeast trend of the fold belt was first imposed by this mid- to Late Ordovician tectonism. Metamorphism was mainly to the greenschist facies, with local development of amphibolite facies. The only discordant area is the Lolworth-Ravenswood Block, characterised by an overall east-west trend. The cause of this anomalous trend is unknown.

An upper limit for the age of deformation is given by Late Ordovician sediments of the Anakie Inlier, which are probably unconformable on the complexly deformed Anakie

Metamorphics. The available data therefore suggests that the Thomson Fold Belt was mid-Ordovician. Local folding of this age is recognised in the Lachlan Orogen, but tectonism was earlier than the widespread Late Ordovician-Early Silurian.

There is no evidence of Silurian deposition in the Thomson Fold Belt. In this respect, the Thomson Fold Belt differs from the Lachlan Fold Belt, where several troughs and volcanic rifts developed during the Middle and Late Silurian. The pre-cratonic regime of the Thomson Fold Belt is considered to have ended with emplacement of post-orogenic Siluro-Devonian batholiths in the northern part.

The sea transgressed over the Thomson Fold Belt from the east in Early and Middle Devonian time. The maximum extent of the transgression was reached in the early Middle Devonian, when the shoreline was located along the eastern side of the Anakie Inlier and continued to the southwest. Deposition of clastic sediments and limestone was accompanied by eruption of andesitic volcanics along a northeast-trending continental margin. The Burdekin Basin was separated from the depositional area to the south, by the slightly emergent southern Lolworth-Ravenswood Block, and marine sedimentation did not commence until late Middle Devonian time, when the sea transgressed southwards from the Broken River Province.

The Early to Middle Devonian strata of the Anakie Inlier were folded in the late Middle Devonian. Folding was dominantly along north-trending axes, and the Anakie Inlier was probably formed as a north-northwest orientated structural unit at this time. No folding occurred in the Burdekin Basin, but uplift caused the withdrawal of the sea at the beginning of the Late Devonian. Post-tectonic granites were emplaced in the southern part of the Anakie Inlier.

Late Devonian red-beds and similar continental sediments were deposited over much of the Thomson Fold Belt. The thickest deposits accumulated in the Drummond Basin, where sedimentation and sporadic volcanism continued into the Early Carboniferous. Volcanics were also erupted in the Burdekin Basin, which was the site of fluctuating continental to marine conditions, from Late Devonian to Early Carboniferous time.

Widespread fold movements, ended the transitional tectonic regime of the Thomson Fold Belt, in the mid-Carboniferous. In most areas, open folds and faults strike northeast, probably reflecting the dominant structural trend imposed during the mid-Ordovician

orogeny. The north-south orientation of the structures in the Drummond Basin is attributed to the influence of the north-northwest trending Anakie Inlier. Variable trends within the Burdekin Basin were controlled by basement topography and faults. Post-tectonic Late Carboniferous granites and associated continental calc-alkaline volcanics were emplaced in the northeastern part of the Thomson Fold Belt.

Subsequently, the Thomson Fold Belt has behaved as a stable cratonic region. Broad down-warping initiated deposition in the Permian and most of the area was covered by the essentially undeformed Jurassic and Cretaceous sediments of the Great Artesian Basin (Murray and Kirkegaard, 1978).

3.2.6 Economic Geology

The following deposits within the Thomson Fold Belt can be located using Figure 2.4 and are briefly described in Table 2.1.

Syngenetic stratabound gold and copper mineralisation occurs along the contact between the basal metavolcanics and overlying metasediments in the Anakie Inlier. The style and setting of mineralisation are very similar to those of Besshi or Kieslager type deposits. This suggests an origin associated with early stages of island-arc development, or possibly with an oceanic spreading ridge (Franklin *et al.*, 1981). The only significant production was from the Peak Downs mine. The stratabound mineralisation may also have been the source of gold in quartz veins of metamorphic origin, such as the Lucky Break deposit.

Volcanogenic massive sulphide mineralisation, of Kuroko-type deposits, are known from several localities within the Seventy Mile Range Group. All occurrences are stratiform and conformable with the enclosing silicic volcanics of the Mount Windsor Volcanics. They have been interpreted as submarine exhalative deposits, and display such typical features as layering and slumping. The proportions of base metal sulphides vary. These type of deposits include Thalanga, Liontown, Highway and the Reward deposits.

Deformation, metamorphism and intrusion of granitoids formed a relatively stable continental crust over the Thomson Fold Belt by Silurian time. During the Silurian and Devonian, emplacement of large granitic batholiths continued in the northern part of the fold belt. These granitic rocks are associated with hydrothermal quartz vein-type gold mineralisation. These deposits include Charters Towers and Disraeli. Morrison (1988)

considered that some of the gold fields were related to Carboniferous porphyries rather than Devonian granite hosts. Several sub-economic porphyry-type copper-molybdenum deposits occur in Devonian intrusives in the Ravenswood area.

The Charters Towers gold field was the most productive field in north Queensland, and lies within the older components of the Late Ordovician to Devonian Ravenswood Batholith. The gold occurs in quartz veins which are cut by Carboniferous dykes and are notably absent from nearby overlying Middle Devonian sediments. Deposits are in simple and composite quartz veins in two sets of moderately dipping fissures. They tend to follow pre-existing planes of weakness in granodiorite, as for example along the margin of a diorite dyke. Displacements on these fissures are mostly 1 to 12 m. The lodes consist of quartz, sulphides and locally crushed granodiorite. They are generally 30 to 150 cm wide, but locally bulge to as much as 12 m wide. Sulphides, in order of generally decreasing abundance, are pyrite, galena, sphalerite, chalcopyrite and arsenopyrite. Other minor gangue minerals are calcite, gypsum and barite. Galena was regarded as the most reliable indication of high grade values. Gold occurred in irregular shoots, usually with greater vertical, than horizontal extent, and decreasing grade with depth. Mineralised sections of reef are mostly 100 to 500 m long, although the largest two or three are about 1500 m (Bain *et al.*, 1990). The auriferous quartz in the main lodes exhibits a systematic variation in $\delta^{18}\text{O}$ from +15.7 to +12.1 per mil with increasing depth. Calculated $\delta^{18}\text{O}$ compositions of the fluids depositing this quartz are +5 to +8 per mil at about 300°C, based on fluid inclusion data of Peters and Golding (1987). Recent isotopic dating of hydrothermal sericite, from the altered wall rocks of the Charters Towers lodes, indicates a Silurian to Devonian age.

A wide variety of mineral deposits are associated with the mid-Carboniferous-Permian magmatic rocks. The orebodies are numerous, of relatively small size, and of high grade. Several types of gold mineralisation are related to the Late Carboniferous-Permian granitoids and volcanics. Past production has been mainly from vein deposits associated with granitic to dioritic plutons. In most cases the ore veins are confined to the adjacent country rocks, which are of variable lithology.

Several bulk tonnage, low-grade gold deposits are related to Late Carboniferous-Permian magmatism. The most wide-spread type occurs in breccia complexes, such as those at Mount Leyshon and Mount Wright (Murray, 1986).

3.3 Georgetown Inlier

3.3.1 General

The Proterozoic sequence in the central part of the Georgetown Inlier has been divided into the Etheridge, Langlovale, Croydon and Inorunie Groups. The geology of the area of interest, within the Georgetown Inlier, is shown in Figure 3.3.

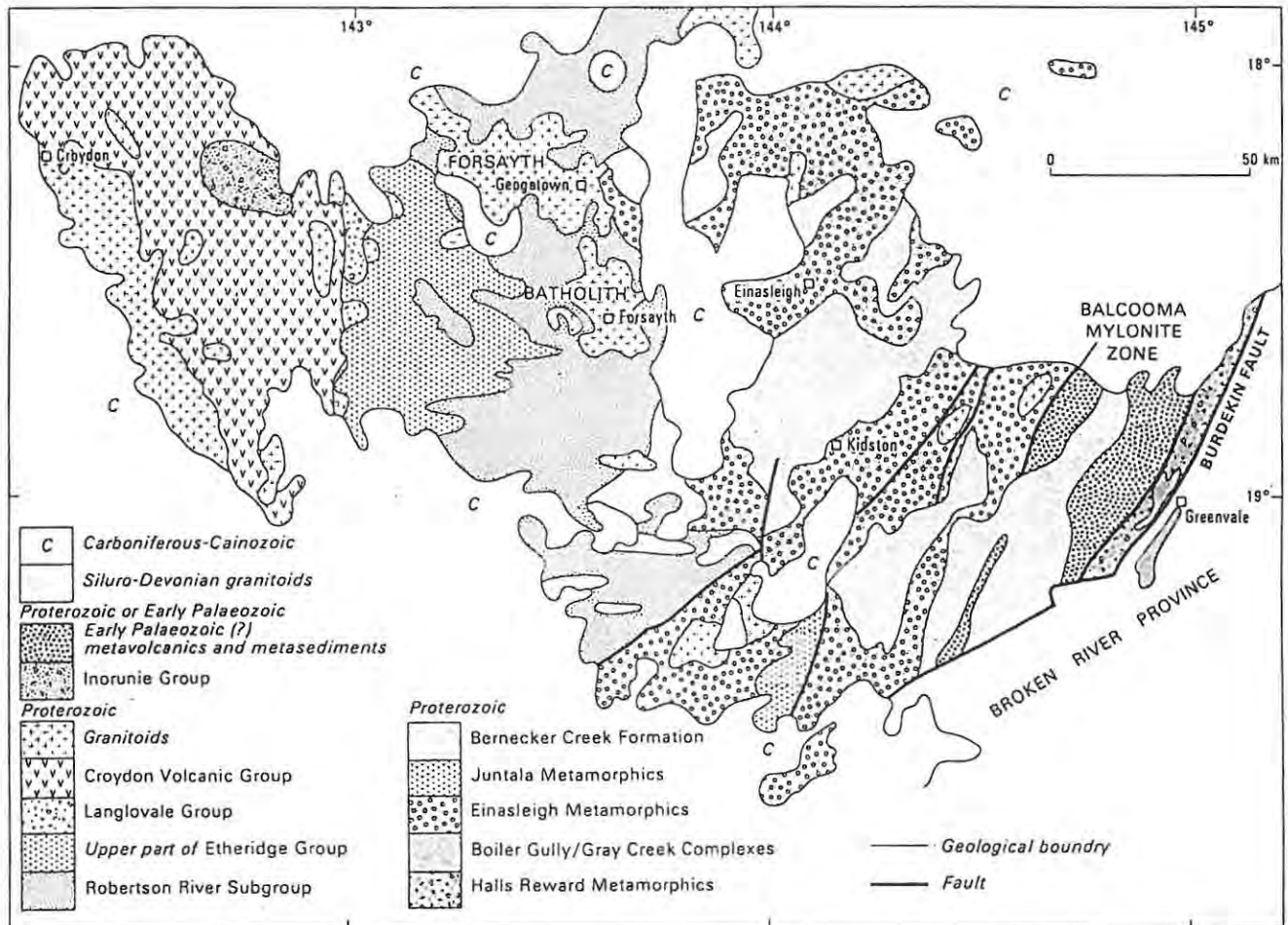


Figure 3.3 : Simplified geological map of the Georgetown Inlier (Bain *et al.*, 1990).

3.3.2 Proterozoic Stratigraphy

Etheridge Group. The Etheridge Group is the main component of the Forsayth Subprovince, and crops out over about half of the Georgetown Inlier (as shown in Figure 3.3). Its constituent units and their relationships are shown in Figure 3.4. The base of the Etheridge Group is not exposed and its age is uncertain. The lowermost known part of the group is the Bernecker Creek Formation, although parts of the Einasleigh Metamorphics could be stratigraphically lower.

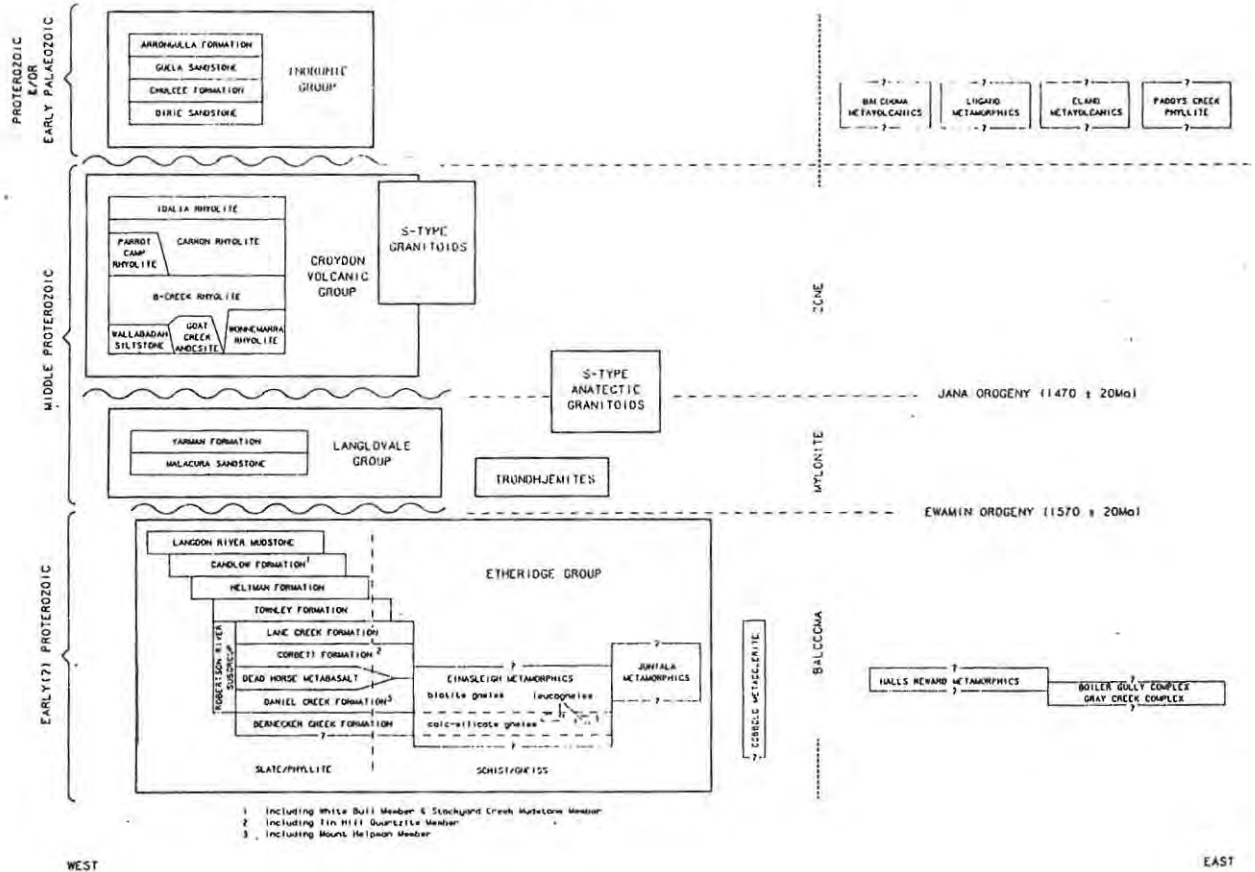


Figure 3.4 : Proterozoic stratigraphic relationships in the Georgetown Inlier (Withnall *et al.*, 1988a).

The grade of metamorphism increases eastwards, and the lower half of the Etheridge Group passes into medium- to high-grade metamorphic rocks. These higher-grade rocks were originally assigned to separate units, the Robertson River Metamorphics and Einasleigh Metamorphics, both of which were thought to be a basement to the rest of the sequence, and possible Archaean in age. The less intense deformation of the low-grade

rocks has allowed the recognition of a detailed stratigraphy which has been traced into the higher-grade, more intensely deformed rocks. Those formations that extended into what were originally mapped as Robertson River Metamorphics, are assigned to the Robertson River Subgroup. Parts of the Einasleigh Metamorphics also grade into some of the lower-grade units.

In general, the Einasleigh Metamorphics are probably equivalent to the Bernecker Creek and Daniel Creek Formations. Zones of Einasleigh Metamorphics, dominated by calc-silicate (hornblende-diopside) gneiss, were probably derived from calcareous to dolomitic psammitic rocks, like those in the Bernecker Creek Formation; the Bernecker Creek Formation can be traced eastwards into calc-silicate gneiss, but it is uncertain whether all areas of calc-silicate gneiss in the Einasleigh Metamorphics are stratigraphically equivalent to the Bernecker Creek Formation (Withnall *et al.*, 1988a)

One significant lithology, in the Einasleigh Metamorphics, with no known low-grade equivalent, is leucogneiss; it is locally associated with metamorphosed, sub-economic, stratiform, base metal sulphide deposits, and generally forms sporadic lenses or beds interlayered with the calc-silicate gneiss facies near contacts with biotite gneiss. The leucogneiss generally contains high Na_2O , (5-9%) and some samples are enriched in Zr (up to 900 ppm) (Withnall, 1984). Bain *et al.* (1985) interpreted the leucogneiss as high-Zr, 'A-type', felsic volcanic rocks. Withnall (1984) suggested that it was either albitised, felsic tuff, or feldspathic dune or beach sand containing concentrations of heavy minerals.

The Juntala metamorphics are mainly mica-schist, lithologically similar to the high-grade parts of the Corbett Formation.

The intense deformation and metamorphism has obliterated most sedimentary structures other than lithologic layering in the Einasleigh and Juntala Metamorphics, so it is not possible to determine directly their environment of deposition. However, primary sedimentary features are well preserved in the low-grade parts of the other units, and these are summarised in Figure 3.5.

The Bernecker Creek Formation (>2000 m) consists predominantly of calcareous to dolomitic, fine-grained, sub-feldspathic sandstone, siltstone, and mudstone deposited in a wave-dominated shoreline to tidal flat environment (Withnall *et al.*, 1988b).

LITHOLOGY	Sedimentary feature		Bedding														INTERPRETED ENVIRONMENT						
	Stratigraphic unit	Lamination	3m-scale trough & stratification	Planar cross stratification	Scour and fill	Flaser	Wavy	Lenticular	Clay drapes	Asymmetric ripplemarks	Climbing ripples	Wrinkled surface	Flute marks	Other current facies	Sandstone dykes	Load casts		Contorted stratification	Mudclasts	Evaporite-dissolution bases	Siliceous siltstone	Concretions	Gypsum molds
INDRUMIE GROUP		P	C	C						P									P				FLUVIATILE
CROYDON VOLCANIC GROUP		<i>rhyolitic ignimbrite, rhyolite, dacite, basalt andesite</i>																				SUBAERIAL IGIMBRITE	
YARMAN FORMATION		C	C							P			P	P				R					TURBIDITE (PRODELTAIC)
MALACURA SANDSTONE		P-C	P					R	R	P				P	P		C				R		FLUVIATILE TO DELTAIC
LANGDON RIVER MUDSTONE		C	R					R	R							R	P						DEEP SUBTIDAL
UPPER CANDLOW FORMATION		C						R										C		R	P	R	INTERTIDAL-SUBTIDAL
Stockyard Creek Mudstone Member																							DEEP SUBTIDAL
MIDDLE CANDLOW FORMATION		C						R	R						R		C	C-R					SUBTIDAL
White Bull Member		P															P	P		C			SUBTIDAL
LOWER CANDLOW FORMATION		C	P	P				R									P	C		R	P	P	INTERTIDAL-SUBTIDAL
HELMAN FORMATION		U	C	R											P	P	C	C		C			SUBTIDAL
		M	C														P			R			SUBTIDAL
		L	C														P	C	C	C			SUBTIDAL
TOWNLEY FORMATION		U	C	R											P		C	P		R			SUBTIDAL
		M	P																				SUBTIDAL
		L	P														C	P			R		SUBTIDAL
LANE CREEK FORMATION		C	R												P		C	P		R			DEEP SUBTIDAL
UPPER CORBETT FORMATION		R																					DEEP SUBTIDAL
Tin Hill Quartzite Member		R																					? CHEMICAL SEDIMENT
LOWER CORBETT FORMATION		C-R													R		P						DEEP SUBTIDAL
DEAD HORSE METABASALT		<i>hyaloclastite; pillows; amygdalae; interbedded sediments and siliceous rock</i>																				SUBMARINE BASALT	
DANIEL CREEK FORMATION		P	P	R	C		R	R		R	P				P	P	R	P	P		C		? SANDY DELTA
BERNECKER CREEK FORMATION		C	C	R		P	P	P	P	P	R	P	P	P	P	P	P	P	P	P	P	P	WAVE-DOMINATED SHORELINE

Figure 3.5 : Summary of sedimentary features, Early to Middle Proterozoic rocks of the Georgetown Inlier (Withnall *et al.*, 1988a).

The overlying Daniel Creek Formation (1000 to 2000 m) is less calcareous or dolomitic and more pelitic overall. It was probably deposited in a deltaic environment. In the southern part of the inlier it is overlain by the Dead Horse Metabasalt (up to 1000 m).

The overlying Corbett Formation (1000 m) consists mainly of monotonous mudstone and minor metachert, and is interpreted as a deep water facies. Carbonaceous mudstone, and minor, thin marly limestone in the succeeding Lane Creek Formation (1000 to 2000 m), suggest continuation of the deep water conditions (Bain *et al.*, 1990).

The Daniel Creek, Corbett, and Lane Creek Formations, and Dead Horse Metabasalt, comprise the Robertson River Subgroup. They grade eastwards into medium- to high-grade mica-schist, quartzite and amphibolite. The Lane Creek Formation and underlying units are intruded by metadolerite sills of the Cobbold Metadolerite. Withnall (1985) showed that the Cobbold Metadolerite, Dead Horse Metabasalt, and amphibolite in the Einasleigh Metamorphics, are low-potassium tholeiites similar to modern mid-ocean ridge basalts.

The units forming the upper part of the Etheridge Group are made up of different proportions of siltstone, carbonaceous mudstone, siliceous siltstone, fine-grained sandstone, and rare thin limestone. The presence of soft-sediment deformation features such as slumping, distorted bedding, disrupted laminae, sandstone/siltstone dykes, load casts, flame structures, and water-escape structures indicate rapid deposition. However, evidence of channelling and scouring is rare.

The overall fine grain-size in the upper part of the Etheridge Group, and the local presence of gypsum, suggest muddy tidal-flat sedimentation as in the Colorado River delta. Low wave energy, a copious supply of silt and clay relative to sand, and unrestricted non-channelled tidal flow, have resulted in laminated muddy flats (Thompson, 1975). Local supra-tidal conditions may have allowed the formation of gypsum. The mud-clast sandstones are interpreted as reworked, algal-bound sediment in shallow water. Massive, carbonaceous mudstone intervals, such as the Stockyard Creek Mudstone Member and Langdon River Mudstone (the uppermost unit in the Etheridge Group), were probably deposited in deeper water and escaped reworking.

The only igneous rocks in the upper part of the Etheridge Group are a few thin (<3 m) layers of albitite of uncertain origin.

Langlovale Group. The Middle Proterozoic Langlovale Group, unconformably overlies the Etheridge Group along the western edge of the Forsayth Subprovince (Figure 3.3), and post-dates the Ewamin Orogeny (D_1 in the Etheridge Group). The group is preserved only in a narrow strip a few kilometres wide and 40 km long, between the Etheridge Group and Croydon Volcanic Group to the west.

The lowermost unit of the Langlovale Group, the Malacura Sandstone, consists predominantly of micaceous feldspathic sandstone. Poor sorting, a wide range of grain sizes, high feldspar content, and abundant mica, indicate a high degree of immaturity. This immaturity and the presence of channels, mud-clast lag gravels and trough cross-bedding, are suggestive of a fluvial environment. However, towards the top of the unit, common wavy and lenticular bedding, and an upwardly increasing mudstone content, indicate a change to shallow, near-shore marine sedimentation.

The Malacura Sandstone passes gradationally up into the Yarman Formation, which consists of massive to laminated mudstone with sporadic intervals in which sandstone beds are common. The sandstone intervals have many characteristics of classic, distal turbidites (fine grain size, presence of flute marks, lack of scours and channels, well-developed mudstone interbeds, and lack of amalgamation of the thin, parallel-sided, regular beds). The association with the underlying fluvial sequence of the Malacura Sandstone suggests proximity to a delta. Locally, thick-bedded, ripple cross-laminated sandstone becomes more abundant, and may represent prograding of delta lobes. Limited palaeocurrent data suggest transport from the south (Withnall *et al.*, 1988a).

Croydon Volcanic Group. The Croydon Volcanic Group unconformably overlies the Langlovale Group, and is of Middle Proterozoic age. It is the dominant unit of the Croydon Subprovince in the west of the Georgetown Inlier (Figure 3.3). Subaerial rhyolitic to dacitic ignimbrite dominate the group, but it also includes minor siltstone, sandstone and basaltic andesite. The Langlovale Group is confined to a large volcanic subsidence structure, 120 by 50 km, and are intruded by comagmatic, subvolcanic granitoids. Quartz veins containing gold, silver and base metals are associated with the granite, particularly in zones rich in graphitic xenoliths, and in fracture systems in the volcanic rocks; Sn deposits occur in greisens associated with late phase granites.

Inorunie Group. The Inorunie Group overlies the Croydon Volcanic Group disconformably, and is preserved in a small, partly fault-bounded, basinal structure 20 by

15 km (Figure 3.3). It consists of strongly indurated, quartzose sandstone, micaceous sub-lithic sandstone, siltstone and mudstone. Common medium- to large-scale trough cross-bedding in the quartzose sandstone, suggests a fluvial environment, although no detailed sedimentological studies have been undertaken. The Inorunie Group is probably Middle or Late Proterozoic or early Palaeozoic. It is intruded by Permian dolerite and granodiorite, and clasts of the quartzose sandstone occur in Early Carboniferous conglomerate.

Eastern Georgetown Inlier. The eastern part of the Georgetown Inlier, the Greenvale Subprovince, is separated from the rest of the inlier by the Balcooma Mylonite Zone. The rocks of this part were previously considered to be Proterozoic in age, but are now thought to be mainly early Palaeozoic (Withnall, 1985). They are tentatively correlated with similar volcanic rocks of known Cambro-Ordovician age, 200 km to the southeast near Charters Towers, and also with some Late Ordovician intermediate volcanic rocks in the western part of the adjacent Broken River Province. However, no reliable radiometric ages are available, and a Proterozoic age cannot be ruled out.

3.3.3 Deformation

The Etheridge Group was deformed by at least two major folding events in the Proterozoic, both of which were associated with metamorphism. In the western and southern parts of the area, D_1 (the Ewamin Orogeny) is characterised by tight, upright to overturned folds. These folds have wavelengths of 1-10 km, and a strong axial plane foliation, ranging from a slaty cleavage to a schistosity depending on the metamorphic grade. In the central and eastern parts of the Etheridge Group, overprinting during D_2 (the Jana Orogeny) makes identification of D_1 features difficult. F_1 folds form a somewhat arcuate pattern, changing progressively from east-west trends in the south, to north-northwest to south-southeast in the northwest.

The Jana Orogeny (D_2), formed generally north-south trending upright folds, with much shorter wavelengths (1-2 km) and common small-scale folds. In the eastern half of the area, the folding was very tight to isoclinal and associated with an axial plane foliation, ranging from a differentiated crenulation cleavage, to a strong layer-differentiated schistosity which obliterates S_1 . Deformation intensity diminishes westwards with the folds becoming more open and associated with simple non-differentiated crenulations. In the far western part of the Etheridge Group there is little obvious F_2 folding, although the

steep to moderate westerly dips in the Langlovale Group are attributed to the Jana Orogeny.

At least four additional episodes of folding are thought to have taken place in later Proterozoic and Palaeozoic time. The later events producing open folds in the central part of the inlier, and open to moderately tight folds in the eastern part.

3.3.4 Metamorphism

The Etheridge Group was affected by regional metamorphism at grades ranging from lower-greenschist facies in the southwest to granulite facies in the northeast (Figure 3.6). Southeast of the granulite facies 'core', the grade drops to lower amphibolite facies. The regional metamorphism accompanied D_1 and D_2 .

In the eastern half of the Etheridge Group, the strong overprint of syn- D_2 fabrics and mineral assemblages causes difficulties in determining the grade of metamorphism during D_1 . However, the area of amphibolite facies during D_1 appears to be roughly coincident with that during D_2 , although the maximum grade was probably lower than D_2 , when most of the migmatisation and granitoid genesis occurred. Extensive migmatisation was associated with the upper amphibolite and transitional granulite facies in the Einasleigh Metamorphics, and migmatitic granitoids were mobilised and intruded into the middle amphibolite facies zone.

Granulite facies mineral assemblages are restricted to mafic rocks; the enclosing metasedimentary rocks range from heterogeneous biotite gneiss and migmatite in the transitional zone, to relatively homogenous garnet-sillimanite-biotite granitic gneiss in the highest grade areas.

The studies of Bell and Rubenach (1983) on the sequential growth of porphyroblasts during D_2 , point strongly to a temperature rise during the development of S_2 crenulation cleavage; they suggested that this rise was related to emplacement of the Forsayth Batholith, which although regionally conformable with the isograds, locally cuts them.

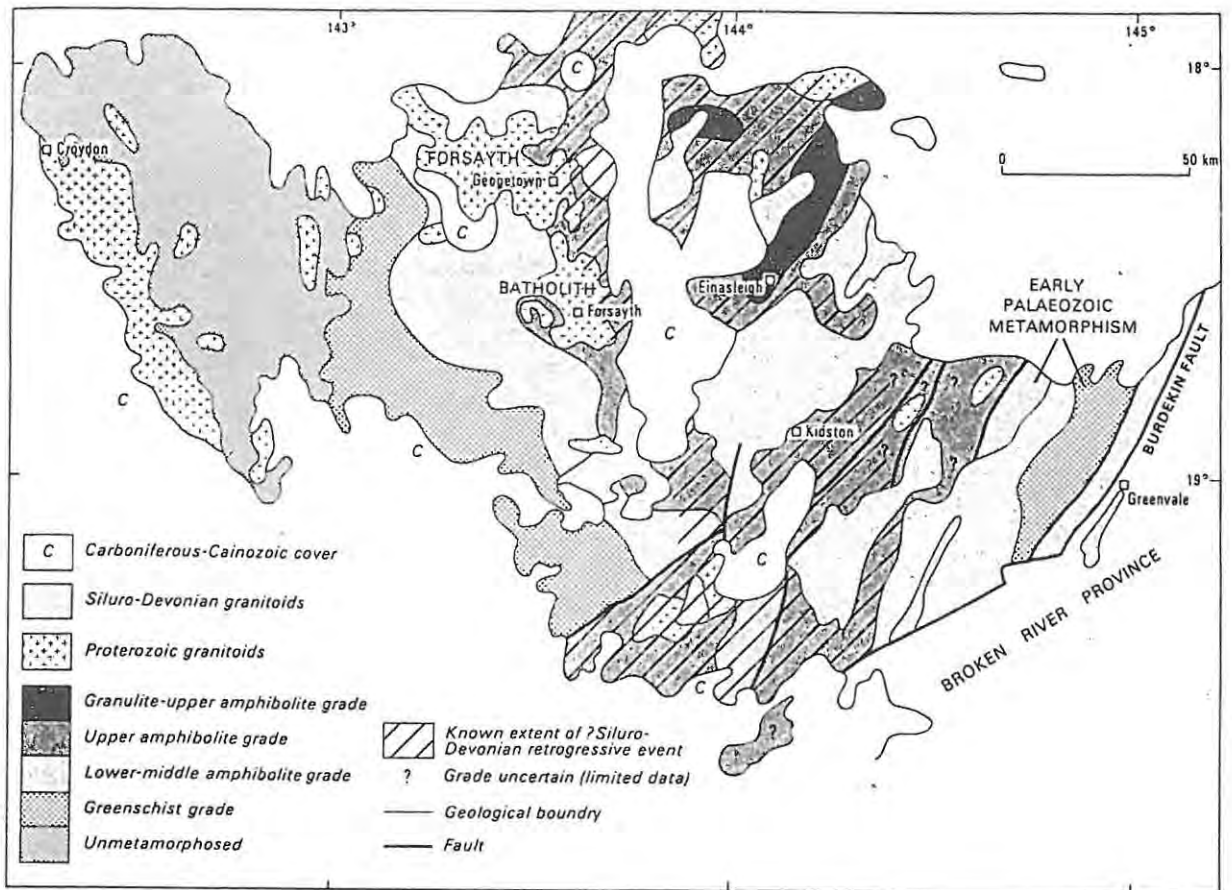


Figure 3.6 : Metamorphic map of the Georgetown Inlier (Withnall *et al.*, 1988a).

Minor retrogression of the prograde metamorphic assemblages occurred late or post- D_2 . A more extensive retrogression is evident in part of the area. It is thought to have occurred during the Late Silurian or Early Devonian when most of the region's gold deposits (which are clustered around the western margin of the retrogresses zone) are thought to have formed (Bain *et al.*, 1988). This event corresponds with the emplacement of extensive, mainly I-type batholiths, and partial to complete resetting of radiometric mineral ages.

The Langlovale Group, Croydon Volcanic Group and Inornie Group are essentially unmetamorphosed, except for contact metamorphism around exposed Proterozoic plutons and some isolated areas thought to be related to plutons at shallow depth.

3.3.5 Proterozoic Granitoids

The oldest granitoids in the Georgetown Inlier are small trondhjemite bodies dated at approximately 1550 million years old. Their chemistry, and very low $^{86}\text{Sr}/^{87}\text{Sr}$ initial ratios, suggest derivation directly from the mantle or by melting of lower crustal material during the Ewamin Orogeny (Withnall *et al.*, 1988a).

Most of the Proterozoic granitoids however, are S-types, formed during the 1470 million year Jana Orogeny, and intruded mainly into amphibolite facies rocks. Their geochemistry are characterised by high K_2O , U, Th, Y, Ce, Nb and La. The largest area of granitoid is the composite Forsayth Batholith, which consists of large plutons of variably porphyritic two-mica granite, as well as smaller plutons of early syn- D_2 migmatitic granitoids and late syn- or post- D_2 leucogranite. It is believed that much of the Forsayth Batholith resulted from mixing of anatectic melts derived from the Etheridge Group, or a similar metasedimentary parent, and more mafic mantle-derived magma.

The felsic igneous rocks of the Croydon Volcanic Group, are S-type, but differ significantly from the granitoids of the Forsayth Batholith. They are more mafic and more potassic, are highly reduced due to the ingestion of carbonaceous material, either at their source or in a near-surface magma chamber, and show weak fractionation trends; graphic xenoliths are common in both the granitoids and volcanic rocks (Withnall *et al.*, 1988a).

3.3.6 Tectonic Environment

Deposition of the Etheridge Group is thought to have taken place on continental crust, either on a broad, stable shelf or in an epicontinental sea. However, the inferred basement of continental crust is not exposed and its age is unknown.

The mafic rocks in the Etheridge Group show geochemical similarities to modern MORB, but as pointed out by Withnall (1985), they are also similar to low-potassium flood basalts of Greenland and Baffin Island, and (except for the low-potassium) to the incompatible element depleted Karoo basalts and dolerites. Therefore the geochemistry does not conflict with an intra-continental tectonic setting. Withnall (1985) suggested that the mafic rocks in the Etheridge Group may be the expression of convective mantle upwelling which produced extension of the crust, resulting in the formation of a shallow epicontinental sea. A temporary change from shallow-water to deep-water facies,

resulting from accelerated subsidence, followed the eruption of the Dead Horse Metabasalt.

The reason for the onset of metamorphism and deformation during D_1 is not known; a possible explanation for the rise in heat flow may be underplating of the crust. The close correspondence spatially of syn- D_1 and syn- D_2 metamorphism suggests that there may have been a single sustained event lasting at least 100 million years, reaching a peak during D_2 . In the western part of the inlier, post- D_2 , felsic, S-type magma reached the surface, and was erupted subaerially to form the Croydon Volcanic Group (Withnall *et al.*, 1988a).

Between D_1 and D_2 , the fluvial to marine Langlovale Group was deposited in the western part of the inlier. The tectonic significance of these rocks is uncertain because of their limited exposure and unknown original extent. They may represent a post-orogenic molasse facies west of the deformed terrain of the Etheridge Group, although their composition and limited palaeocurrent data, suggest a plutonic-metamorphic provenance to the south.

After the Croydon Volcanic Group was laid down in the Middle Proterozoic, and sometime before the Carboniferous, quartzose fluvial sediments of the Inorunie Group were deposited. Their original extent is also unknown.

The relationship of the Georgetown Inlier to the rest of the Australian Proterozoic terrains is uncertain. Correlation is difficult because the age of the Etheridge Group has yet to be determined. Etheridge *et al.* (1987) have presented a model of Proterozoic, ensialic, basin evolution, magmatism, and orogeny for northern Australia which could provide constraints on the age of the Etheridge Group. However, the Georgetown Inlier differs from the other terrains and does not fit the model particularly well, and hence some of the constraints may not be valid.

Etheridge *et al.* (1987) have recognised two major tectonostratigraphic cycles separated by an extensive orogenic and magmatic event between 1920 and 1820 million years (particularly from 1880 to 1850 million years) in northern Australia. They postulated that lithospheric stretching and mantle-derived magmatism were related to small-scale mantle convection that began between 2200 and 2000 million years ago, resulting in underplating of the crust. The underplated mafic material was the source for the extensive I-type magmatism in the orogenic phase between the cycles. Each cycle commenced with a

period of crustal extension and rifting, accompanied by extensive bimodal volcanism and coarse fluvial sedimentation, representing the 'rift phase'. The 'rift phase' of each cycle was followed by a transgressive, finer-grained, clastic sequence (commonly carbonaceous and containing abundant carbonates) which represents wide-spread post-extensional subsidence, the 'sag phase'. A turbiditic or molasse facies is present in some terrains in the early cycle and may mark the beginning of the orogenic phase. The pre-1920 million year cycle contains fewer igneous rocks, and mafic compositions are dominant, whereas the second cycle has felsic rocks (A-type) throughout, and mafic rocks concentrated in the 'rift phase'.

The lack of felsic igneous rocks in the Etheridge Group (with the possible exception of the leucogneiss in the Einasleigh Metamorphics) suggests a correlation with the first cycle. However, evidence for the 1920-1820 million year orogenic event is conspicuously absent. This could suggest that the rocks belong to the second cycle, although not all Early Proterozoic sequences are intruded by granite at this time. Because of the lack of evidence for rifting (no coarse clastic sedimentary rocks, penecontemporaneous faults, or rapid thickness changes along strike) the Etheridge Group would correspond mainly with the 'sag phase'. The 'rift phase' (if it exists) must occur below the Bernecker Creek Formation, either at depth or beneath younger rocks beyond the Georgetown Inlier. The mafic rocks in the Etheridge Group may reflect the final stages of the extensional part of the cycle. The Langlovale Group could represent the 'molasse phase', except that it post-dates D₁ (Withnall *et al.*, 1988a).

The deformation history of the Georgetown Inlier differs from that of the other Proterozoic terrains of northern Australia in the lack of nappe-style deformation. The granitoids emplaced during D₂ are also different in that they are exclusively S-type. By contrast, the felsic igneous rocks of other terrains, such as Mount Isa, appear to be mainly I- or A-type (Wyborn, 1981). The relatively low-pressure metamorphism is typical of the other terrains.

Etheridge *et al.* (1987) noted that there is no evidence for the formation of oceanic crust during either of the two cycles in northern Australia. The bimodality of orogenic magmatism and absence of andesitic compositions is also a feature of northern Australian Proterozoic terrains. It is one reason for assigning an early Palaeozoic age to the metavolcanic sequences in the eastern part of the Georgetown Inlier, apart from similarities to known early Palaeozoic rocks in the region. If they should prove to be

Proterozoic, they would not fit with the model of ensialic orogenesis. However, the Proterozoic craton presumably had an edge somewhere, and perhaps subduction and island-arc-style magmatism occurred on this edge (Withnall *et al.*, 1988a).

3.3.7 Economic Geology

The deposits associated with the **Precambrian** time period are as follows :

Metamorphosed Stratabound and/or Stratiform Base Metal Deposits. The Einasleigh Metamorphics host more than twenty small base metal deposits in the Einasleigh and Gilberton districts. These are generally massive stratabound concentrations of iron and copper sulphides \pm silver (e.g. Einasleigh), iron and zinc sulphides (e.g. Eveleigh), iron-lead-zinc-copper sulphides \pm silver (e.g. Mount Misery), and cupriferous, ferruginous, siliceous and barytic gossans (e.g. Werrington area). They have been regarded as epigenetic, fracture-controlled deposits of Archaean, Proterozoic, or even late Palaeozoic age. The deposits are apparently concentrated at a common stratigraphic level within the Einasleigh Metamorphics: at the transition between a lower, dominantly calcareous psammitic sequence and an upper psammopelitic sequence. Epidote-diopside quartzite and gneiss, that may be of volcanic origin, are commonly associated with these deposits.

Mafic/Ultramafic Associated Nickel-Cobalt and Chromium Deposits. Podiform chromite deposits and nickel-cobalt bearing laterites are confined to the Boiler Gully and Grey Creek complexes on the Halls Reward, Minnamoolka and Gunnawarra districts. The principal nickel-cobalt bearing Cainozoic laterite deposits are Greenvale (40 million tonnes of ore averaging 1.57% nickel and 0.12% cobalt), Gunnawarra (9.8 million tonnes of ore at 1.55% nickel, aggregate of three deposits), and Minnamoolka (3.15 million tonnes of ore at 1.27% nickel, aggregate of four deposits).

Quartz Vein Gold Deposits. The deposits of the Croydon gold field, the second most productive in the Georgetown Inlier, occur in the Croydon Volcanic Group and Esmeralda Granite within 20 km of Croydon. Most of the gold produced, came from deposits near Croydon in the roof zone of a biotite granite pluton (Esmeralda Granite). The pluton was intruded to the base of the highest preserved unit of the Croydon Volcanic Group (Mackenzie *et al.*, 1985).

The principal lodes consist of numerous shallowly dipping, subparallel, quartz reefs in sheared granite. They are up to several kilometres long, extend down dip at least 400 m, and although generally about 10 m wide, they are commonly widest and richest where they traverse graphitic zones in the granite, interpreted as preserved roof zones of successive intrusions. The reefs contain graphite, arsenopyrite, minor pyrite, galena and sphalerite, and traces of gold (electrum), copper, and rarely, native silver. Gold to silver ratios tend to decrease with depth. Ore shoots also occur at the intersections of the lodes with westerly dipping reverse faults, but they do not extend down dip beyond the faults.

Lodes up to 3 km long in the volcanics are commonly simple pyritic quartz reefs that are mostly narrow (about 1 m wide) and near vertical. Shallow dipping lodes tend to be Proterozoic, as they are associated with extensive areas of hydrothermal alteration that appear to be related to the volcanism, and there are no nearby Palaeozoic igneous rocks (Bain *et al.*, 1990).

Vein Deposits of Tin in Granite and Ignimbrite. The two principal concentrations of cassiterite bearing lodes exist in the Esmeralda Granite and Croydon Volcanic Group, at Stanhills and Mount Cassiterite. The deposits, comprising irregular seams or shoots of cassiterite in dyke-like zones of greisen (Warnick, 1985), are spatially closely associated with cupolas of fine-grained Nonda Granite that intrude the Middle Proterozoic Esmeralda Granite and the uppermost unit of the Croydon Volcanic Group (Mackenzie *et al.*, 1985).

The deposits associated with the **Siluro-Devonian** time period are as follows :

Quartz Vein Gold-Silver Deposits. The quartz vein deposits of the Etheridge gold field are mostly hosted by Proterozoic granite. However, Silurian and Devonian aged deposits have been genetically linked to the Cape York Plutonic Belt.

The gold field lies parallel to, and immediately west of an extensive zone of greenschist facies retrograde metamorphism, which overprints amphibolite grade schist and gneiss, (Etheridge Group) and Middle Proterozoic mica granites. This metamorphic zone is spatially and temporally associated with batholiths of the Cape York Plutonic Belt.

The gold reefs are single and composite quartz veins, 10 cm to 5 m thick, in generally steeply dipping fracture or shear zones in granite, schist or metabasalt. Most have narrow, generally chloritic or propylitic alteration envelopes, although some wider systems also

contain sericitic alteration zones. They are mostly grouped in clusters 1 to 5 km across, and concentrated in the Forsayth Batholith. Reefs within a cluster mostly have a common orientation, and all reefs have at least one of the dominant regional fault, fracture or lineament trends.

Below the water table, the mineralised parts of the quartz reefs are typically strongly pyritic, but also contain galena, sphalerite and chalcopyrite (to 50% of total sulphides). No distinct or regional metal zoning patterns have been defined, although there is some suggestion that deposits on the eastern side of the field are most likely to have accessory copper. Silver-lead veins of unknown age and affiliation are mostly on the western side of the field.

Stopes in the old mines suggest that ore shoots have lateral dimensions of 20 to 200 m, and few mines were worked to depths greater than 100 m.

Preliminary studies of ore-fluid characteristics (Bain *et al.*, 1988) indicate that the mineralising fluids were at temperatures of 200 to 350°C, had salinities of about 6 to 10 wt % equivalent NaCl, and contained SiO₂, H₂O, CO₂, S and metals. Oxygen isotope values of vein quartz indicate that the veins formed from fluids with $\delta^{18}\text{O}_{(\text{SMOW})}$ values of about +5 to +9 per mil. Microthermometric data from fluid inclusions indicate fluid homogenisation temperatures of about 200 to 350°C. The highest temperatures correspond with the highest $\delta^{18}\text{O}$ values, and collectively these data suggest that the ore fluid may have been highly modified meteoric water, or had a significant magmatic component. Meteoric fluid (negative or low positive $\delta^{18}\text{O}$ values) was apparently involved in at least one deposit. The other deposits have intermediate values, suggesting a mixing of meteoric and magmatic fluids, or extreme modification of meteoric fluid.

The deposits associated with the **Early Permian** time period are as follows :

The oxidised compositions of the Middle to Late Carboniferous I-type magmas, and extended fractionation involving removal of phases such as hornblende, biotite and sphene, are favourable for enrichment of elements such as tungsten, molybdenum and base metals in the magmas, and thus into potentially ore forming residual fluids. Under oxidising conditions, elements such as tungsten and molybdenum tend to be partitioned into the liquid, whereas elements such as tin are more strongly partitioned into fractionating minerals. In contrast, reduced compositions, a scarcity of fractionating ferromagnesian

minerals, and high fluorine contents in the Permian A-type magmas are more favourable for enrichment of metals such as tin and uranium in metals or fluids. In addition, the shallow level of emplacement of felsic A-type magmas would enable generation of ground water-dominated hydrothermal systems.

It has been observed that mineral deposits associated with post-orogenic, ignimbrite-dominated, extrusive sequences are commonly formed appreciably after the major eruptive stage(s). A critical factor, apart from fluid and metal availability, and fluid chemistry and temperature, is the occurrence of zones of high permeability, such as faults with a history of recurrent structural instability. Fracture-intrusion systems in and around cauldron structures may represent such zones, and eruptive vents may be preferentially developed along them. In the Precambrian inliers, roughly north and east trending (Carboniferous) and northwesterly (Permian) fracture-intrusion systems, and their intersections, appear to be most prospective for a variety of precious and nonferrous mineral deposits (Bain *et al.*, 1990).

Deposits Associated with Shallow-Level Felsic Intrusions. Tin, tungsten, molybdenum and bismuth vein, pipe, greisen and skarn deposits are the most abundant deposits in the region, but are mostly confined to late Palaeozoic igneous rocks or adjacent earlier Palaeozoic metasediments.

The breccia pipe gold deposits, such as Kidston, are clearly formed by Permian and Carboniferous magmatic hydrothermal systems associated with subvolcanic intrusive components of the Coastal Ranges Igneous Province. Early (pre-main stage breccia) stockwork molybdenum mineralisation in these deposits suggest a close link with the porphyry-type copper-molybdenum deposits.

Gold and base metal skarn deposits are confined to the Chillagoe-Mount Garnet district, virtually the only extensive area of carbonate rocks intruded by subvolcanic magmas.

The O'Briens Creek topaz field, northwest of Mount Surprise, is the source of most of Australia's best gem quality topaz. Cainozoic alluvial deposits of topaz and small amounts of beryl and aquamarine, derived from pegmatites and greisens within the Carboniferous Elizabeth Creek Granite, are worked by both full time and weekend fossickers.

Diamonds of unknown age and origin have been found in the gravels of the O'Briens Creek field. A possible source of the diamonds may be placers in Mesozoic sandstone which cap the hills near the Lancewood Creek, in which case the primary source could have been more distant (Bain *et al.*, 1990).

Deposits Associated with Felsic Volcanism and Related Hydrothermal Activity. There are many small uranium-fluorine-molybdenum deposits known in the region, but most are minor mineral occurrences or radiometric anomalies. Most deposits are associated with the extensive late Palaeozoic continental felsic volcanics and related intrusives of the Coastal Ranges Igneous Province.

Silver-Base Metal Vein Deposits of Unknown Affiliation. Numerous silver-rich base metal sulphide veins occur within the Precambrian metamorphics. Although some of these deposits are late Palaeozoic, some may be much older, even Middle Proterozoic. They include silver-lead deposits consisting of discontinuous lenses and pods of galena, and minor pyrite, sphalerite and chalcopryrite in quartz-siderite-dolomite veins. These are mostly in 1 to 2 m wide dislocation zones cutting carbonaceous schist and phyllite in the Robertson River Subgroup, and less commonly gneiss in the Einasleigh Metamorphics.

Small silver-copper deposits, consisting of chalcopryrite and pyrite, in quartz-siderite veins in en echelon shears or fractures, occur in Precambrian rocks (usually metabasics but also quartzite, gneiss and schist) and less commonly in Carboniferous subvolcanic intrusives. Wall rock alteration is mostly absent.

The copper-rich veins tend to be located within basic rocks and the lead-rich veins in metasediments, suggesting that rock composition in the immediate vicinity of the deposits may have determined the ultimate composition of the mineralising fluids. The presence, in some of the copper-silver veins in the Einasleigh Metamorphics, of elements typically associated with Carboniferous mineralisation (uranium, tin and fluorine), and the proximity of the veins to similar deposits in Late Carboniferous subvolcanic granite, suggest that at least some of these Precambrian hosted deposits formed in Carboniferous time. The lead veins tend to be spatially associated with, and to have similar $\delta^{18}\text{O}$ quartz values to, the gold bearing veins of the Etheridge gold field, suggesting that some deposits may have formed in Silurian or Devonian time as part of the Etheridge gold field metallogenic event (Bain *et al.*, 1990).

4.0 Gold-Related Volcanogenic Breccia Complexes

4.1 Introduction

Much of north Queensland was the emplacement of granitic batholiths and eruption of comagmatic silicic volcanics in Late Carboniferous to Late Permian time. The magmatic activity was not influenced by previous tectonic boundaries. It extended over the northern part of the Thomson Fold Belt, the whole of the Hodgkinson and Broken River Fold Belts, and much of the Precambrian Georgetown-Coen Province. Scattered plutons and volcanic outcrops occur as far north as Torres Strait (Willmott *et al.*, 1973). Numerous and varied mineral deposits are associated with the silicic magmatism.

The intrusive rocks range from small plutons and ring complexes to large batholiths. Petrographically and chemically they are dominantly I-type granitoids, but S-type intrusions are present in some areas. Many granites with related tin mineralisation have been pervasively altered by late-stage hydrothermal fluids (Murray, 1986).

Geochemical data and isotopic age determinations, strongly support a comagmatic origin for the intrusive and extrusive rocks of the North Queensland Volcanic and Plutonic Province. Isotopic age determinations on volcanics range from 321 to 267 million years which is the main period of granite emplacement. The isotopic dates are supported by sparse palaeobotanical collections from associated sediments, mainly at the base of the volcanic sequences (Murray, 1986). Detailed geochemical studies of individual volcanic suites suggest that they formed at an Andean-type continental margin above a west dipping subduction zone (Bailey *et al.*, 1982).

Several bulk tonnage low-grade gold deposits have been recognised which are related to the Late Carboniferous - Permian magmatism. The most widely-spread type occurs in breccia complexes, such as those at Mount Leyshon, Kidston and Mount Wright deposits (Figure 4.1). The following chapter describes these three breccia complexes and then discusses the characteristics similar to each deposit. These characteristics will then be used to establish exploration parameters in chapter five.

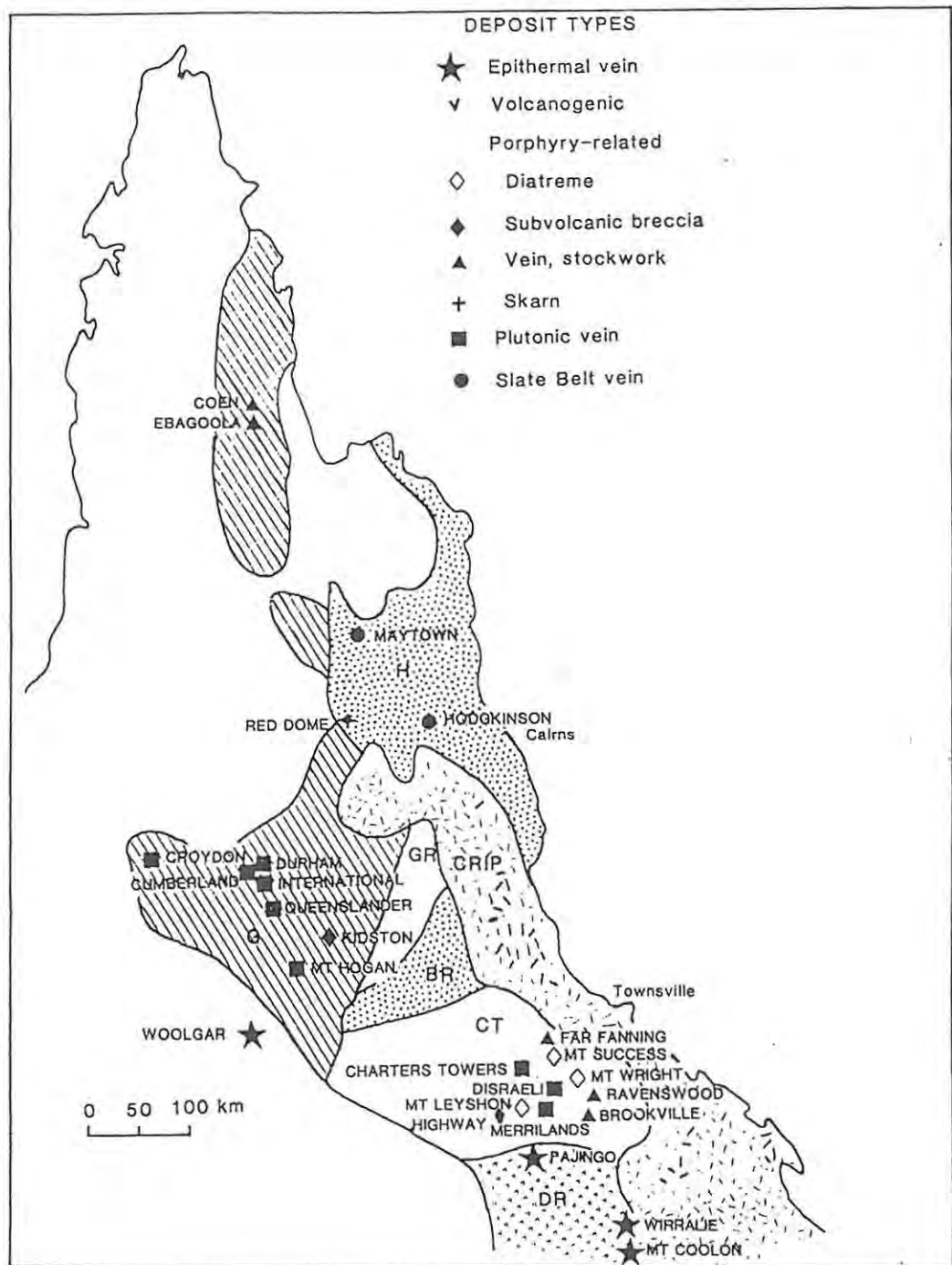


Figure 4.1 : Distribution of the major gold deposits with respect to structural-tectonic provinces of northeast Queensland. The provinces are : G = Georgetown, GR = Greenvale, CT = Charters Towers, H = Hodgkinson, BR = Broken River, DR = Drummond, CRIP = Coast Range Igneous Province (Morrison, 1988).

4.2 Mount Leyshon Gold Mine

4.2.1 Introduction

The Mount Leyshon gold mine breccia complex is located 24 km south of Charters Towers in northeast Queensland. The name 'Mount Leyshon' was given to the highest peak in a group of prominent 'pyramidal' hills rising above a gently undulating plain.

The breccia complex lies within a major east-west trending terrain, the Lolworth-Ravenswood Block (Peters, 1987), composed mainly of Cambrian to Permian granitoid rocks, with remnant metamorphic complexes and meta-volcano-sedimentary sequences (Wormald *et al.*, 1991). The principal host to the mineralisation is a breccia pipe, approximately 300 m in diameter, in the northwest of the breccia complex. The geological evolution of the Mount Leyshon breccia complex is represented in Table 4.1.

The open pit mining operation is based on conventional shovel and truck techniques on 10 m benches. All waste is trucked to dumps, while ore is either delivered directly to the primary crusher, or taken to a run-of-mine dump, or a low-grade stockpile for later processing. Initial supergene ore was stockpiled for future processing of the copper and gold. The primary sulphide ore is treated using a hybrid of CIL (carbon-in-leach) and CIP (carbon-in-pulp) cyanide leach processes with a 92% gold recovery.

Ore reserves were upgraded in June 1992 to 36.32 million tonnes of primary ore at 1.75 g/t gold. Calculations of the ore reserves are by log-normal kriging. Current mining operations produce approximately 4.2 million tonnes of primary ore for 220000 oz of gold per year.

4.2.2 Exploration and Production History

Even though gold was discovered at Mount Leyshon in 1872, official records of production only began in 1887 (Hedenquist and Lindqvist, 1985). Underground and open cut mining operations up to 1916, produced 200000 tonnes of ore averaging 6.2 g/t Au from oxidised veins, fractures and breccia fillings (Morrison *et al.*, 1988). A number of small open cuts were developed immediately south of the summit in relatively rich disseminated ore within the main breccia body. There are no records of early alluvial production, although this was probably quite significant (Paull *et al.*, 1990).

Breccia and Magmatic Phases	Geological Events	Rock Types	Related Alteration	Mineralisation	Age
Pre-breccia Phase 1	1. Deposition of Puddler Creek Formation	Metamorphosed sandstones, siltstones, and greywackes	-	Pyrite, minor chalcopyrite and gold	Cambrian
Pre-breccia Phase 2	2. Intrusion of the Ravenswood Batholith Complex	I-type granites, granodiorites and porphyritic variants	-	Pyrite, pyrrhotite (?), minor gold	Ordovician-Devonian
Breccia Phase 1	3. Intrusion of the Main Pipe breccia	Matrix-supported breccia with clasts of previous rock types	Sericite-pyrite-biotite	Pyrite and pyrrhotite	Permo-Carboniferous
Magmatic Phase 1	4. Intrusion of porphyry phase I in the eastern part of the Main Pipe breccia and as 'early' dykes	Quartz-feldspar porphyry with 5% feldspar and <1% quartz phenocrysts	Carbonate-sericite-pyrite	Pyrite and minor chalcopyrite	Permo-Carboniferous
Magmatic Phase 2	5. Intrusion of porphyry phase II in the eastern part of the Main Pipe breccia.	Xenolithic quartz-feldspar porphyry which has the appearance of a breccia	Carbonate-sericite±base metal sulphides	Sphalerite, chalcopyrite, silver, and gold	Permo-Carboniferous
	6. Development of a quartz-molybdenite vein system	Quartz-molybdenite veins	Potassium feldspar	Molybdenite	Permo-Carboniferous
Magmatic Phase 3	7. Intrusion of porphyry phase III in the eastern part of the Main Pipe breccia.	Quartz-feldspar porphyry with 35% phenocrysts of quartz	Sericite-carbonate-pyrite±base metal sulphides	Pyrite, sphalerite, chalcopyrite, silver, and gold	Permo-Carboniferous
Breccia Phase 2	8. Intrusion of the Mount Leyshon breccia in the northwestern part of the Main Pipe breccia and the Mount Hope breccia to the south.	Clast-supported breccia with clasts of previous rock types	Pyrite-chlorite-quartz-sericite-carbonate-base metal sulphides	Pyrite, sphalerite, chalcopyrite, galena, bismuthinite, silver, and gold	Permo-Carboniferous
Breccia Phase 3	9. Intrusion of tuffisite and breccia dykes	Well-sorted fine-grained tuffisite and poorly sorted matrix supported breccia	Carbonate-sericite-pyrite-base metal sulphides	Sphalerite, galena, bismuthinite, chalcopyrite, pyrite, minor gold	Permo-Carboniferous
Magmatic Phase 4	10. Intrusion of porphyry phase IV and 'late' dykes	Quartz-feldspar porphyry with 30% phenocrysts	Carbonate-sericite-pyrite	Pyrite	Permo-Carboniferous
Post-breccia Phase 1	11. Late-stage intrusion of basic dykes	Trachy-andesite	Carbonate	Not Mineralised	Permo-Carboniferous

Table 4.1 : The geological evolution of the Mount Leyshon breccia complex.

Approximately 92000 t of tailings were cyanided during the early years of World War II, yielding 185 kg of gold.

Recognition of the true scale of the auriferous potential of the area, dates from the early 1980's with the commencement of a joint venture between Noranda Australia Limited and Marathon Petroleum Australia Limited. Early diamond drilling intersected widespread gold mineralisation with an estimated mining reserve of 16.5 million tonnes at 1.5 g/t gold. Pan Australian Mining Limited acquired a 50% interest in the joint venture following a local management buy out of Marathon Oil's local mineral interests in 1984. Noranda Pacific Limited sold its remaining 50% interest to Pan Australian Mining Limited in May 1986.

Development of the project proceeded rapidly from mid-1986. Pre-production mining on the summit of Mount Leyshon commenced in September 1986, leading to the stockpiling of 100000 t of oxide ore. A total of 19941 m of diamond drilling (101 holes) and approximately 22200 m of reverse circulation drilling (440 holes) defined the ore reserves in the early mining stages. Full operational status was achieved during the first quarter of 1987 with the first gold pour taking place in February 1987. Mining concentrated on oxide ore and gold was extracted by the heap leach process.

The completion of a carbon-in-pulp plant in February 1989 allowed the mining and processing of primary sulphide ore.

Australian Development Limited purchased the management company, Pan Ocean Resources Limited, in June 1989, effectively placing Pan Australian Mining Limited within the Normandy-Poseidon Group of companies. In 1992, the company name 'Pan Australian Mining Limited' was changed to 'Mount Leyshon Gold Mines Limited'.

Poseidon Gold Limited ('PosGold'), the gold arm of the Normandy-Poseidon Group, has a 76% interest in the capital of Mount Leyshon Gold Mines Limited.

4.2.3 Regional Geology

The Mount Leyshon breccia complex, straddles the contact between Cambro-Ordovician metasedimentary and metavolcanic rocks of the Seventy Mile Range Group and Ordovician-Devonian I-type granitoids of the Ravenswood Batholith (Figure 4.2).

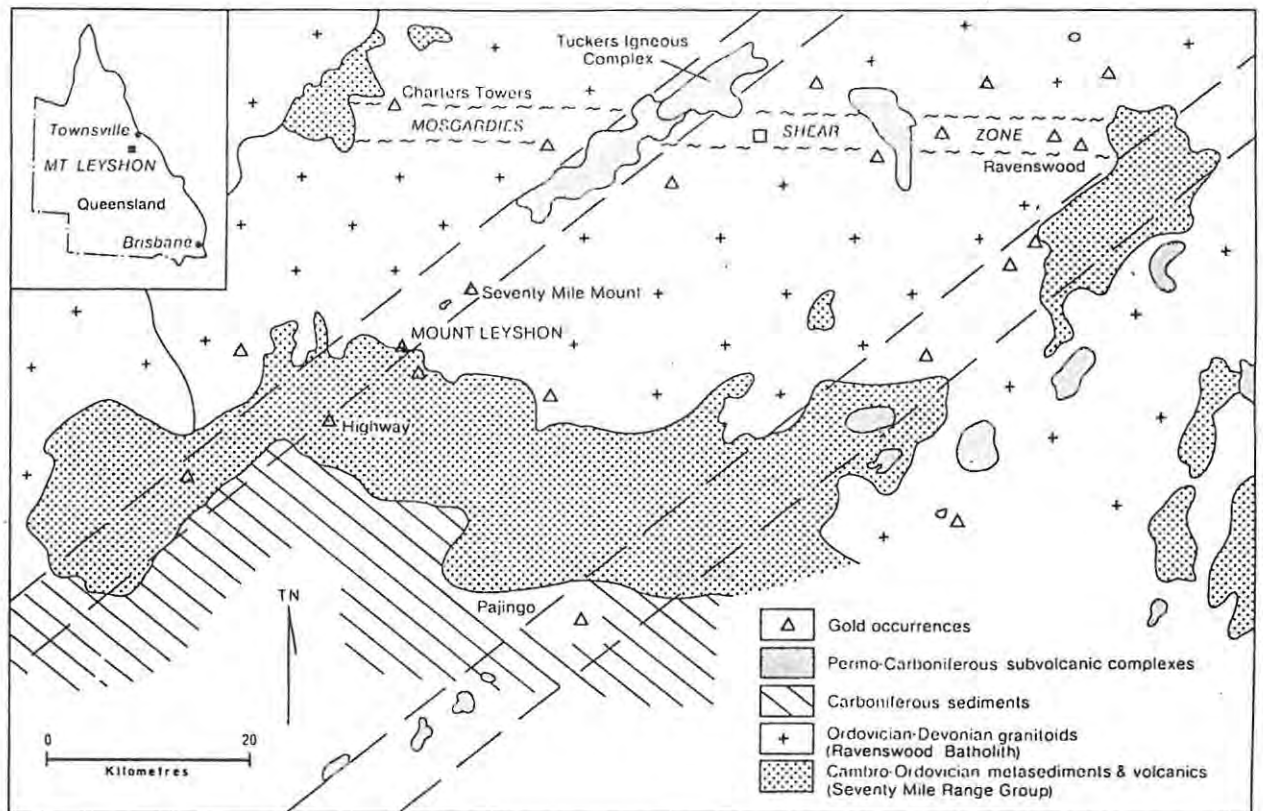


Figure 4.2 : Location and regional geological setting, Mount Leyshon gold deposit. Note the concentration of gold occurrences in the northeast trending corridors, which also contain many of the Permo-Carboniferous subvolcanic complexes (Paull *et al.*, 1990).

The basement units are part of a lower Palaeozoic active continental margin terrane that extends the full length of eastern Australia (Henderson, 1986). To the south, the Seventy Mile Range Group is overlain by Carboniferous continental to shallow marine strata (Paull *et al.*, 1990).

The basement units are cut by Permo-Carboniferous volcanic to subvolcanic complexes that are predominantly rhyolitic, but range in composition through dacite, trachy-andesite and andesite. These complexes are aligned in northeasterly trending corridors. The Mount Leyshon breccia complex is at the intersection of one such corridor with the southern boundary of the Ravenswood Batholith. The basement rocks around Mount Leyshon consist of weakly foliated and metamorphosed siltstones, sandstones and greywackes of the Puddler Creek Formation of the Seventy Mile Range Group. These are intruded by a distinctive pink, porphyritic, leucocratic variant of the Ravenswood

Granodiorite. Abundant doleritic dyke swarms exist in the immediate area of the breccia complex and are considered to represent an influx of basic magma before the main complex development.

4.2.4 The Mount Leyshon Breccia Complex

The Mount Leyshon breccia complex lies within a roughly circular structure 1.5 km in diameter, recognisable on aerial photographs and satellite images. The complex contains a diverse sequence of breccias, tuffs and dykes (Figure 4.3). These are intimately related to a suite of rhyolitic porphyry bodies. The location and size of the deposit relates very closely to the interaction of a number of closely related magmatic events, as represented in Figure 4.4.

Pre-Breccia Basement. The basement rocks have undergone several structural events prior to the emplacement of the breccia complex. These include the development of steeply plunging, isoclinal and gently plunging, inclined folds, two steeply dipping cleavages (090° and 030°) and a number of ductile shear zones. Various degrees of partial to complete fragmentation occur within the basement rocks. Where they are monomictic and crackle to rubble brecciated, they retain their original designation (e.g. metasediment or dolerite).

Main Pipe Breccia. The Main Pipe breccia was the first event within the complex and resulted in being the most volumetrically significant unit. Contacts between the Main Pipe breccia, surrounding basement stratigraphy and internal basement blocks are generally steep, and display a chaotic 'antler' like geometry. A progression from rubble-breccia through mosaic-breccia, crackle-breccia to cohesive basement (Laznicka, 1988) is variably developed.

Main Pipe breccia consists of fragments and rock 'flour' (matrix) derived from basement lithologies. Both fragment size and matrix proportion show a complex variation. Two distinct sub-facies are distinguished on the basis of average clast grain size; coarse and fine Main Pipe breccia. The former ranges from clast- to matrix-supported breccia, with sub-angular to sub-rounded fragments generally between 10-50 mm, and up to 30% matrix. The latter is a matrix-supported breccia with approximately 70-100% matrix and fragments generally <5 mm. 'Accretionary structures' are commonly found in the fine matrix-supported Main Pipe breccia.

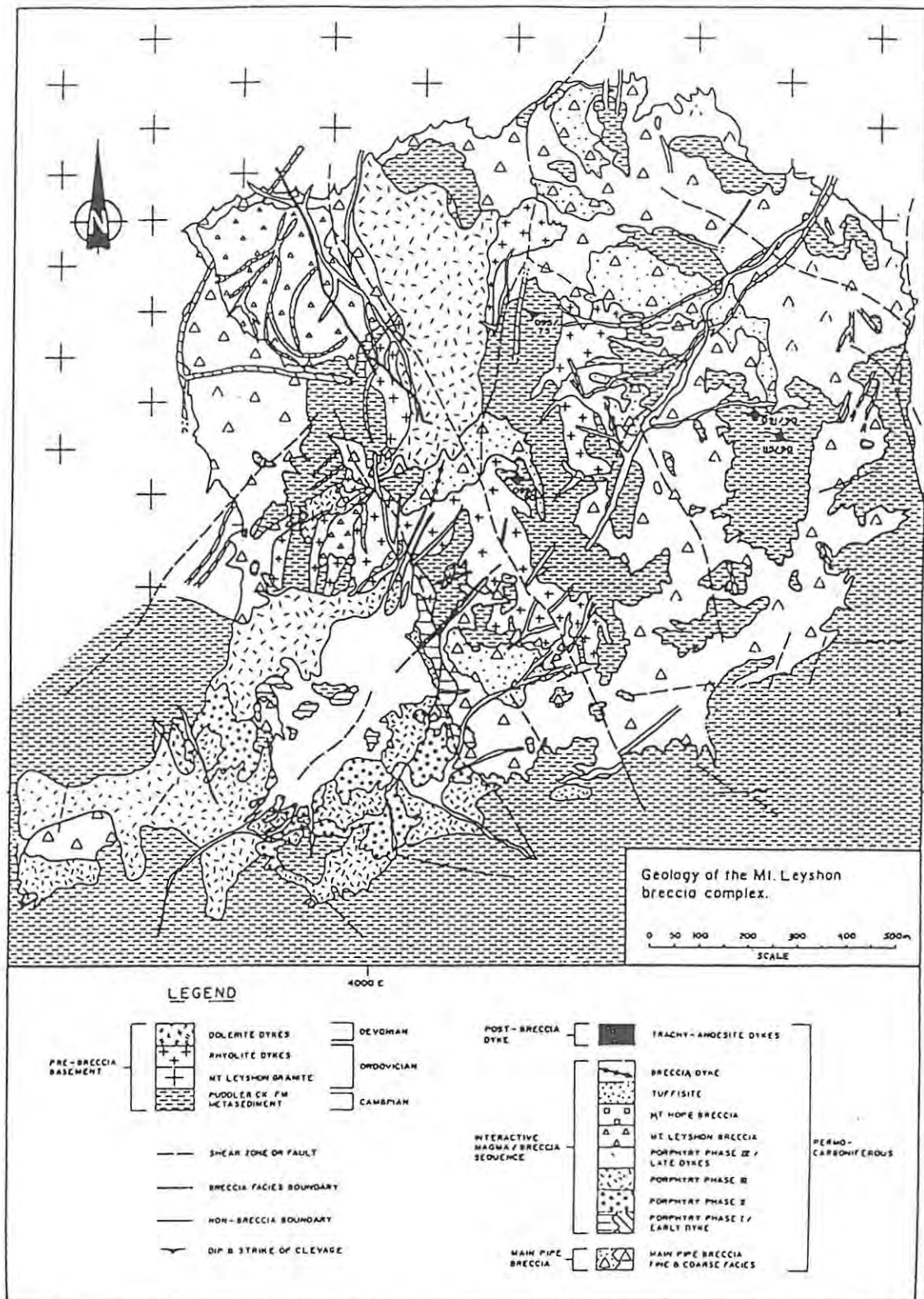


Figure 4.3 : Detailed geological map of the breccia complex based on outcrop mapping at 1 : 2000 scale. The majority of the basement rhyolite and dolerite dykes have been omitted for clarity (Wormald, *et al.*, 1991).

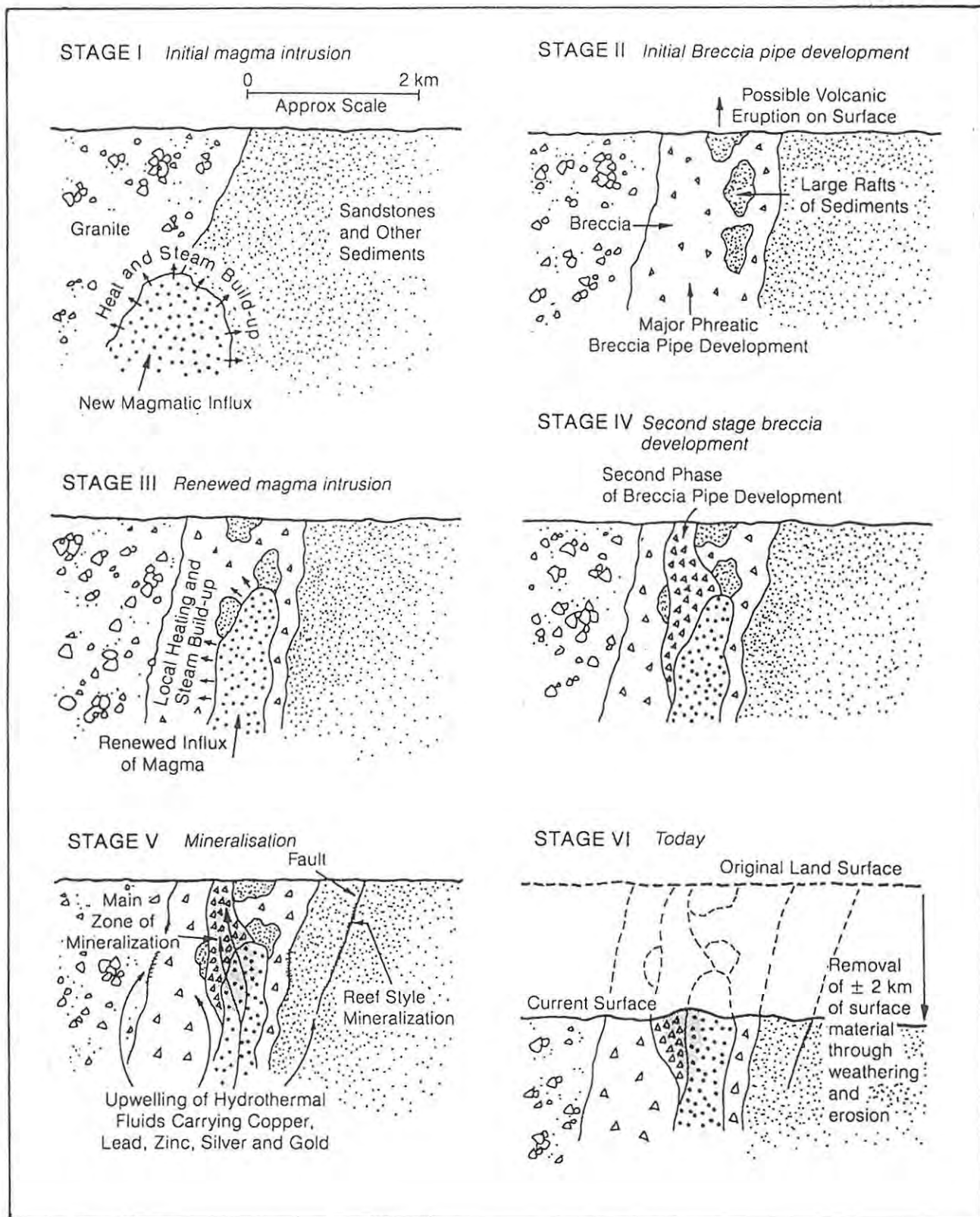


Figure 4.4 : The evolution of the Mount Leyshon gold mine breccia complex (Hodkinson, 1990).

Magmatic Phases. The porphyritic rocks within the Mount Leyshon breccia complex can be sub-divided into porphyry phases I, II, III and IV (Figure 4.5) on the basis of cross-cutting relationships and primary igneous textures (Wormald *et al.*, 1991).

Visual estimated modal proportions indicate that the major igneous phases range from pheno-quartz-trachytes to pheno-rhyolites (Streckeisen, 1979), however, XRF analysis suggests a rhyo-dacitic composition (Wormald *et al.*, 1991).

The first intrusive phase, porphyry phase I, is sparsely porphyritic with up to 5% feldspar and <1% quartz phenocrysts in an aphanitic groundmass, and may be locally brecciated. It occurs as a narrow zone on the eastern margin of the magmatic centre and as remnant zones within later igneous phases. Steeply dipping flow-banding is locally developed within this dark coloured 'glassy unit'. A sparsely porphyritic 'early dyke' phase is also developed with up to 10% 1-2 mm sized feldspar and 1% rounded quartz phenocrysts. This dyke phase occurs extensively throughout the northern half of the complex and is cross-cut by the Mount Leyshon breccia.

Porphyry phase II ('xenolith porphyry') contains 50% xenolithic fragments of basement, Main Pipe breccia, porphyry phase I and a number of cognate igneous xenoliths. It has the appearance of a breccia, although the inter-fragment material is a porphyritic igneous groundmass composed of quartz and feldspar phenocrysts set in a fine intergrowth of the same. This unit is distinct from local xenolith-bearing zones in other igneous phases, occurring as irregular patches and linear zones, locally intruded by porphyry phase III. A strong carbonate-sericite \pm sulphide alteration assemblage is generally present within porphyry phase II (Wormald *et al.*, 1991).

Porphyry phase III is the most extensive and occurs as elongate bodies up to 200 m wide. A 500 m long north-south body is present along the eastern margin of the mine and as east-west and northeast to southwest trending bodies further to the south. They display steeply dipping interfingering, chilled and xenolith-bearing margins. The porphyry generally contains up to 35% phenocrysts in an aphanitic groundmass, although 0.2-0.5 m wide zones of up to 50% quartz phenocrysts are locally present. The groundmass and most of the feldspars show a strong sericite-carbonate \pm pyrite \pm basemetal sulphides \pm gold alteration, producing a pseudo-fragmental texture. The quartz phenocrysts are distinctively angular or cusped, a result of both primary resorption and alteration.

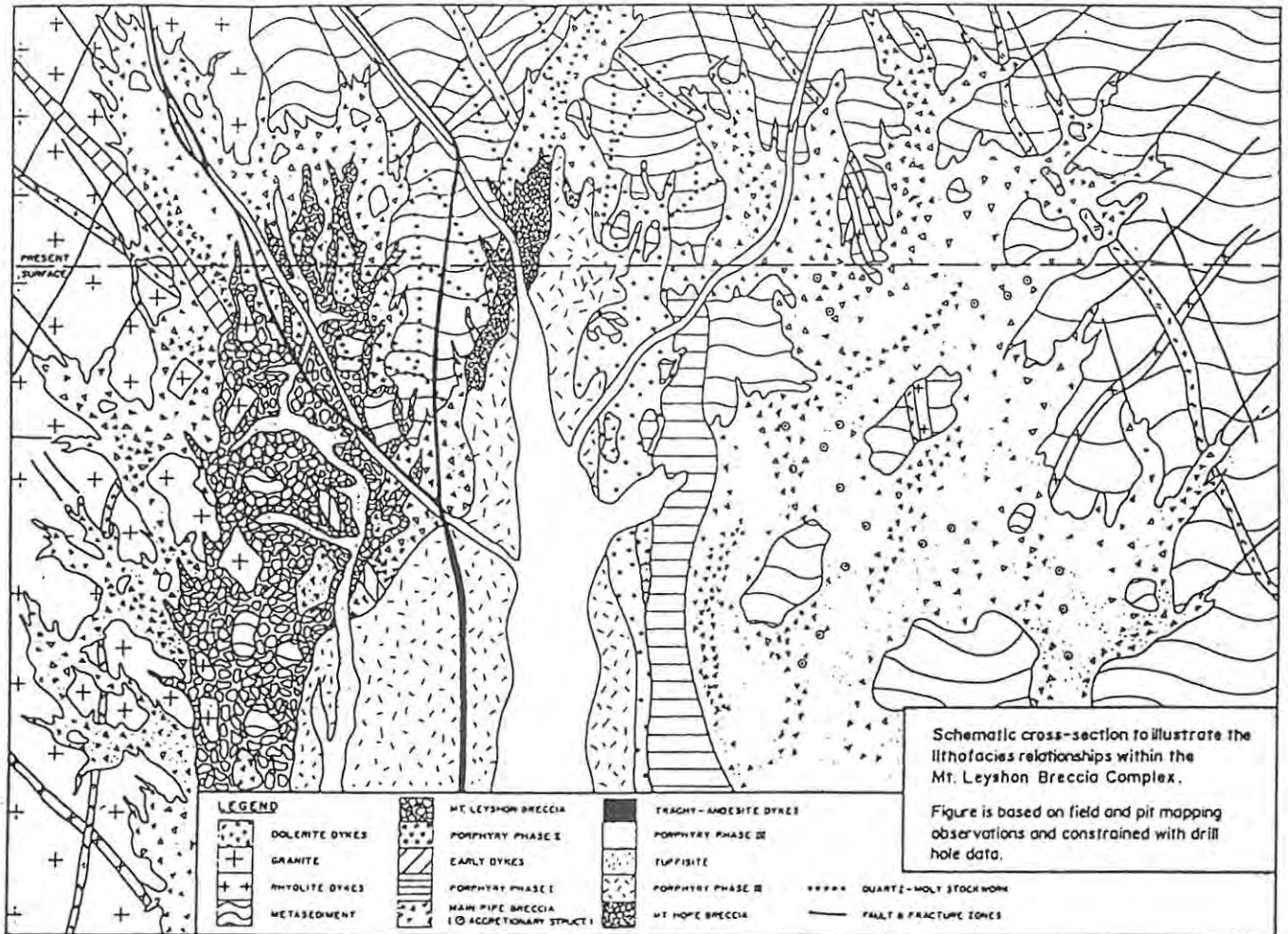


Figure 4.5 : Schematic cross-section. Note : (1) The steeply dipping, chaotic antler-like geometry of the Main Pipe breccia, (2) complex variation and gradation between the Main Pipe breccia sub-facies, (3) steeply dipping, inter-fingering porphyry contacts, (4) spatial relationship between Mount Hope breccia and porphyry phase III, (5) gross textural differences between Mount Leyshon and Mount Hope breccias compared to the Main Pipe breccia, (6) inter-fingering and intrusive nature of the tuffisite dykes, and (7) the largely in situ basement blocks (Wormald *et al.*, 1991).

An early, sheeted, quartz-molybdenite vein system was generated after emplacement of the Main Pipe breccia. Although the timing of this system is not known, quartz-molybdenite veins occur as fragments within porphyry phase III.

The last significant intrusive event resulted in porphyry phase IV. The porphyry is an elongate body up to 250 m wide and cross-cuts porphyry phase III. It is an orange

coloured phase, contains 30% phenocrysts of feldspar, quartz and hornblende (<5%) and is partly compositionally similar to porphyry phase III, but does not show strong alteration. Xenolithic pods from <0.01-0.5 m in diameter are locally present, consisting of a fine grained intergrowth of feldspar and hornblende crystals, with up to 2% feldspar phenocrysts. Their margins with the enclosing porphyry are sharp. A suite of 'late dykes' with characteristic rounded quartz phenocrysts emanate from this body, which locally intrude breccia dykes. These late dykes cut all the breccia phases and provide an upper age limit for the termination of large-scale brecciation (Wormald *et al.*, 1991).

A series of minor, narrow (generally <1 m wide) trachy-andesite dykes cross-cut all the rock units making up the breccia complex. They are post-gold mineralisation and the last recorded igneous event within the complex.

Breccia phases subsequent to the Main Pipe breccia. These phases are confined to the northwest corner of the complex, except for small-scale crackle-rubble brecciation and a number of minor breccia dykes.

The Mount Leyshon breccia occurs as a zone largely composed of re-brecciated Main Pipe breccia and basement lithologies. It is roughly ovoid with approximate dimensions of 400 by 300 m in plan, and a vertical extent of at least 600 m. The polymict Mount Leyshon breccia progresses from rubble breccia to cohesive host. It is predominantly a clast-supported breccia with compositional and textural heterogeneity.

Significant void space and cavity-fill mineralisation occurs within the Mount Leyshon breccia. The mineral assemblage, in order of decreasing abundance, is pyrite-chlorite-quartz-sericite-carbonate-base metal sulphides-silver-gold. Rare matrix-rich regions with a gently dipping apparent flow fabric occur locally.

Mount Hope breccia has a similar texture to the Mount Leyshon breccia, but is distinguished on the basis of its close spatial and temporal association with porphyry phase III, together with often more rounded fragments. The alteration minerals show a different intensity of development and consists, in order of decreasing abundance, of carbonate-pyrite-sericite-chlorite-base metal sulphides-silver-gold. This breccia is always developed at or close to the margin of porphyry phase III and is locally intruded by this porphyry. Most contacts are relatively sharp and the rubble-breccia to cohesive-host progression is poorly developed.

The last stages of brecciation resulted in two distinct facies, termed 'tuffisite dyke' and 'breccia dyke'. The term 'tuffisite dyke' refers to the formation, at least in part, of a gas-solids mobilisation process and is not intended to infer a tuff association.

Tuffisite dykes are particularly well developed within the Mount Leyshon breccia, forming dykes from 0.01-15 m thick. These dykes are often complexly interconnected and appear to be confined to the northwest corner of the complex. Their contacts are generally sharp, although they locally display gradational contacts where the tuffisite dykes appear to re-work the Mount Leyshon breccia. The tuffisite dykes are of variable strike and dip. Occurring as both steeply and shallow dipping bodies. They contain sub-rounded to well-rounded fragments of all the previously described rock units, including fragments texturally similar to porphyry phase III (Wormald *et al.*, 1991).

Three types of tuffisite dykes have been defined according to their average grain size. These being fine, medium and coarse (<2 mm, 2-10 mm, >10 mm respectively) tuffisite dykes. They are generally well sorted and occur independently or as composite bodies with gradational to sharp contacts. Fine scale (1-10 mm) layering is locally observed. The tuffisite dykes usually show intense carbonate-sericite-pyrite-base metal sulphides-silver-gold alteration.

Breccia dykes occur as narrow (up to 2 m wide), discrete bodies and are always near vertical. Although volumetrically much less important than the tuffisite dykes, they occur throughout the breccia complex. They are associated with a particular variety of late dyke, occupying the same structure or one nearby. Fragments within breccia dykes are sub-angular to sub-rounded and much less well sorted than those in the tuffisite dykes. They typically contain <5% 'flour' matrix but locally grade into zones with up to 100% matrix (texturally identical to the fine tuffisite dykes). Small scale breccia dykes occur within porphyry phase III that show a gradual decrease in both fragment size and proportion as they pinch out, becoming 100% matrix. The breccia dykes contain a number of igneous fragments, some texturally similar to the late dyke they are associated with, while others (more rarely developed) are 'plastically deformed' igneous fragments.

Small-scale re-brecciation of tuffisite and breccia dykes occurs. Porphyry phase IV also shows small scale brecciation with massive magnetite cavity fill.

4.2.5 Structural Framework

Structural control on the development of the breccia complex is evident at all scales. The location and subsequent emplacement of breccia and magmatic phases, as well as the syn- to post-complex structures appear to be related to regional shear zones and faults.

Major lineaments in the Lolworth-Ravenswood Block include the northeast trending Mount Leyshon-Tuckers lineament, the east trending Alex Hill and Mosgardies shear zone and the southeast trending Burdekin River lineament. Most brittle structures are re-activations of earlier foliations and mylonites (Heidecker and Rynn, 1984).

A number of significant fault zones and intensely jointed domains are present within the complex, both pre-dating and post-dating development of breccia phases. These structures take the form of anastomosing spaced cleavage, zones of cataclastic shearing and intense fracture development, associated with variable carbonate and clay alteration. They generally trend to the north, northeast, east and southeast, and compare closely to the orientation of regional scale shear zones, faults and major lineaments.

Cleavage and bedding in metasediment, south of the mine, dominantly strike 090° , with a steep to vertical dip. A subordinate steeply dipping cleavage, striking 030° , is also present. The more incompetent shaly horizons within the metasediment commonly show ductile shearing. The Mount Leyshon granite, and a number of granite bodies to the north, trend to the east, suggesting re-activation of the early striking fabrics during emplacement which probably contributed to breccia complex emplacement. Porphyritic rhyolite dykes and larger bodies were generally intruded along north-trending, steeply plunging, structures. A large number of dolerite dykes are northeast trending.

Four major structural trends occur within the breccia complex; north-northeast, northeast, east-southeast and southeast, with a less common group of north and east orientations. Although the strike of metasediment cleavage inside the breccia complex is widely scattered, it generally trends around 070 - 090° and steeply dipping. A weakly defined, steeply dipping cleavage, striking 030° is also preserved (Wormald *et al.*, 1991).

Contacts between the Main Pipe breccia and basement show apparent preferred orientation to the east, north and locally east-southeast and northeast. Pre-Mount Leyshon breccia igneous phases (porphyry phase I and early dyke) have a preferred

orientation to the east and north. The early dykes show a change to northeast strike at the northeastern corner of the complex.

A sub-horizontal stretching lineation or slickenside is locally developed on fault surfaces. The majority have a pitch between 0° and 30° (rarely >60°), suggesting that strike-slip faulting was the dominant type. The steeply dipping stretching lineations imply a component of normal faulting was also present. Sense of movement criteria are poorly developed and inconsistent.

4.2.6 Mineralisation

At Mount Leyshon gold mine, most of the gold mineralisation is hosted in the Mount Leyshon breccia, with lesser amounts in the adjacent rocks. The detailed distribution of the gold within the different rock types is irregular and complex and can only be determined analytically. The visual classification of ore and waste is virtually impossible.

The mineralisation is spatially related to small scale fracture patterns, fracture density and other permeability controls. Several crudely pipe-like zones of mineralisation have been identified. They reflect the presence of major mineralising conduits from which subsidiary feeders developed to produce an apparently erratic ore distribution pattern. Permeability barriers, such as dykes and lithological boundaries, have locally had a significant control on the distribution of gold mineralisation.

Ore Mineralogy. The dominant sulphides within the deposit are pyrite, chalcopyrite, galena, plus low- and high-iron sphalerites. Pyrite and sphalerite occur as disseminations throughout most rocks in the mine area, in association with all other sulphides and sulphosalts which are dominantly vein or cavity related. The only other significant sulphide is molybdenite which occurs in laminated quartz veins. The main non-metallic gangue minerals are chlorite, carbonates, micas and quartz (Table 4.2).

Gold is present as free gold and rarely in solid solution in an unidentified bismuth-silver sulphosalt. The gold grains predominantly fall within the 1 to 600 µm range, but a significant number of grains reaching 1 to 1.5 mm diameter have been recognised in drill core. The silver content of gold grains ranges from 3 to 31%, with many grains exhibiting zoning with silver rich rims. The copper content of the gold reaches 0.7%. The most

silver-rich gold has been observed healing fractured pyrite, in bismuth-rich vein assemblages.

Gold associated with bismuth sulphides and sulphosalts, either as inclusions or at grain boundaries, accounts for approximately 84 vol. % of the total gold. The bismuth bearing phases may exhibit complex intergrowths with one another as well as wide compositional variations (Paull *et al.*, 1990).

	MAJOR	MINOR	TRACE	RARE
S U L P H I D E S	Pyrite	Bismuthinite	Gold	Electrum
	Low iron sphalerite	Pekoite*	Pyrrhotite	Matildite
	High iron sphalerite	Lindstromite**	Friedrichite(?)****	Cu-rich matildite
	Galena	Hammarite***	Ag wittichenite	Cubanite (?)
	Chalcopyrite	Aikinite	Molybdenite	Benjaminite-gustavite
		Cosalite		
		Wittichenite		
		Berryite		(Two unknown sulphosalts observed)
		Emplectite		
		Lillianite		
	(One unknown similar in composition to Cosalite)			
G A N G U E	Quartz	Anatase	Rutile	Andradite-grossular garnet
	Fe-Mn chlorite	Adularia	Monazite	Epidote
	Mn siderite	Zn siderite	Apatite	Gypsum
	Mn calcite		Cr-muscovite	
	Fe-Mg calcite			
	Mg chlorite			
	Fe muscovite and hydromuscovite			
Hematite				

* $PbCuBi_{11}(S,Se)_{18}$

** $Pb_3Cu_3Bi_7S_{15}$

*** $Pb_2Cu_2Bi_4S_9$

**** $Pb_5Cu_5Bi_7S_{18}$

Table 4.2 : Observed sulphide and gangue phases from the primary zone, Mount Leyshon gold mine (Paull *et al.*, 1990).

Styles of Mineralisation. Replacement, cavity fill, disseminated and vein styles of mineralisation have been recognised at Mount Leyshon gold mine.

Replacement of the matrix of the Mount Leyshon breccia by hydrothermal chlorite, euhedral pyrite and the various sulphide and sulphosalt phases may be partial or complete. Matrix replacement is almost always associated with cavity fill mineralisation.

Cavity fill mineralisation is typified by an association of fine comb quartz, carbonate, pyrite, basemetal sulphides or sulphosalts, chlorite and minor gypsum (Figure 4.6). Short veinlets with the same mineral assemblage interconnect adjacent cavities either replacing matrix or crosscutting clasts. Within the cavity fill assemblage, individual pyrite euhedra may reach large sizes with cube edges up to 15 mm being recorded.

Disseminated pyrite pervades all rocks at Mount Leyshon gold mine, with the exception of the Main Pipe breccia which is mineralised only locally.

The six vein styles present at Mount Leyshon are as follows :

1. Laminated quartz-molybdenite veins with rare pyrite and chalcopyrite. These veins form stockworks in shattered rocks adjacent to the composite rhyolitic porphyry body on the eastern side of Mount Leyshon.
2. Banded quartz-pyrite veins occur sporadically in metasediment and dolerite clasts in the Mount Leyshon breccia.
3. Quartz-pyrite-basemetal sulphide veins in the Mount Leyshon breccia. They contain sugary quartz, granular pyrite and bands of chalcopyrite, sphalerite, galena and bismuthinite.
4. Pyrite-basemetal sulphide-carbonate veins occur within the Mount Leyshon Breccia and adjacent brecciated units.
5. Quartz-pyrite-basemetal sulphide veinlets with irregular form occur in and adjacent to dykes in the area south of the old Mount Leyshon open cut, and in faults cutting the rest of the complex. The veinlets have fine clear comb quartz, but are locally dominated by basemetal sulphides.
6. Fine, wormy basemetal sulphide veins commonly occur in the tuffisite dykes, breccia dykes, porphyry dykes and flows where these are mineralised. Sphalerite is the dominant sulphide, with lesser galena, bismuthinite, chalcopyrite and pyrite, and minor quartz and carbonate.



Figure 4.6 : This specimen of Mount Leyshon breccia is composed mainly of fine grained metasediments which form the framework of the breccia. The fragment interstices are occupied by pyrite, smaller fragments and dark resin which has impregnated during polishing. The fragments are mostly angular, but significant rounding can be seen on many of the small, interstitial fragments. Cavity fill mineralisation is very dominant (Taylor, 1992).

4.2.7 Alteration

Widespread hydrothermal alteration is confined to two dominant types; phyllic and potassic. However, a third type exists locally in the form of propylitic assemblage which is responsible for the matrix replacement in the Mount Leyshon breccia. Oxidation constitutes a fourth type of alteration.

Phyllic Alteration. Sericite-pyrite alteration was dominant within the early phases of the breccia complex. Evidence of the early phase of alteration is derived from clasts within the Mount Leyshon breccia. The clasts in some instances having been overprinted by propylitic alteration. The phyllic alteration is a pervasive, but not texturally destructive, replacement. In the breccias, clasts often have intensely altered rims and partially altered and veined interiors, particularly adjacent to cavities, around which potassium feldspar locally forms an outer alteration rim (Paull *et al.*, 1990).

Potassic Alteration. Biotite is the dominant potassic alteration product and is present as relict patches in large fragments of metasediment, dolerite and porphyry within the Mount Leyshon breccia and in the epiclastics and metasediments to the northeast of Mount Leyshon. A significant proportion of biotite in the Mount Leyshon breccia is, however, considered to be the result of thermal metamorphism rather than potassic alteration. In the genuinely altered rocks biotite has replaced the original feldspar and mafic minerals, and biotite-pyrite-ankerite veins are common. Actinolite and magnetite accompany the biotite in altered dolerites. Veinlets of magnetite-chlorite-quartz and pyrite-chlorite-ankerite with epidote and potassium feldspar rims commonly occur in the dolerites. Early quartz-molybdenite veins typically display small to microscopic potassium feldspar alteration haloes.

Propylitic Alteration. Propylitic alteration occurs as a pervasive assemblage of hydrothermal chlorite-carbonate-anatase within the Mount Leyshon breccia, replacing the original matrix. It is most likely associated with the introduction of basemetal sulphide assemblages. The chlorite is a ripidolite variety and the carbonate is mangano-calcite. In many instances previously phyllic altered phenocrysts are replaced by an intimate mixture of chlorite-carbonate \pm galena \pm sphalerite \pm pyrite.

Oxidation and Supergene Enrichment. Tropical weathering has generally resulted in almost complete oxidation of the primary mineralisation and host rocks to a maximum

depth of 60 m below the summit of Mount Leyshon. Within this oxide zone gold is associated with iron oxides and hydroxides, jarosite, alunite and kaolinite in cavities and veins. The gold is generally disseminated throughout the host rocks. The oxide ore is variably bleached and ferruginised, displaying a wide colour range from white to red. Intense leaching has resulted in extremely low copper (<200 ppm) and zinc (<100 ppm) values within the oxide zone without affecting gold content or distribution.

An irregular transitional supergene zone is present immediately below the base of oxidation. The zone is best developed within the Mount Leyshon breccia, where it reaches thicknesses to 20 m, averaging less than 10 m, but thins to generally less than 2 m in the porphyries and other volcanic units. The supergene material has a very distinctive white to light grey colour and is characterised by the development of abundant alunite veins, veinlets and matrix replacement, together with secondary chalcocite overgrowing pyrite. Copper is strongly, but erratically, enriched within the supergene zone, reaching values of 1 to 2% copper, compared to values of generally less than 0.2% in the primary mineralisation. The dominant copper minerals are chalcocite and digenite with minor bornite and covellite. Silver is enriched in the supergene zone within bornite (up to 1600 ppm silver) and in chalcocite (up to 3200 ppm silver).

4.2.8 Isotope and Fluid Inclusion Studies

The calculated oxygen isotope composition of the water within fluid inclusions of quartz, carbonate, potassium feldspar and micas is approximately 6 to 8‰, suggesting that the fluid is of magmatic derivation. The fluid inclusions also show a limited range of values for high temperature (300-500°C), high salinity fluids responsible for the mineralisation.

Carbon isotopic composition of carbonate in veins and cavities suggest a magmatic or deep seated source of carbon. The sulphur isotopic composition in pyrite is consistent through all the mineralisation stages and co-existing sphalerite and chalcopyrite are in isotopic equilibrium. The range of values is 4.9 to 8.2‰, but most of the data cluster at $7 \pm 1\%$ which is higher than typical values for magmatic sulphur in hydrothermal mineral deposits. The limited range of values and the known mineral assemblage suggest that this variation is not due to unusual oxygen fugacity or pH conditions, but may reflect hydrothermal homogenisation of two different sulphur sources (Morrison *et al.*, 1987).

The age of mineralisation, determined by K-Ar isotope studies obtained from muscovite from altered porphyry, is 280 ± 2 and 281 ± 3 million years. The lead isotope values indicated a normal crustal source for the lead and an age of 280 million years.

4.2.9 Ore Genesis

The Mount Leyshon gold deposit is hosted within a breccia complex related to a Permo-Carboniferous porphyry system. Within the complex a series of flows and epiclastics with associated rhyolitic to dacitic and mafic intrusives were emplaced within a pipe-like structure rimmed by an early phreatic Main Pipe breccia. Subsequent developments involved the emplacement of a further phreatic breccia pipe (Mount Leyshon breccia), spatially related phreatomagmatic tuffisites and a final phase of predominantly rhyolitic intrusives (Paull *et al.*, 1990).

Mineralising fluids developed from the final, volatile phases of the porphyry system and invaded structurally controlled pipe-like zones within and adjacent to the Mount Leyshon breccia. Early mineralisation is characterised by the association of porphyritic intrusives with high temperature stockwork quartz-molybdenite mineralisation. This was followed by a major mesothermal (300° to 450°C) copper-zinc-lead-bismuth-silver-gold mineralisation event giving rise to replacement, cavity fill, veining and disseminations within the Mount Leyshon breccia body and adjacent rocks.

4.3 Kidston Gold Mine

4.3.1 Introduction

The Kidston gold mine is approximately 280 km west-northwest of Townsville and 260 km southwest of Cairns, Queensland. Up to the early 1980's, the Kidston gold mine project appeared to be an attractive low-grade deposit but was initially rejected as uneconomic. Critical re-examination revealed that the rejection was based upon managerial inflexibility and traditionally over-conservative methods of mine evaluation, construction, operation, projected commodity prices and contingency factors. A fresh alternative to the traditional approach was taken, and today the project is a recognised success (Mining Magazine, 1986).

The Kidston orebody is hosted within a kilometre-diameter breccia pipe of Permo-Carboniferous age associated with rhyolitic dykes and hosted by Proterozoic granodiorite and metamorphic rocks. Gold is known to be particularly associated with post-brecciation cavity fill and late sheeted veins (Andrew and Baker, 1987). The geological evolution of the Kidston gold deposit is shown in Table 4.3.

The open pit mining operation is based on conventional shovel and truck techniques on 12 m benches. All waste is trucked to dumps, while ore is either delivered directly to the primary crusher, or taken to a run-of-mine dump, or a low-grade stockpile for later processing. The primary sulphide ore is treated using conventional cyanide leach CIP (carbon-in-pulp) processes with a 90% gold recovery.

Mineable ore reserves are 36.2 million tonnes at 1.74 g/t gold and 2.11 g/t silver (Murray, 1990). Calculation of ore reserves is by log-normal kriging.

4.3.2 Exploration and Production History

Alluvial gold was discovered at Kidston in the 1880's, and between 1907 and 1910 approximately 620 kg of alluvial gold was won from gullies draining the breccia pipe (Baker, 1987). As alluvial reserves dwindled, small scale open cuts and underground mining of narrow quartz veins were undertaken with varying profitability. Between 1915 and 1921 three sizeable open pits were bulk mined in the southwest portion of the orebody at Wise's Hill. These mines closed in 1924, and intermittent small scale mining continued until 1948 when the last stamp battery was closed. The total recorded production (excluding alluvials) for this early period was 200 945 t of ore which returned 1309 kg of gold at an average grade of 6.5 g/t.

Since the 1930's the Kidston breccia pipe has been tested by a large number of geological, geochemical and geophysical exploration techniques. In 1934 Gold Mines of Australia Limited, followed by Anglo Queensland Gold Limited, tested it as a bulk mineable deposit by sampling adits and open cuts.

Anaconda Australia Incorporated explored Kidston between 1965 and 1967, and again between 1974 and 1977. They recognised it as a major gold bearing breccia pipe deposit (Bain and Withnall, 1980), but found it sub-economic at the prevailing gold price.

Breccia and Magmatic Phases	Geological Events	Rock Types	Related Alteration	Mineralisation	Age
Pre-breccia Phase 1	1. Formation of the Einasleigh Metamorphics	Biotite-gneiss, leucogranodiorite, and amphibolite	Sericite-carbonate	Quartz-pyrite veins	Cambrian
Pre-breccia Phase 2	2. Intrusion of the Oak River Granodiorite	Grey-medium-grained porphyritic granodiorite and a hornblende bearing, biotite tonalite	Orthoclase-epidote-chlorite	Quartz-pyrite-magnetite-minor gold	Silurian-Devonian
Pre-breccia Phase 3	3. Intrusion of rhyolite porphyry dykes and development of rhyolite porphyry	Fine-grained quartz-feldspar porphyry	Epidote-chlorite-sericite-carbonate	Quartz-epidote-pyrite-pyrrhotite, molybdenite stockwork	Permo-Carboniferous
Breccia Phase 1	4. Development of a tourmaline breccia pipe	Rhyolite or granodiorite clast supported breccia with tourmaline-quartz matrix	Quartz-tourmaline replacement	Not Mineralised	Permo-Carboniferous
Breccia Phase 2	5. Development of the breccia pipe and collapse breccia	Clast supported breccia with previous rock types as clasts	Biotite, siderite, orthoclase	Pyrite-pyrrhotite-gold	Permo-Carboniferous
Post-breccia Phase 1	6. Intrusion of rhyolite porphyry dykes and the formation of sheeted fractures/joints	Quartz-feldspar porphyry with 40% phenocrysts	Muscovite, quartz, calcite, ankerite	Quartz-pyrite-pyrrhotite-base metals-gold	Permo-Carboniferous
Post-breccia Phase 2	7. Intrusion of basic dykes	Andesite	-	Not Mineralised	Permo-Carboniferous

Table 4.3 : The geological evolution of the Kidston breccia complex.

Placer Exploration Limited took over the option to lease in 1978, and drilled 145 diamond drill holes totalling 22273 m to define the reserves prior to mining.

4.3.3 Regional Geology

The Kidston breccia pipe is situated within the Einasleigh Metamorphics and the Oak River Granodiorite of the Georgetown Inlier (Figure 4.7). The pipe is spatially and temporally related to Permo-Carboniferous sub-volcanic dykes and plugs which include several generations of rhyolite and quartz-feldspar porphyry. These intrusives are part of a widespread calc-alkaline volcanic sequence throughout northeast Queensland, associated with areas of cauldron subsidence underlain by ring complexes and granitic batholiths. The pipe is on the eastern edge of a rhyolitic dyke swarm which stretches between the Lochaber Ring Complex, 15 km south of Kidston, and the Newcastle Range Volcanic Group volcanotectonic depression, approximately 25 km to the northwest. The rhyolitic dyke swarms roughly coincide with the trend of a regional gravity low, which is interpreted as indicating the presence of an underlying Permo-Carboniferous batholith (Baker and Tullemans, 1990).

The pipe is located on a major lithological contact between the Einasleigh Metamorphics and the Oak River Granodiorite. A further control on the localisation of the breccia pipe could possibly be the intersection of the northeast trending Gilberton Fault with the lithological contact and the dyke swarm (Wilson *et al.*, 1986).

4.3.4 The Kidston Breccia Pipe

Local Geology. The Einasleigh Metamorphics consist of interlayered, multiply deformed and strongly foliated biotite gneiss, leucogranodiorite and amphibolite. In the mine area the Einasleigh Metamorphics grade southwards into a foliated equigranular phase of the Oak River Granodiorite, which is separated from a porphyritic granodiorite phase to the south by a narrow selvage of biotite gneiss. The contacts between the basement units are subparallel to the foliation, which strikes northwest and dips to the east and west.

The pre-breccia rhyolite dykes are characteristically fine grained and contain less than 10 vol. % quartz, plagioclase and orthoclase as phenocrysts. The phenocrysts are generally less than 3 mm in diameter.

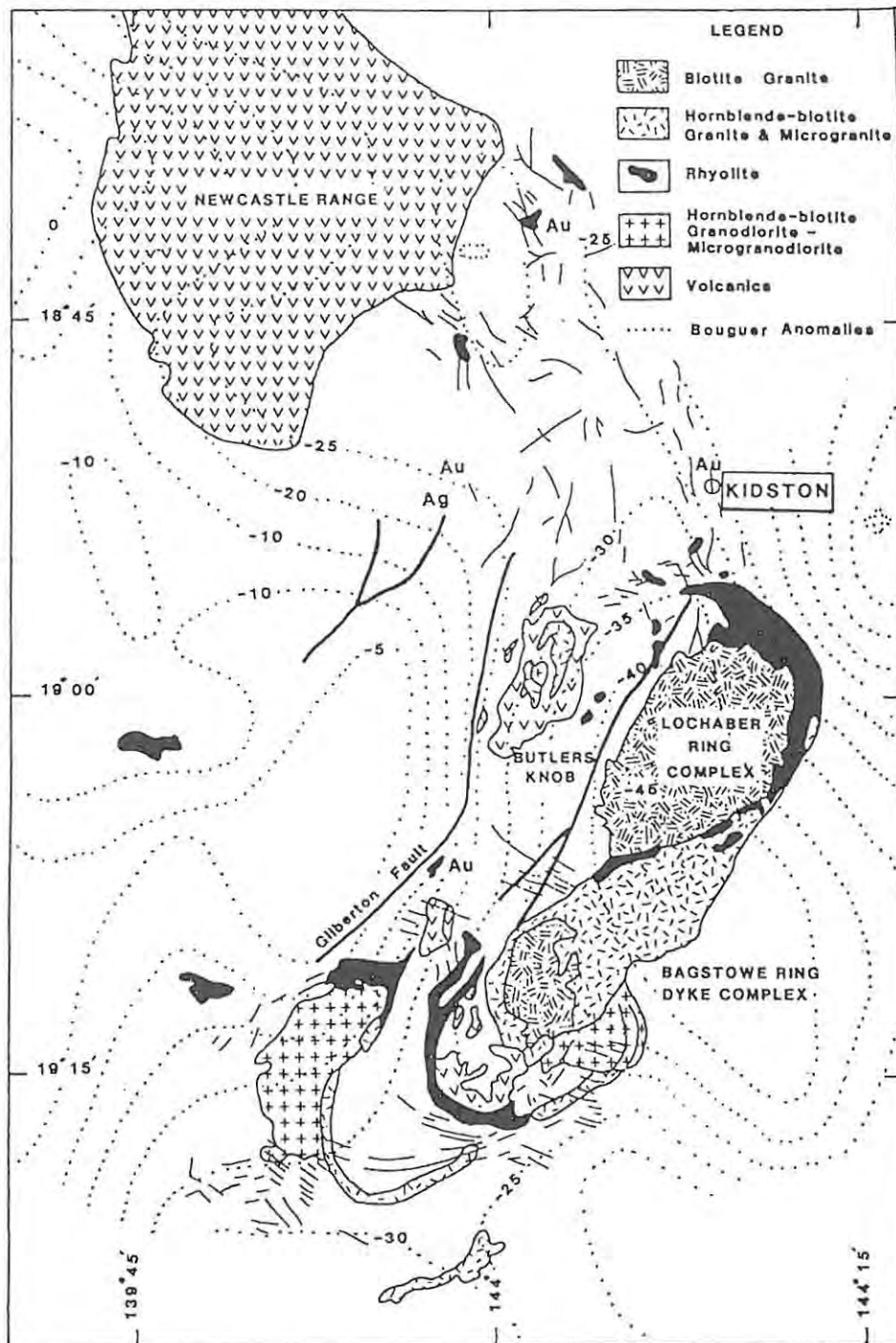


Figure 4.7 : Regional geology of the Kidston breccia pipe showing the relationship to the Lochaber Ring Complex, northwest trending rhyolite dyke swarm and coincident gravity low, interpreted as reflecting an underlying batholith (Baker, 1988).

The plug at Wise's Hill has a fine grained cap of rhyolite, which grades downwards and inwards into more porphyritic material with up to 20 vol. % phenocrysts. This gradational contact is often marked by the presence of thin contorted layers of quartz crystals, with their terminations pointing downwards into the porphyry. These crenulate quartz layers form in response to periodic build up and release of volatiles in the apical portion of a melt during crystallisation.

The post-breccia dykes are characterised by the abundance of large quartz, orthoclase and plagioclase phenocrysts up to 7 mm in diameter, comprising around 40 to 50 vol. % of the rock. A single post-mineralisation andesite dyke, up to 8 m wide, trending north-northwest and dipping 75° west, cuts through the southeastern portion of the pipe.

Brecciation. The breccia at Kidston is confined to a trapezoid shaped pipe roughly 1100 by 900 m at surface (Figure 4.8). The breccia pipe margins are sharp and dip steeply inwards at more than 80°, but locally dip steeply outwards. The breccia consists of angular, rectangular shaped clasts of granodiorite, metamorphic rocks and rhyolite. The corners of the granodiorite and metamorphic rock clasts are generally more rounded than the corners of the rhyolite clasts. The matrix generally comprises less than 20% of the breccia by volume, and consists of small clasts and individual mineral fragments. Cavities filled with varying hydrothermal infill assemblages comprise in the order of 1 to 3 vol. % of the breccia. Large blocks within the breccia indicate no significant rotation subsequent to incorporation in the breccia pipe.

In the northeastern portion of the pipe the breccia clasts and matrix are predominantly composed of metamorphics and in the southwest they are mainly granodiorite. The amount of rhyolite clasts present mimics the pre-breccia distribution of rhyolite dykes. The contacts between the various lithologically distinct types of breccia can be traced from the host rocks through the pipe (Figure 4.8), indicating that brecciation did not involve significant mixing of material. The lack of any significant movement of material during brecciation and the limited amount of rock flour present, suggest that collapse was the most likely mechanism causing brecciation.

Breccia dykes which intrude the breccia within the central portion of the pipe (Figure 4.8) are characterised by the presence of rounded rhyolite clasts, and clasts of granodiorite and rhyolite containing quartz-magnetite stockwork vein mineralisation.

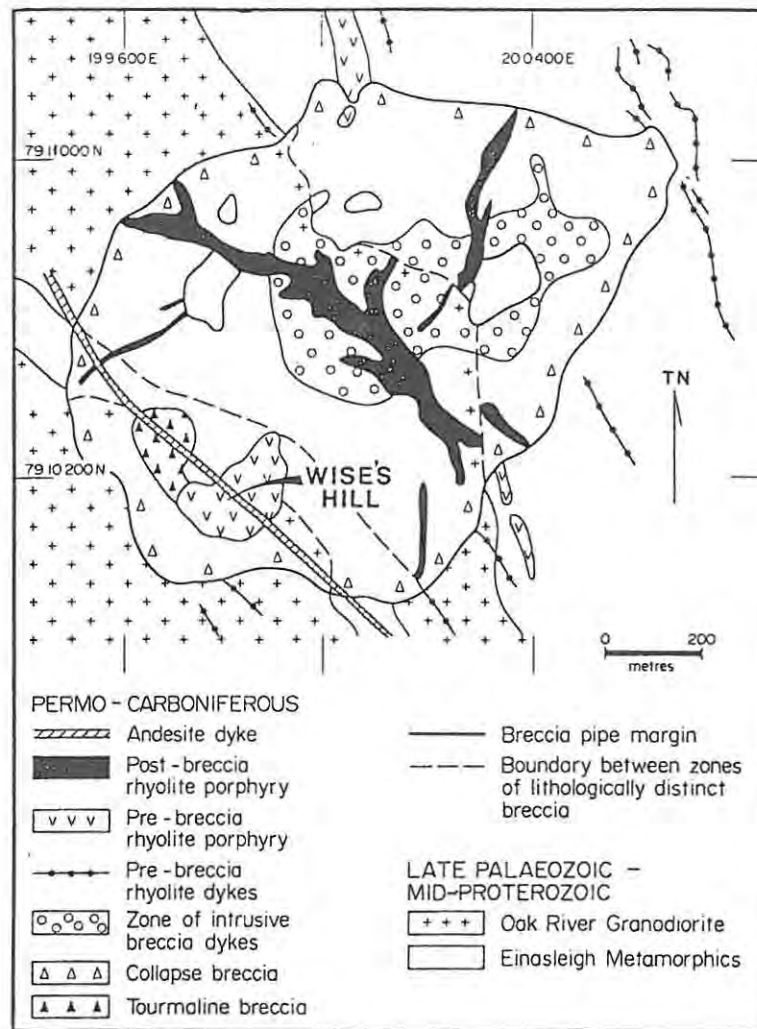


Figure 4.8 : Surface geology of the Kidston breccia pipe showing the distribution of breccia types and relation between intrusives and brecciation (Baker and Tullemans, 1990).

The rounded clasts have low ridges on their surfaces, interpreted as resulting from hypogene exfoliation of the clasts. This is in response to decompression during upward emplacement of the intrusive breccia phase. The absence of this style of stockwork vein mineralisation elsewhere at this level of exposure, supports the interpretation that the intrusive breccia phase was emplaced upwards from a considerable depth (Baker and Tullemans, 1990).

Tourmaline breccia clasts occur within a 100 by 200 m area of the breccia pipe to the northwest of Wise's Hill (Figure 4.8). The breccia consists of either rhyolite or

granodiorite clasts cemented by a tourmaline-quartz matrix. Shingle like clasts of rhyolite are imbricated parallel to the faces of larger clasts, indicating that this breccia was also produced by hypogene exfoliation. Many of the rhyolite clasts contain stockwork quartz-pyrite veining.

4.3.5 Mineralisation and Alteration

Mineralisation and alteration at Kidston can be divided into pre- and post-breccia on the basis of timing relative to breccia pipe formation.

Pre-breccia mineralisation is minor, and restricted to breccia clasts which contain stockwork quartz veins associated with a variety of sulphide phases and magnetite. The veins consist of a fine grained mosaic of quartz grains with laminations parallel to the vein wall, where various sulphide and silicate phases are concentrated. The upper part of the pre-breccia plug at Wise's Hill is cut by numerous quartz-pyrite \pm molybdenite-arsenopyrite-chalcopyrite veins. These stockwork veins do not extend downwards from the rhyolite cap into the porphyry which is present below the zone of crenulate quartz layers. Isolated clasts showing stockwork quartz veins within the centre of the pipe contain varying amounts of magnetite and pyrite and are occasionally associated with anomalous but uneconomic gold mineralisation. The quartz-pyrite stockwork veins are associated with alteration selvages of muscovite and carbonate. The magnetite bearing stockwork veins are associated with either muscovite-quartz or orthoclase-epidote-chlorite alteration, both within the vein lamination and as selvages to the veins.

Post-breccia mineralisation is widespread and more complex, consisting of early stage cavity infill assemblages associated with only minor amounts of gold, and late stage cavity infill and sheeted veins which together comprise the economic ore. The alteration associated with post-breccia mineralisation is confined to the breccia matrix and the outer 20 to 30 mm of the clasts.

The early stage post-breccia cavity infill assemblages are quartz-epidote and calcite, with or without pyrite and/or pyrrhotite. The quartz-epidote assemblage is confined to two semicircular zones around the periphery of the pipe, with the calcite infill assemblage being present throughout the rest of the pipe. The quartz-epidote assemblage is associated with anomalous but uneconomic grade gold mineralisation. Quartz-epidote in cavities is associated with white coloured, weakly developed (orthoclase type) potassic alteration,

which consists of orthoclase replacing plagioclase, primary biotite in clasts, and matrix adjacent to the cavities.

Calcite cavity infill, surrounding quartz-epidote filled cavities, is associated with a cream coloured (muscovite-calcite type) phyllic alteration in which plagioclase and biotite are replaced by a mixture of muscovite, calcite, orthoclase, albite and chlorite. Throughout the remainder of the pipe calcite cavity infill is associated with pink coloured propylitic alteration. This differs from the phyllic alteration in being less intense, and consisting of less muscovite and more calcite and chlorite replacing matrix plagioclase and primary biotite.

Isolated patches of secondary biotite-siderite-pyrite cavity infill are restricted to the Wise's Hill area (Figure 4.9). Within this zone about 10 vol. % of the breccia is affected by this infill assemblage. The adjacent breccia is altered to a black colour due to the replacement of plagioclase and biotite by secondary biotite and siderite. This (secondary biotite type) potassic alteration overprints the earlier quartz-epidote cavities and associated (orthoclase type) potassic alteration. Locally the grade of gold mineralisation within these patches is as high as 1.2 g/t (Baker and Tullemaans, 1990).

Late stage post-breccia mineralisation consists of quartz-calcite-ankerite-sulphide cavity and sheeted vein infill associated with the economic grade gold mineralisation. The earliest infill phase is combs of quartz growing inwards from the cavity and vein walls. Carbonate and sulphide are interstitial phases. Sulphides in decreasing order of abundance are pyrite, pyrrhotite, sphalerite, chalcopyrite, molybdenite, galena, bismuthinite and a bismuth telluride mineral.

More than 90 wt % of the gold occurs as discrete grains generally from 20 to 100 μm in diameter. The remainder is a bismuth telluride mineral. The bulk grades of gold mineralisation decrease with an increase in the proportion of pyrrhotite to pyrite. Silver abundance is similar to gold but no silver minerals have been identified. Less than 25% of the silver can be accounted for by the silver content of gold which ranges from 0.5 to 30%. The location of the remaining silver is unknown but may be associated with galena.

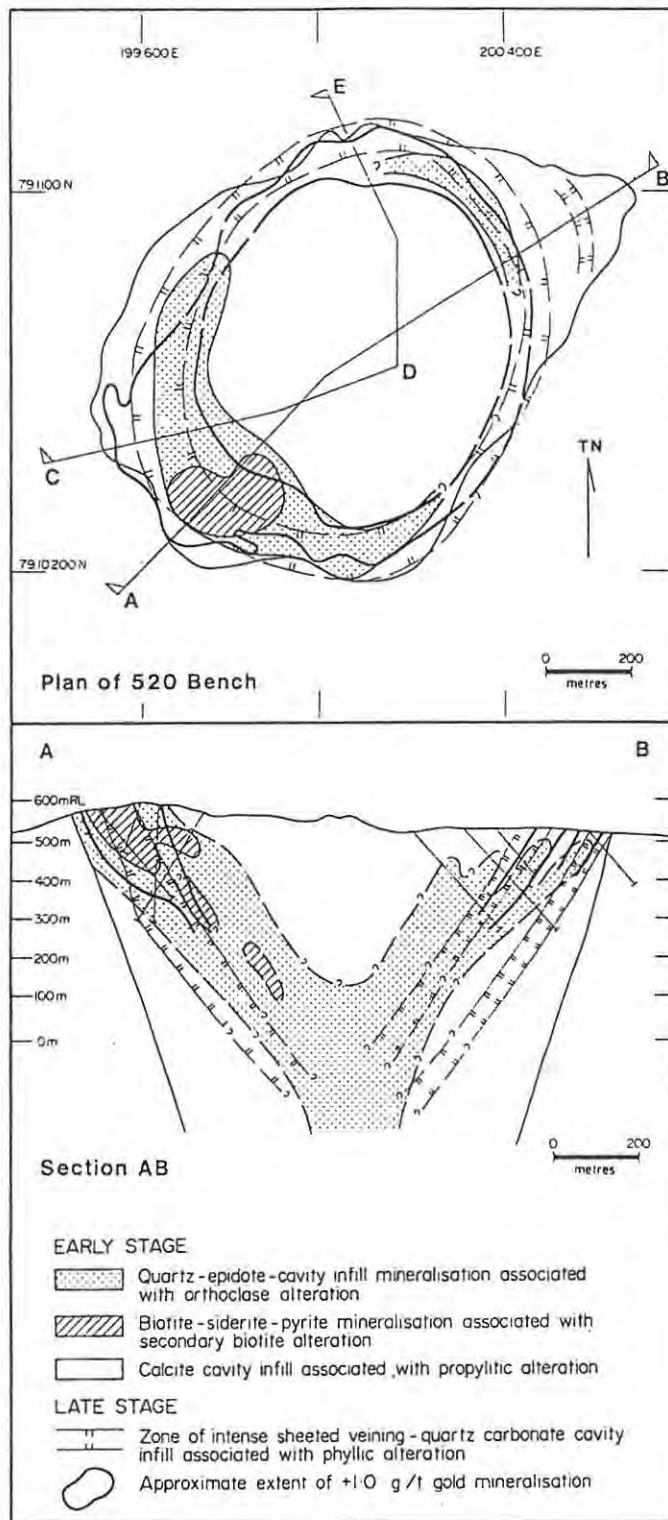


Figure 4.9 : Distribution of post-breccia early stage and late stage mineralisation and associated alteration (Baker and Tullemans, 1990).

The distribution and relation of gold mineralisation to base metal zoning is represented in cross-sections shown in Figure 4.10. The cross-sections show a vertical zoning from high gold plus base metals down into a lower grade gold zone with a suggestion of an increase in copper and molybdenum. The inner and upper portions of the copper and molybdenum zones probably reflect pre-breccia stockwork vein mineralisation.

The late stage cavities and sheeted veins are associated with white coloured (muscovite-quartz and muscovite-carbonate type) phyllic alteration. Quartz and muscovite decrease relative to carbonate as the intensity of alteration decreases away from cavities and vein walls. This alteration overprints the earlier potassic alteration where the two stages overlap, as shown in Figure 4.10. Some cavities show a transition in infill assemblages from early stage quartz-epidote associated with (orthoclase type) potassic alteration to late stage quartz-carbonate-sulphide infill associated with phyllic alteration. In these transitional cavities the early stage epidote is replaced by muscovite and carbonate (Baker and Tullemans, 1990).

Oxidation. The sulphides have been oxidised to an average depth of 25 m throughout most of the orebody. The upper half of the oxidation profile is stained a red-brown colour due to limonite, hematite and jarosite after pyrite and pyrrhotite. The lower half of the profile is a bleached white colour without any limonite or hematite staining. Within the lower half pyrite and pyrrhotite are partly replaced by jarosite. Fractures and spaces produced by dissolution of carbonates have been filled with fine grained supergene alunite. Supergene chalcocite, chalcantite and minor covellite and cuprite have been concentrated in sufficient quantities at the base of the oxidation profile. The supergene copper minerals are preferentially concentrated within fractures, shears and pods of secondary biotite-siderite-pyrite cavity infill, preferentially replacing the siderite (Baker and Tullemans, 1990).

Oxidation has caused no apparent remobilisation or supergene enrichment of gold and silver (Graylin, 1981).

4.3.6 Isotope and Fluid Inclusion Studies

Isotope Studies. Alteration in the pipe has been dated at 320 ± 15 million years (Middle Carboniferous) using the Rb-Sr method (Wilson *et al.*, 1986), which is comparable to the Carboniferous age of the nearby ring complexes.

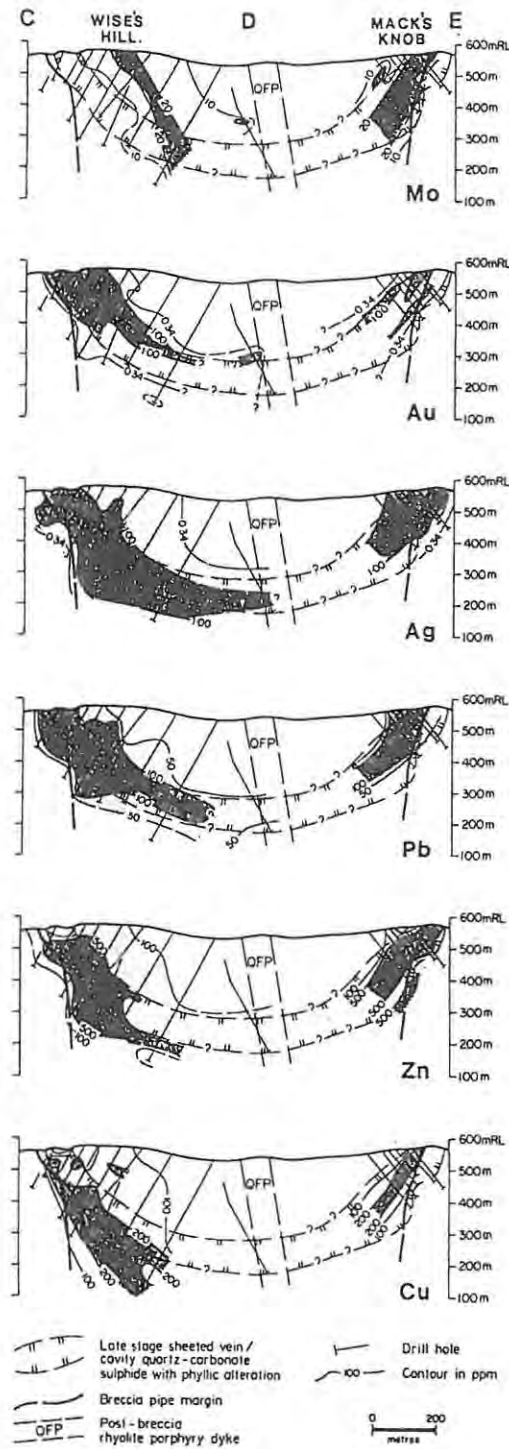


Figure 4.10 : Cross section C-D-E through the breccia pipe showing the distribution and relation between mineralisation and the late stage alteration (refer to Figure 4.9). Note that the actual dips of the zonations in the centre of the section are steeper than suggested. The apparent shallowing results from the section being offset from the centre of the mineralised zone (Baker and Tullemaans, 1990).

Stable isotope values are presented using the del-notation in per mil relative to V-SMOW for O and H, PDB for C and CDT for S.

Quartz in stockwork veins (from the pre-brecciation stage) have a well defined range of $\delta^{18}\text{O}$ values between +9.4 and +9.8. A single analysis of quartz from crenulate layers is enriched in ^{18}O ($\delta^{18}\text{O} = +10.6$) relative to the stockwork veins probably reflecting preferential partitioning of ^{16}O into the volatile phase. Epidote and chlorite from the selvages to quartz-pyrite-magnetite stockwork veins have δD values of -57 and -81 respectively.

The calculated hydrogen isotope composition for a fluid, using δD values for epidote and chlorite alteration associated with stockwork veining, are between -50 to -20 assuming a 500-600°C temperature range. The oxygen isotope data and high salinities in fluid inclusions fall within the relatively narrow range typical of waters in equilibrium with igneous rocks at high temperatures. δD values of -50 to -20 cannot be explained by normal magmatic or local meteoric fluids or by mixtures of the two, but a magmatic fluid which has exchanged isotopes with predominantly igneous rocks down to 300°C at low water/rock ratios, can explain the isotopic data (Baker and Andrew, 1988).

Quartz in quartz-epidote cavities (from post-brecciation early-stage) has a $\delta^{18}\text{O}$ value of +10.3 to +10.5. Orthoclase ($\delta^{18}\text{O} = +10.8$), muscovite ($\delta^{18}\text{O} = +8.8$, $\delta\text{D} = -68$) and epidote ($\delta\text{D} = -51$) alteration are associated with this cavity infill. Calcite cavity infill ($\delta^{18}\text{O} = +11$ to +14, $\delta^{13}\text{C} = -7.5$ to -6) is associated with chlorite and muscovite alteration with oxygen and hydrogen isotope values of $\delta^{18}\text{O} = +7.7$, $\delta\text{D} = -80$ and $\delta^{18}\text{O} = +9.3$, $\delta\text{D} = -71$ respectively. Secondary biotite alteration includes chlorite with a δD value of -87.

Using temperature estimates of 340-500°C, oxygen and hydrogen isotope values of +5 to +8 and -50 to -20 respectively are calculated for the fluid in equilibrium with early-stage cavity infill and alteration. This compositional range is similar to that calculated for the pre-breccia fluid except for a wider range in $\delta^{18}\text{O}$, due largely to a larger temperature uncertainty, and a somewhat lower salinity in fluid inclusions (Baker and Andrew, 1988).

Quartz cavities (from post-brecciation late-stage) and quartz-ankerite-pyrite sheeted veins are enriched in $\delta^{18}\text{O}$ relative to earlier quartz. Textural relations, as well as the large quartz-calcite fractionations, suggest calcite and ankerite fills cavities and veins post-date

quartz precipitation. Hydrogen isotope analyses from fluid inclusion extracts from sheeted veins and cavity infill have depleted δD values to between -111 and -71.

Using temperature estimates from quartz in sheeted veins and cavity infill, the oxygen isotope compositions of calculated water in equilibrium with late-stage mineralisation are +3 to +7. These depleted oxygen and hydrogen isotope values, together with the low salinities of the inclusion fluids, are diagnostic of meteoric waters and show that meteoric waters were a component in the latest gold depositing phase of the mineralising fluid. Oxygen isotope values from carbonates which are paragenetically later than quartz and sulphides within sheeted veins, have a much wider range of $\delta^{18}O$ values than earlier formed minerals. This suggests there were large variations in temperature and/or water/rock ratios throughout the pipe in the waning stages of alteration. For temperatures less than 400°C, all computed $\delta^{18}O$ values for the fluid in equilibrium with late stage carbonates are similar to, or lower than, the values calculated for water in equilibrium with quartz from late-stage mineralisation.

Oxygen isotope values from whole rock samples representing unmineralised granodiorite remote from the pipe ($\delta^{18}O = +8.3 - +9.4$) and altered granodiorite associated with late-stage mineralisation ($\delta^{18}O = +9.1 - +10.9$) show enrichment in $\delta^{18}O$ with alteration. The maximum shift in $\delta^{18}O$ values can be explained by interaction of late-stage fluid with $\delta^{18}O$ composition of +3 to +7 at temperatures 250-350°C and water/rock ratios of 1 atom% oxygen.

Sulphur isotope values in pyrite, pyrrhotite and basemetal sulphides, from late-stage cavities, veins and their alteration haloes, have values between +1.1 and +4.3. Sulphur isotope fractionations between coexisting sulphide pairs suggest temperatures around $300 \pm 80^\circ C$.

The narrow range of $\delta^{34}S$ and $\delta^{13}C$ values from the entire mineralisation sequence at Kidston, together with the absence of sulphates and graphite, and the presence of pyrrhotite and muscovite, indicates relatively reducing conditions prevailed at relatively neutral pH conditions. Under these conditions the values measured for the sulphides and carbonates approximate the sulphur and carbon isotope composition respectively of the mineralising fluid (Ohmoto, 1972). $\delta^{34}S$ values in the range -4 to +4 are commonly associated with felsic igneous rocks where the sulphur has been derived from an igneous

source. Similarly, weakly depleted $\delta^{13}\text{C}$ values are also typically associated with CO_2 degassed from a magmatic source (Baker and Andrew, 1988).

Fluid Inclusion Studies. Four types of fluid inclusions have been recognised in the mineralisation at Kidston, as shown in Table 4.4.

Type of Mineralisation	Inclusion Type	Homogenisation Temperature	Salinity (range)
Pre-breccia	S	350 - 600	40 - 50
	V	350 - 600	2 - 20
	L	260 - 500	2 - 20
	L (hydrate)	250 - 460	+20
	Critical	380 - 460	5 to 10
Post-breccia Early-stage	L	300 - 400	2 - 20
	V	350 - 600	10
	S	480 - 600?	<50?
Transitional & overprinted early- stage	V	300 - 400	3 - 10?
	L	200 - 460	1 - 8
	S	320 - 600	<50
Late-Stage	L	250 - 500	2 - 20
	V	300 - 400	2 - 10
	C (L+V)	300 - 400	0 - 10

Table 4.4 : Summary of homogenisation and salinity data for primary inclusions. The inclusion types are listed in order of abundance (Baker and Andrew, 1988).

Type S contains up to 5 daughter minerals, Types L and V homogenise into a liquid and vapour respectively, or less commonly critically, and Type C homogenise into liquid or vapour CO_2 .

Pre-breccia mineralisation contains abundant Type S inclusions, with Type V inclusions being more abundant than Type L. Vapour bubbles in Type S inclusions are relatively small and homogenise into liquid between 130°C and 350°C . Daughter phases homogenise over a range of temperatures, with KCl below 150°C , NaCl between 200°C and 500°C and iron \pm potassium chlorides below 400°C . Salinities for Type S inclusions are in the range 40 to 50 wt. % NaCl equivalent with a NaCl/KCl ratio of 1 to 2. Most Type V inclusions homogenise between 350°C and 500°C whereas Type L inclusions

generally homogenise below 400°C. Salinities for Type L and V inclusions are in the range 3 to 20 and 3 to 12 wt. % equivalent respectively (Baker and Andrew, 1988).

In pre-breccia stockwork veins, Type S, L and V inclusions appear to have been trapped together. Homogenisation of Type S inclusions by dissolution of daughter minerals indicates that the fluid did not boil and was trapped at pressures in excess of 800 bars.

In early stage post-breccia mineralisation, Type L inclusions are more abundant than Type V while Type S inclusions are rare. Most Type L inclusions homogenise between 200°C and 400°C, Type V inclusions homogenise at a mean temperature of 375°C. Inclusions which homogenise critically are in the range 400°C to 500°C. Rare Type S inclusions homogenise by dissolution of daughter phases between 350°C and 480°C, vapour bubbles in these inclusions homogenise below 250°C.

The homogenisation temperatures of inclusions within late-stage mineralisation were lower, with Type L inclusions homogenising over a range 120°C to 400°C. Type C inclusions homogenise critically into liquid or vapour between 350°C and 400°C.

The salinities of inclusions from all phases of post-breccia mineralisation range between 2 and 10 wt. % NaCl equivalent. Analyses of the salt from decrepitated fluid inclusions using the SEM/EDS method show significant amounts of Na, Mg, K, Ca, Fe, Mn, Cu, Zn, S, and Cl, indicating a composition similar to the pre-breccia fluid.

The composition of Type C inclusions range between 5 and 10 mol. % CO₂, with salinities similar to pre-breccia Type L and V inclusions. The introduction of CO₂ during transitional to late-stage mineralisation caused a drop in the critical temperature by about 75°C and the fluid to become immiscible and trapped as Type L and V inclusions (Baker and Andrew, 1988).

4.3.7 Ore Genesis

The genesis of the Kidston gold deposit is directly related to near surface emplacement of a volatile-rich, acid magma and involved a sequence of magmatic and hydrothermal events which included the formation of a large breccia pipe. A model for the formation of the Kidston gold deposit is shown in Figure 4.11.

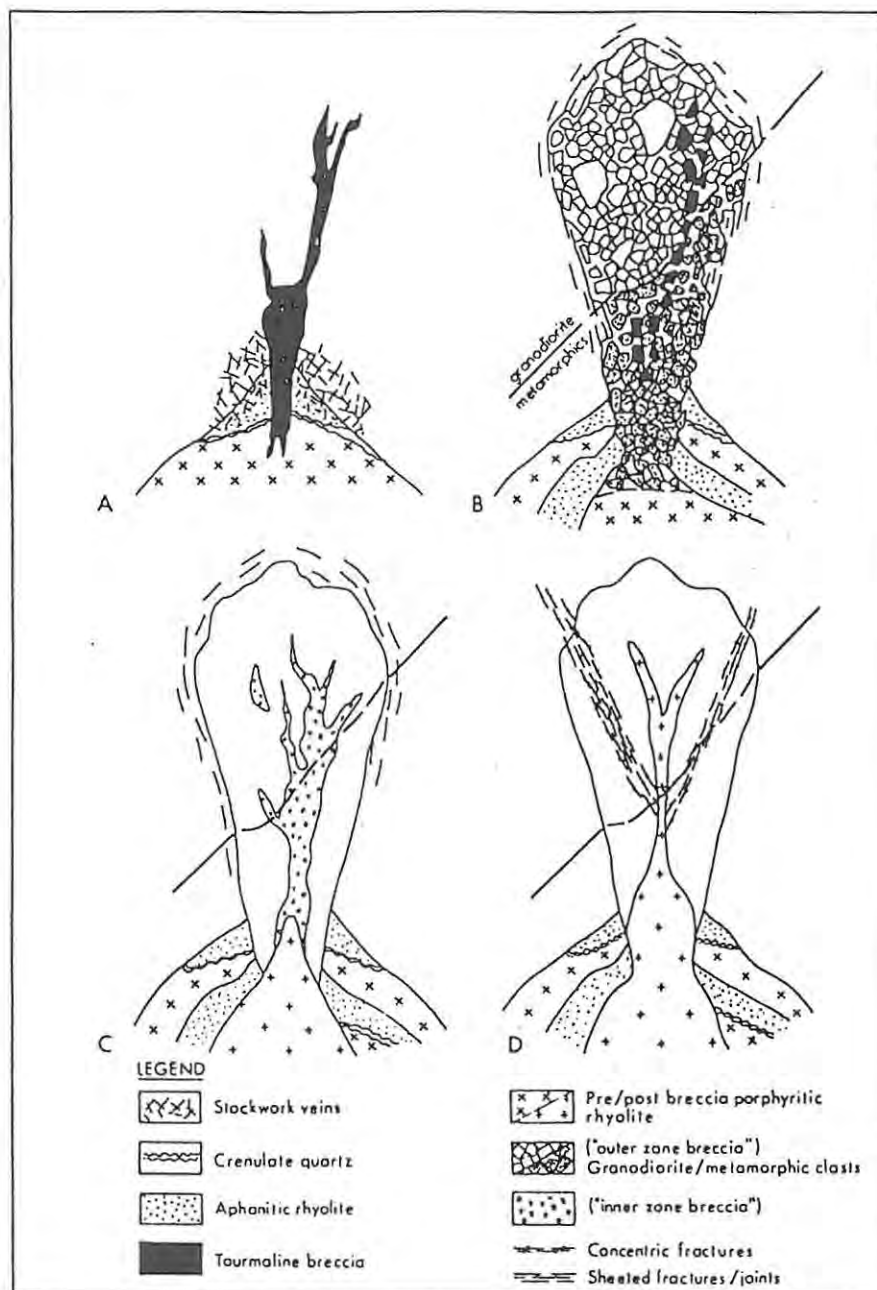


Figure 4.11 : Model for the formation of the Kidston breccia pipe. A., Development of pre-main stage stockwork veins and tourmaline breccia associated with the build up of hydrothermal fluid during crystallisation of the underlying batholith. B., Formation of main stage 'outer zone' breccia, resulting from the collapse of the overlying rocks into the space produced during the escape of hydrothermal fluid. C., Emplacement of the main stage 'inner zone' breccia associated with the emplacement of post-breccia rhyolite. D., Formation of radial and concentric fractures filled by post-breccia rhyolite and sheeted veins respectively, associated with the emplacement of post-breccia rhyolite (Baker, 1988).

The concentration of pre-main stage breccia events and rhyolite breccia in the southwestern sector of the pipe, suggests that there may have been some structural influence in localising the activity in this area (Mustard, 1986).

Brecciation and mineralisation at Kidston are spatially and temporally associated with the emplacement of dykes and plugs of quartz-feldspar porphyry and rhyolite. The lack of any significant mixing of clast material, the angular shape of clasts and the limited amount of matrix, suggest that most of the breccia was produced by collapse. The initial space required to begin collapse was probably produced by the escape of volatiles from the apical portion of a partly crystallised batholith. The emplacement of the intrusive breccia containing mineralised and rounded clasts in the centre of the pipe, is probably related to the emplacement of the post-breccia radial dykes.

Pre-breccia stockwork quartz veins are localised around the roof portions of the small plugs. They were produced as a result of hydraulic fracturing by an overpressured magmatic fluid derived from the crystallising melt below. Tourmaline brecciation resulted from the escape of an overpressured boron rich fluid.

Post-breccia cavity infill and sheeted veining are most strongly developed in a narrow circular zone around the periphery of the breccia pipe. This zone formed in response to the forceful emplacement of the post-breccia porphyry. Early stage post-breccia mineralisation consisted of quartz-epidote-pyrite-pyrrhotite and biotite-siderite-pyrite cavity infill assemblages associated with potassic alteration. The fluid associated with early stage post-breccia alteration and mineralisation was produced by boiling of an overpressured saline magmatic fluid at a deeper level (Baker and Andrew, 1988). Late stage post-breccia cavity and sheeted vein infill assemblages are associated with phyllic alteration; this mineralisation hosts the economic gold mineralisation. The fluid associated with late stage post-breccia mineralisation was of a lower temperature than the early stage post-breccia, contained minor carbon dioxide and was at least partly meteoric (Baker and Andrew, 1988). Throughout the remainder of the pipe, cavity infill consists of early stage post-breccia calcite associated with phyllic to propylitic alteration.

4.4 Mount Wright Breccia Pipe

4.4.1 Introduction

Mount Wright is located approximately 8 km northwest of Ravenswood, north Queensland. It forms a 120 m high conical hill within undulating plains of the Ravenswood Granodiorite Complex.

The gold mineralisation at Mount Wright occurs in a breccia pipe. Mining of the breccia pipe took place in the early 1900's. Low gold grades and poor evaluation of the Mount Wright breccia pipe has presently made the prospect uneconomical to mine.

The Mount Wright gold mineralisation is currently being investigated by Carpentaria Exploration (Mount Isa Mines Limited). The depletion of ore reserves, from the Ravenswood gold mine owned by Carpentaria Exploration, has led to further exploration in the Ravenswood area to replenish the ore reserves. Carpentaria Exploration has aimed their exploration program around Mount Wright to accomplish this goal.

Carpentaria Exploration drilled a diamond hole into the Mount Wright breccia pipe, during late 1992, and intersected approximately 400 m grading 3 g/t gold. This intersection has allowed continued exploration drilling in the Mount Wright area.

Little geological information is known about the Mount Wright breccia pipe but it may prove to be another low-grade gold breccia complex within the Thomson Fold Belt in north Queensland.

4.4.2 Exploration and Production History

A mine called the 'Mother Lode' was the first attempt to extract gold from the Mount Wright breccia pipe. It was opened in 1917 but was not worked extensively until 1923. Until 1927 various small parties worked the deposit but without success. Mother Lode Gold Mines Limited was formed in 1927, but it too was unsuccessful, and the mine was abandoned in 1929. The mine was re-opened and worked with moderate success during the 1938 to 1942 period (Clarke, 1969).

Total production is approximately 35 kg of gold and 20 kg of silver over the 1917-1942 period (Murray, 1990).

The Queensland Mines Department drilled the breccia pipe in 1956. They concluded that the zone of gold mineralisation is restricted to an annular area, approximately 20 to 30 m in diameter, surrounding a core of unaltered granite. They also concluded that the drilling has shown beyond doubt that the zone of gold mineralisation is too small for large scale exploitation (Clarke, 1969).

4.4.3 The Mount Wright Breccia Pipe

The Millaroo Granite is the host rock of the breccia pipe gold deposit at Mount Wright, the breccia consisting mainly of biotite granite. The granite intrudes the Kirk River Beds (micaceous shale, lithic sandstone and siltstone), the Mount Windsor Volcanics (rhyolite flows, minor acid pyroclastics, intermediate volcanics, and sediments), and the Glenell Granodiorite (medium-grained, porphyritic, grey hornblende-biotite granodiorite). The outcrop of the southwestern contact of the granite is strongly controlled by topography, and it is inferred that the contact here dips gently northeastward. The contacts of the Millaroo Granite are generally not sheared.

The Millaroo Granite, near Mount Wright, is coarse-grained and contains fractured, slightly strained quartz phenocrysts with a maximum diameter of 1 cm. The groundmass consists of micropertite which occurs as large 'pools' enclosing numerous rounded quartz grains, of average diameter 2 mm, and laths of oligoclase. The composition of the granite is quartz (50%), micropertite (22%), oligoclase (14%), and partly chloritised biotite (4%). Spene occurs as an accessory mineral of subhedral crystals up to 1.5 mm long. Biotite occurs both as large flakes up to 5 mm diameter, which are slightly chloritised at the edges, and as small flakes up to 1 mm diameter, which are completely chloritised (Clarke, 1969).

Abundant acid (felsite) and intermediate dykes intrude the Millaroo Granite. Microdiorite to fine-grained diorite dykes are fairly frequent near the contact with the tonalite of the main granodiorite phase (Clarke, 1969).

The Mount Wright breccia pipe is a clast supported breccia that consists dominantly of angular Millaroo Granite clasts but also contains fragments of fine-grained acid volcanics

and dyke material. The matrix of the breccia is sparse and consists of crushed granite rock flour. The hydrothermal alteration of the breccia pipe caused feldspars to be strongly kaolinised and the mafic minerals of the granite to be obliterated. Small masses of siderite occur throughout the pipe. Pyrite is disseminated irregularly in the pipe, and is associated with very minor sphalerite, molybdenite, and secondary copper. Breccia near the summit of Mount Wright consists chiefly of rhyolite and greisenised granite fragments. Rhyolite dykes intrude the breccia and the nearby granite. The largest dyke forms a ridge projecting from the west-northwest side of Mount Wright (Clarke, 1969).

4.4.4 Ore Genesis

The Mount Wright breccia pipe is believed to be related to Late Carboniferous-Early Permian volcanism within the Ravenswood Granodiorite Complex. The near surface emplacement of an acid magma, and associated hydrothermal events, formed the breccia pipe. A deep seated porphyry body would most likely be the initial source of fluids.

Brecciation allowed the mineralising fluids to proceed through the pipe and to deposit the sulphides in cavities and fractures. Gold mineralisation is mostly disseminated within pyrite and minor basemetal sulphides.

4.5 General Discussion

The volcanic landform-ore deposits association of northern Queensland is a direct result of the genetic connection between shallow ore-forming processes and volcanic and subvolcanic activity. Mineralised breccia complexes represent the most common style of post-orogenic acid-volcanic gold mineralisation in northern Queensland. High-level breccia pipes are invariably intrusive in character due to their high volatile contents and shallow emplacement depths. They vary in characteristics according to their original volatile contents. Widespread sericitisation, kaolinisation, and pyrite mineralisation are common and disseminated and fracture/vein-controlled gold and base metal sulphides can be present (Horton, 1987).

Porphyry-related breccia complex deposits are best developed in the Georgetown and Charters Towers Provinces. All the significant occurrences are associated with Permo-Carboniferous subvolcanic complexes with dykes, plugs, stocks and breccias of rhyolitic

to trachytic composition. There are distinct clusters of deposits adjacent to the major outcrop areas of Permo-Carboniferous granitoids and volcanics, but very few occurrences are actually hosted within these units. Rather the occurrences are in discrete corridors characterised by concentrations of subvolcanic intrusions, with gravity and magnetic anomalies suggesting underlying plutons, and in some cases crustal scale faults (Morrison, 1988).

Porphyry-related vein and stockwork deposits are widespread and may occur on their own or in association with other porphyry deposit styles. The common association is with porphyry dykes in re-activated shear zones, or in complex fault and fracture sets formed in a regional stress field or during intrusion emplacement. Fissure rather than shear lodes predominate in most deposits and individual veins have sharp walls and minor wall rock inclusions. The veins themselves are dominated by fine clear elongate euhedral quartz crystals growing in combs, lining vughs or as cockade overgrowths. Carbonate is a common associate and sulphides typically constitute 15-20% of the shoots.

There are numerous Permo-Carboniferous breccia bodies in northeast Queensland but only a few contain significant gold mineralisation. The mineralised breccias are typically localised near the intersection of the intrusive 'corridors' with major structural or lithologic contacts. The breccia bodies are up to 2 km in diameter, have a pipe-like form and are characterised by multiple breccia and intrusive phases.

Two major styles of gold-bearing breccia complexes are recognised by Morrison (1988) :

1. The subvolcanic breccias, typified by Kidston have the form of an inverted cone centred above a porphyry plug or stock, a predominance of angular clast-supported breccia with a tabular style typical of the pipe margin, a partly rounded style in the core and in some cases a collapsed roof that partly preserves original host rock stratigraphy. Such breccia pipes are interpreted to form in the subvolcanic environment in direct response to magmatic hydrothermal evolution in porphyry bodies, and to have limited interaction with surface waters (Baker *et al.*, 1986). The Mount Wright breccia pipe would most likely have formed under these conditions.

2. The diatreme breccias, typified by Mount Leyshon are more complex. They are nested multiple breccia bodies related to various igneous intrusive events. Gold mineralisation occurs within intrusive breccias, altered porphyritic intrusives and partially brecciated basement. The breccia complex is interpreted to result from several phases of magma-derived volatile release. Unit geometry and facies characteristics are consistent with subsurface development of the complex.

Despite the variations in breccia origin, there are a lot of similarities in mineralisation distribution, style and mineralogy between the subvolcanic and diatreme breccia complexes. Mineralisation is most commonly in structurally controlled post-breccia veins that may be restricted to one portion of the pipe or as cavity fill. Mineralisation can generally be related to a resurgent or late intrusive phase that may or may not be accompanied by a new breccia phase. The overall mineral paragenesis is early, often pre-breccia, Cu-Mo quartz stockworks with potassic alteration, post-breccia main stage pyrite-basemetal sulphide- Bi + Te + Ag + Au with sericitic alteration and a late carbonate stage. There are prominent metal zoning stages and gold distributions comparable to that described for the porphyry related veins. The overall features of the mineralisation are comparable to the magmatic-hydrothermal breccias described by Sillitoe (1985).

Despite the variation of deposit styles within the Permo-Carboniferous porphyry environment, there are unifying geomorphic, geologic, paragenetic and fluid characteristics that suggest many of the deposits have a similar origin. Using the Mount Leyshon, Kidston and Mount Wright deposits, these characteristics can be described as follows :

1. The breccia complexes exist as prominent topographic highs with radiating drainage.
2. Alluvial gold has been exploited in streams and creeks draining each breccia complex.
3. Each breccia complex has related volcanics, porphyries and breccias that are of Permo-Carboniferous age.
4. Localisation in or adjacent to a regional scale lineament or structural corridor.
5. Association with I-type granite/granodiorite batholiths and their contacts with older, fine-grained sedimentary rock sequences.

6. Association with a multiphase subvolcanic intrusive complex and a close timing between intrusive and mineralisation phases.
7. Brittle mineralisation structures with a predominance of fissure fill and open space ore textures. The presence of clast supported breccias enhances permeability resulting from open spaces between fragments allowing mineralising fluids to pass into the breccia.
8. Early potassic alteration with Mo-Cu stockwork mineralisation formed from overpressured magmatic fluids at approximately 500°C and 30-50% salinity.
9. The main mineralisation stage, with overprint of sericitic alteration and basemetal-rich mineralisation, has formed from a magmatic gas condensate at approximately 300-400°C with less than 10% salinity and minor CO₂.
10. Gold is best developed in the bismuth stage as free grains, inclusions in sulphides or as alloys with Te, Ag.
11. Little or no development of advanced argillic alteration and possible minor late stage meteoric water input.
12. A 20-30 m oxidised zone is developed at the surface of the breccia complexes with a thin (0.5-5.0 m) supergene zone below.
13. There is a favourable geophysical expression that the breccia complexes exhibit. This is generally a radiometric high and a magnetic low.
14. The gold distribution within the breccia complexes is log-normally distributed and log-normal kriging is applied to delineate ore reserves.

Most of these features are more typical of continental rhyolitic porphyry Cu-Mo or alkaline porphyry molybdenum systems, rather than island-arc intermediate Cu-Au porphyry systems (Sillitoe, 1983). The distinctive feature of the northeast Queensland deposits is the development of major low-grade gold deposits superimposed on sub-economic, poorly developed Cu-Mo mineralisation. All of the major deposits have been shown to relate to magmatic hydrothermal systems with little or no evidence of meteoric water input or development of peripheral epithermal mineralisation (Sillitoe, 1983).

An exploration model to incorporate the Mount Leyshon, Kidston and Mount Wright gold deposits will be developed in Chapter 5.

5.0 Exploration for Gold-Related Volcanic Breccia Complexes

5.1 Introduction

Exploration is primarily directed at identifying hydrothermal alteration, followed by detailed ground studies including geological, mineralogical, petrological and geochemical work, with the idea of constructing a 'model' that can be tested with subsequent subsurface work (e.g. drilling). A mineral deposit model combines a number of essential features shared by a group of mineral deposits. In modelling ore deposits, facts and evidence must be evaluated in the light of common factors, using geological, geochemical and geophysical data bases. Consideration of insufficient pieces of evidence may be grossly misleading. Ore deposit modelling is a cheap and highly effective tool for mineral exploration and resource assessment, and its flexibility allows for new evidence to be rapidly evaluated and the exploration philosophy and methodology changed accordingly. High cost techniques for a detailed economic evaluation of the deposit should follow only if a model has been tested and proved correct, even if only on a regional or broad scale.

The following chapter establishes an exploration ore genesis model for gold-related volcanic breccia complex deposits in the Thomson Fold Belt and Georgetown Inlier, and then describes various methods that may be used to explore for these type of deposits. The model envisaged is a general simplification of the combined Kidston and Mount Leyshon deposit environments.

5.2 Model for Volcanic Breccia Complexes in North Queensland

5.2.1 Volcanism and Tectonic Setting

Partial melting of hornblende-bearing mafic rocks of igneous origin, whether amphibolitised oceanic basalts in subduction zones beneath island-arcs or hornblende gabbros in the lower continental crust, yield I-type calc-alkaline magmas with the requisite chemical composition to be the direct progenitors of typical hornblende-bearing copper-gold porphyries. Partial melting of biotite-bearing continental crust rocks, such as

tonalitic and granodioritic gneisses, yields more alkali I-type magmas with the requisite properties to be the progenitors of typical molybdenum porphyries, as well as some copper-molybdenum porphyries. Other molybdenum porphyries appear to represent partial melts formed from mixed biotite- and muscovite-bearing source rocks (mixed I- and S-types).

The Kidston, Mount Leyshon and Mount Wright breccia complexes are intrusion-related gold deposits that were generated at a Phanerozoic convergent plate margin above a zone of active subduction. The convergent margins of these deposits, range from primitive through mature island-arcs to continental margins throughout the world. The overall constitution and thickness of the lithosphere are not fundamental controls of intrusion-related gold deposits.

Extensional conditions were commonly accompanied by bimodal magmatism dominated by silicic products. These conditions may have characterised northern Queensland in the Carboniferous, when gold deposits were generated in association with rhyolitic to trachytic intrusions (Morrison, 1988). Alkaline magmatism also marks extensional situations, commonly in back-arc environments, as exemplified by the Late Cretaceous to mid-Tertiary intrusions and gold deposits of Montana, South Dakota, Colorado, and New Mexico in the western USA.

Many convergent plate boundaries were constructed by accretion of numerous tectono-stratigraphic terranes, some including parts of volcano-plutonic arcs, which attained their present sites as the combined results of subduction and transform faulting. Such tectonically emplaced allochthonous terranes may contain intrusion-related gold deposits. Intrusion-related deposits are generally considered to be the products of convergence that resulted in continental collision. Magmatism and associated gold mineralisation may have been triggered by crustal thickening consequent upon collisional tectonics as, for example, in the Damaran part of the Pan-African orogen in Namibia (Miller, 1983).

The tectonic model representing the volcanism within the Thomson Fold Belt and the Georgetown Inlier can be represented as in Figure 5.1. The marginal basins are the product of successive splitting and rifting of subduction-related volcanic arc blocks, and the ocean-ward migration of the frontal half of the rifted block, by the opening of a new back-arc or inter-arc basin containing a small-scale seafloor spreading centre. This is suggested by irregular topography, little or no sediment cover, high heat flow and limited

magnetic anomaly patterns over elevated basin centre areas. The successive splitting of the arc block, and the seaward migration of the frontal arc, produced a sequence of progressively younger back-arc basins ocean-wards, by successive 'small-scale' seafloor spreading in these basins. The part of the rifted block that stays behind is called the remnant or third arc. The basins and ridges or rises of eastern Australia, and east of the Chinese mainland, have the ages predicted by this model, and are floored by oceanic crust (Karig, 1974). The Thomson Fold Belt and Georgetown Inlier would of been represented as an active-marginal basin progressing into a remnant arc environment (Figure 5.1) at the time of Permo-Carboniferous magma activity.

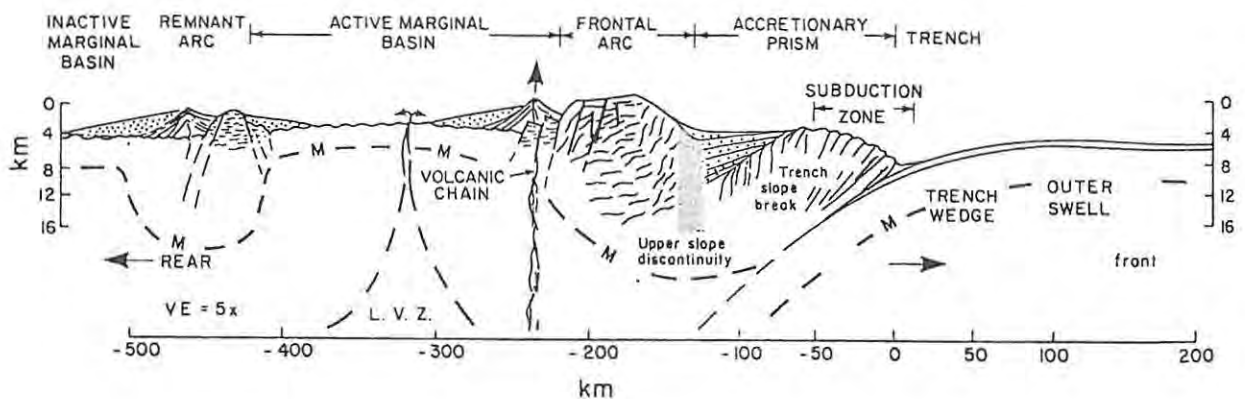


Figure 5.1 : Essential elements of an active back-arc-inter-arc-marginal basin and its associated arc-subduction complex (Karig, 1974).

5.2.2 Classification of Volcanic Breccia Complexes

A broad spectrum of gold mineralisation styles is found in the epizonal intrusive environment, and a number of these give rise to world-class gold deposits (Figure 5.2).

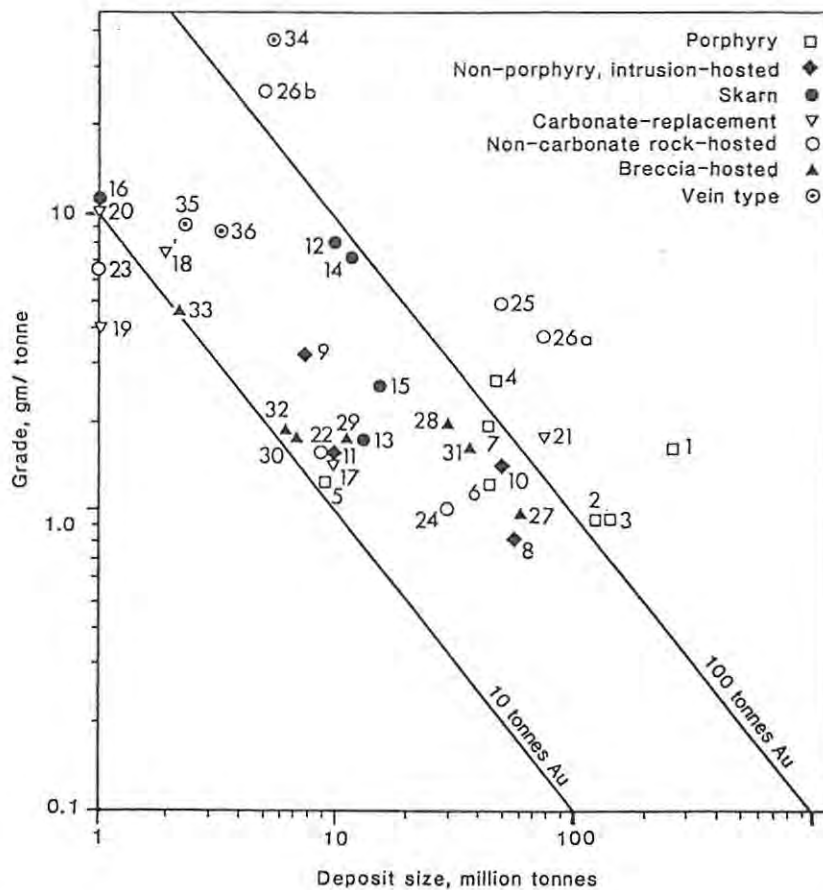


Figure 5.2 : Grade-tonnage plot for some representative gold deposits (Sillitoe, 1991).
 Numbers : (1) Lepanto, (2) Santo Tomas II, (3) Dizon, (4) Ok Tedi, (5) Cuervo, (6) Marte, (7) Boddington, (8) Zortman-Landusky, (9) Salave, (10) Gilt Edge, (11) Kori Kollo, (12) Fortitude, (13) McCoy, (14) Nickel Plate, (15) Red Dome, (16) Thanksgiving, (17) Barney's Canyon, (18) Tai Parit, (19) Star Pointer, (20) Ketz River, (21) Cove, (22) Beal, (23) Quesnel River, (24) Equity Silver, (25) Mount Morgan, (26a) Porgera (Waruwari), (26b) Porgera (Zone VII), (27) Montana Tunnels, (28) Golden Sunlight, (29) Colosseum, (30) Ortiz, (31) Kidston, (32) Mount Leyshon, (33) Chadbourne, (34) Charters Towers, (35) Los Mantos de Punitaqui, (36) Masara.

The spectrum of deposits is subdivided by Sillitoe (1991) into five categories classifying the intrusion-related gold deposits :

1. Intrusion-hosted stockwork/disseminated deposits of both porphyry and non-porphyry types, the former possessing all the essential geological attributes (especially multi-directional stockworks) of typical porphyry copper and/or molybdenum deposits.
2. Skarn and non-skarn replacement deposits in carbonate wall rocks.

3. Stockwork, disseminated and replacement deposits in non-carbonate wall rocks.
4. Wall rock-hosted breccia pipes.
5. Veins in both intrusions and wall rocks

The class of deposits, that are of interest within this report, are classified into the 'wall rock-hosted breccia pipes'. Although hydrothermal breccias are common components of intrusion-related gold deposits, especially those hosted by the intrusions themselves, a discrete class of gold deposits confined to pipe-like breccias is evident. These breccias (as shown in Table 5.1) generally transect wall rock lithologies, and therefore must be related to concealed intrusions. However, outcropping intrusions, commonly in the form of felsic dykes and/or sills (e.g. Kidston, Montana Tunnels, Golden Sunlight, Colosseum, Mount Leyshon and probably Ortiz), may be interpreted to possess genetic and perhaps physical connections with the inferred intrusions at depth. Porphyry copper or molybdenum protore is associated with the auriferous breccia pipes and pre-dates brecciation at Kidston (Baker, 1987), Mount Leyshon (Morrison *et al.*, 1988) and Golden Sunlight. At Kidston and Mount Leyshon the protore was incorporated as clasts in the pipe breccias.

Deposit	Status	Contained Au, tonnes	Age, Ma	Ore-related intrusion	Associated mineralization	Host rocks	Metal association	Key hypogene alteration, minerals	Data source(s)
Montana Tunnels, Montana, USA	Mine: open pit, flotation	60	45-50	Quartz, latite porphyry dykes	None	Late Cretaceous and middle Eocene andesitic and felsic volcanics	Au-Ag-Zn-Pb-Mn- (Cu)	Sericite, carbonates	Sillitoe <i>et al.</i> (1985)
Golden Sunlight, Montana, USA	Mine: open pit, CIP	59	Early Tertiary	Latite porphyry sills	Minor porphyry Cu-Mo protore, Au veins	Proterozoic calcareous shale	Au- (Cu-Pb-Zn-Bi-Te)	Silicification, decalcification	Porter and Ripley (1985)
Colosseum, California, USA	Mine: open pit, CIP	20	100	Rhyolite plug and dykes	Ag veins	Precambrian gneiss	Au- (Zn-Cu- Pb)	Sericite, carbonates	Sharp (1984)
Ortiz, New Mexico, USA	Abandoned mine (open pit, heap leach)	11	34	Monzonite stock, latite porphyry plugs and dykes	Au breccias and veins, Cu-Au skarns	Late Cretaceous quartzite and argillite	Au-W-Cu- (Pb)	Sericite, carbonates	Lindquist (1980); Wright (1983)
Kidston, Queensland, Australia	Mine: open pit, CIP	101	321	Rhyolite plugs and dykes	Porphyry Mo protore	Proterozoic metamorphics and Proterozoic or Palaeozoic granodiorite	Au-Zn-Cu-Mo-Pb- (As-Bi-Te)	Orthoclase-biotite-siderite, sericite-carbonates	Mustard (1986); Wilson <i>et al.</i> (1986); Baker (1987); Baker and Andrew (1988)
Mount Leyshon, Queensland, Australia	Mine: open pit, heap leach	26	280	Trachyte plugs and dykes	Porphyry Cu-Mo protore	Cambrian metasediments	Au-Zn-Pb- Cu- (Mo-Bi)	Biotite-K-feldspar, sericite	Morrison <i>et al.</i> (1987, 1988)
Chadbourne, Quebec, Canada	Mine: underground, flotation	9	Archaean	Syenite stocks	None	Archaean felsic and mafic metavolcanics	Au- (Cu-Zn)	Sericite, carbonates	Walker and Cregheur (1982)

Table 5.1 : Characteristics of selected breccia-hosted gold deposits (Sillitoe, 1991).

The gold-bearing breccia pipes/complexes of north Queensland may be subdivided into two distinct systems, as shown in Figure 5.3:

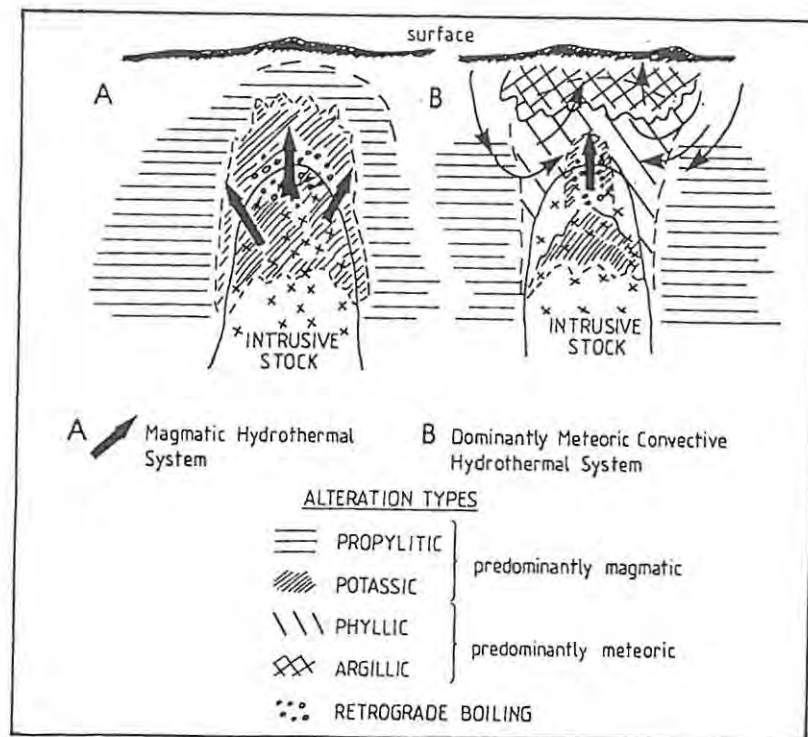


Figure 5.3 : Stages A and B in the development of a magmatic-hydrothermal system in a porphyry system, with later input of meteoric water and associated alteration patterns. Drawing not to scale (McMillan and Panteleyev, 1980).

1. **Magmatic-hydrothermal breccia systems** (Figure 5.3A) at Golden Sunlight, Colosseum, Ortiz, Kidston and Chadbourne. These systems are usually generated in H₂O-rich magmas, such as muscovite-bearing granitoids (>8 wt. % H₂O). The magmas tend to crystallise at depths ranging from a few kilometres to 10 km, and do not usually vent at the surface. Although they may, at certain stages, intrude into wet crustal rocks and interact with connate or metamorphic waters. In a closed system, the magma cools and crystallises, H₂O, other volatiles and incompatible elements remain largely excluded from the consolidating mass. Volatile components are at first randomly distributed throughout the upper and central regions of the magmatic body. During late stages of magmatic crystallisation, fluids are contained in the interstices of the granitic minerals.

Eventually, the residual fluid phases may coalesce and concentrate into zones to induce auto-metasomatism of the igneous parent. In other words, the newly consolidated igneous body 'stews in its own juice'. This usually begins with late-stage alkali metasomatism. The aqueous and gas phases exsolved from the magma will form a hydrothermal solution. This leads to a stage of hydrogen-ion metasomatism during which greisen-related deposits may form (Breccia Phase 1 at Kidston; Table 4.3). With decreasing temperature and pressure, and the presence of channel ways, the fluids may eventually escape into the surrounding country rocks.

2. **Magmatic-meteoric-hydrothermal breccia systems (phreatomagmatic)** (Figure 5.3B) at Montana Tunnels and Mount Leyshon. The magmatic-meteoric-hydrothermal breccia system commonly starts as described for magmatic-hydrothermal breccia systems, in the closed system of a plutonic body. In this case, however, by virtue of its relatively low initial water content, the magma rises closer to the surface and may vent to form a stratovolcano. This is most typical of both porphyry and epithermal systems. The cooling pluton supplies the thermal energy and in the initial stages the fluids. At a later stage, the fluids may be supplied from meteoric waters and ground waters (aquifers). These waters become heated as they are approached by, or descend into, the region influenced by the igneous body or bodies. Cooling of igneous bodies at depth provides powerful heat engines. Meteoric or ground waters will form convection cells whose activity will last at least until the thermal energy of the cooling igneous rocks has entirely dissipated (Pirajno, 1992).

The gold-bearing magmatic-hydrothermal and phreatomagmatic breccias post-date the development of a porphyry-type protore at Kidston and Mount Leyshon. The magmatic-hydrothermal breccias were initially emplaced largely without the involvement of meteoric-hydrothermal fluids, within a closed system. Later magma impulses reached higher levels in the cooled upper magma chamber, where meteoric water invaded the fracture system, to produce meteoric-hydrothermal fluids and an explosive emplacement of phreatomagmatic breccias. This type of mechanism of initial magmatic-hydrothermal breccia development, followed by phreatomagmatic breccias, is especially characterised at the Mount Leyshon breccia complex.

One of the pre-eminent features apparent from the Permo-Carboniferous gold-related volcanic breccia complexes in north Queensland, is the intimate association between wall rock-hosted gold deposits and porphyry-type copper-molybdenum or molybdenum

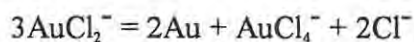
mineralisation in the progenitor intrusions. Hydrothermal overprinting and/or telescoping are common complicating factors in many intrusion-centred districts, and result in the juxtaposition or superimposition of earlier and later gold deposit types. Breccia-hosted gold deposits, of the gold-related volcanic breccia complex-type, have multiple episodes of intrusions that cut through and partially destroy at least the upper parts of the porphyry-type stockworks and related hydrothermal alteration.

5.2.3 Hydrothermal Chemistry of Gold

A hydrothermal system, can be loosely defined as the distribution of hot fluids circulating laterally and vertically at various temperatures and pressures, below the Earth's surface. The system consists of two essential components: a heat source, and a fluid phase. An actively convective hydrothermal cell will consist of a recharge system, a circulation cell and a discharge system. A hydrothermal mineral deposit is formed by the circulation of warm to hot fluids (about 50 to >500°C) that leach, transport and subsequently precipitate their mineral load in response to changing physio-chemical conditions. The rocks within which the deposit is formed undergo varying degrees of hydrothermal alteration, the intensity of which, as a rule, decreases away from the discharge site(s), and hence from the mineralised body.

In hydrothermal systems in the Earth's crust, mineral solution equilibrium gave rise to ore-forming fluids, which are characterised by low oxidation potentials (Seward, 1984), such that the dominant oxidation state of dissolved gold is +1. Thus, it is the coordination chemistry of Au(I) when considering the transport and deposition of gold in hydrothermal ore-forming systems. Au(I) complexes are generally not very stable in aqueous solutions and disproportionate to elemental gold and Au(III). However, depending upon the composition, temperature and pressure of the ore-forming fluid, complexes with other ligands such as chloride, may also contribute to, or in some cases comprise, the total gold in solution.

The dichloridogold(I) complex, AuCl_2^- , is potentially of geochemical interest in so far as AuCl_2^- has been considered to be of some importance in the transport of gold in hydrothermal ore-depositing systems. However, AuCl_2^- decomposes in water at 25°C according to the reaction :



Uematsu and Franck (1980) have shown that AuCl_2^- occurs as a stable, identifiable complex in high-temperature aqueous solutions, especially those containing excess chloride ligands.

The increasing stability of Au(I) complexes formed with ligands of increasing ionic radius and polarizability (i.e., increasing softness), is illustrated by the equilibrium constants for the formation of the dihalogenidogold(I) species. These have stabilities in the order, $\text{F}^- < \text{Cl}^- \ll \text{Br}^- \ll \text{I}^-$.

Soft ligands such as HS^- and S^{2-} also form extremely stable complexes with Au(I). The simple $\text{Au}(\text{HS})_2^-$ complex is approximately 20 orders of magnitude more stable than AuCl_2^- . Hard ligands such as F^- , HCO_3^- , and HSO_4^- do not form stable complexes with Au(I). Thus, Cl^- and HS^- are the most likely candidates for gold complexing and transport, and occur in appreciable concentrations in the fluids of hydrothermal ore solutions.

In the weakly alkaline hydrothermal fluids, the most important hydrosulphido-complex is $\text{Au}(\text{HS})_2^-$. Other species, such as AuHS^0 and $\text{Au}_2\text{S}_2^{2-}$ occur in acid and strongly alkaline solutions, respectively.

A hydrothermal fluid ascending buoyantly to the surface reaches a depth at which the confined hydrostatic pressure is equal to the equilibrium-saturated vapour pressure. At this point, boiling occurs and two-phase conditions predominate as the fluid rises farther. The depth at which boiling commences varies greatly with the gas content of the ascending fluid (Seward, 1991).

When an aqueous solution boils, volatile components are partitioned into the vapour phase. Gaseous species which participate in hydrolytic equilibrium (e.g. H_2S and CO_2) are more soluble in the liquid phase, whereas gases such as H_2 and CH_4 partition strongly into the gas phase during boiling.

The loss of volatile component produces important changes in the chemistry of the residual liquid phase. There is significant loss, such as H_2 and H_2S volatiles, which results in an increase in the oxidation potential of the residual liquid. The decrease in reduced sulphur concentration and increasing pH, primarily because of CO_2 loss, has a major effect on the stability of $\text{Au}(\text{HS})_2^-$.

There are many variations in the multi-step boiling process involving gas-phase (and steam) removal in one or more steps, depending upon the permeability conditions in any hydrothermal system. The result is always to precipitate all the gold in solution over a small temperature and depth interval under conditions not far removed from the boiling point with depth curve. Permeability conditions in any system which permit some gas-phase removal in a single- or two-step process will also lead to quantitative deposition of gold in a localised environment.

Sulphide colloids may act as extremely efficient scavengers of gold and provide an additional potent mechanism for concentrating gold. Even if a hydrothermally precipitated sulphide colloid undergoes recrystallisation shortly after having formed, if the initial sulphide precursor was a colloid, then gold adsorption on to the charged surface could be important. In this situation, the localisation of gold is not only a function of the sulphide colloid surface chemistry but also of the conditions under which a particular metal sulphide colloid (or colloids) precipitates. The adsorption and subsequent reduction of gold complexes on mineral surfaces, such as pyrite, may also be important (Seward, 1991).

5.2.4 Hydrothermal Alteration and Fluids

The main styles of alteration are 'pervasive', 'selectively pervasive' and 'non-pervasive'. Pervasive alteration is characterised by the replacement of most, or all original rock-forming minerals. This results in the partial or total obliteration of the original textures. Selectively pervasive alteration refers to the replacement of specific original minerals, e.g. chlorite replacing biotite, or sericite replacing plagioclase. In this case, the original textures are preserved. Non-pervasive alteration means that only certain portions of the rock volume have been affected by the altering fluids. The types of hydrothermal alteration are shown in Figure 5.4.

Generally, the Kidston and Mount Leyshon breccia complexes have hydrothermal alteration and mineralisation characteristics of the 'Lowell-Guilbert Model' (Lowell and Guilbert, 1970). The earliest alteration is due to the effects of alkali metasomatism (generally potassic, but can also be sodic) within and around the productive intrusive porphyry body. This constitutes a core of potassic alteration which gives way to a more diffuse zone of propylitic alteration.

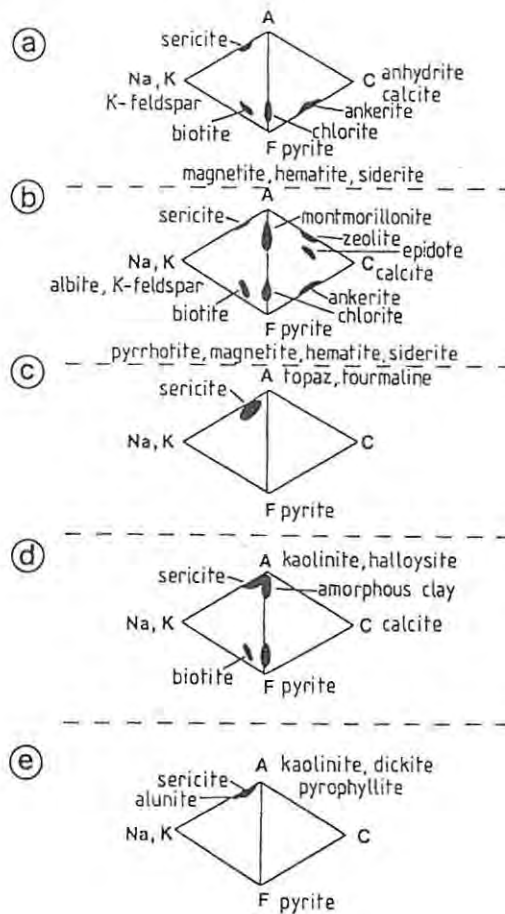


Figure 5.4 : ACF ($\text{Al}_2\text{O}_3\text{-CaO-FeO}$) AKF ($\text{Al}_2\text{O}_3\text{-Na}_2\text{O+K}_2\text{O-FeO}$) diagrams showing alteration types and related dominant mineral assemblages. **a.** Potassium silicate; **b.** propylitic; **c.** phyllic or sericitic; **d.** intermediate argillic; **e.** advanced argillic (Pirajno, 1992).

The incursion of meteoric waters, at a later stage, has caused phyllic alteration overprint of the early alkali-metasomatic effects, causing a redistribution of the sulphide mineralisation. The hydrothermal zones form more or less concentric shells around the potassic zone, around which are distributed the phyllic or quartz-sericite-pyrite zone, a minor argillic zone and the propylitic zone. The 'potassic' minerals that typify the zone are orthoclase and biotite.

The potassic zone contains the assemblage quartz + K-feldspar + biotite + sericite + anhydrite + pyrite + chalcopyrite + bornite \pm magnetite \pm molybdenite. This alteration is pervasive and characterised by the replacement of primary biotite and feldspars. Hydrothermal biotite occurs as micro-fracture fillings accompanied by pyrite/chalcopyrite

and anhydrite. The altered porphyries display a smoky-grey colour and the 'ore shell' is typically contained within the outer limits of the potassic core.

The phyllic zone, known also as quartz-sericite-pyrite zone, surrounds and overlaps the potassic zone. Contacts between the phyllic and potassic zones are gradational. Phyllic alteration is characterised by the assemblage of quartz + sericite + pyrite \pm chlorite \pm rutile \pm chalcopyrite. Fe is leached out of the primary mafic silicates to form pyrite. Sericite predominates in the inner portions of the zone, while clay minerals and hydromicas become more abundant towards the outer portions. Pyrite can reach up to 30% by volume and forms veinlets and granular disseminations. Chalcopyrite may be present in subordinate amounts. Contacts between the phyllic and argillic zones are gradational and indistinct.

The argillic zone is generally not well defined at Mount Leyshon and Kidston. The argillic alteration is most probably supergene alteration because it is associated with chalcocite mineralisation. However, complete acid attack with the formation of kaolinite-dickite and varying amounts of alunite and amorphous silica does occur.

The propylitic zone is the largest of the alteration shells forming a wide halo in the country rocks around the porphyry intrusives. It is especially well developed in the Mount Leyshon breccia. The main assemblage consists of chlorite + epidote + pyrite + calcite \pm clay minerals.

The action of magmatic and meteoric fluids in the volcanic breccia complex system, consists of a series of many continuous, time staged processes rather than a single event. Magmatic waters are first exsolved from the crystallising porphyry intrusion. These early magmatic-hydrothermal solutions form at temperatures ranging from 750 to 450°C and at depths of between 5 and 1 km below the surface. The action of these waters is essentially confined to the apical portions of the intrusive stock and immediate surrounding areas. The early magmatic-hydrothermal fluids are generally succeeded by convective fluids of meteoric origin, with which they mix at first until the magmatic component relating to that particular intrusion tends to disappear completely. Meteoric-hydrothermal fluids of the porphyry systems have temperatures ranging from 450 to 250°C and form at depths between approximately 1 and <0.5 km.

Fluid inclusion studies at Mount Leyshon and Kidston show high salinities. The presence of abundant NaCl in the fluid inclusions indicate that the ore forming fluids travelled and deposited gold as chloride complexes at temperatures higher than 350°C. Aqueous species such as AuCl_2^- , ZnCl_2 , CuCl_3^{-2} , AgCl_2^- form in chloride-rich solutions. This type of complexing for the transport of gold is probably valid in the deeper and hotter regions of magmatic and hydrothermal systems (Pirajno, 1992). Later intrusive episodes within the breccia complexes probably introduced metal remobilisation by thio-complexes of gold up to 300°C and 1500 bar, with pH 3-10.

There are no known studies of rare earth elements (REE) at Mount Leyshon, Kidston or Mount Wright. However, they may play an important role in the understanding of the hydrothermal alteration and fluids of the deposits. REE are thought to be transported in aqueous solutions as complexes, as most REE salts possess extremely low solubility products. Hydrothermal fluids derived from a crystallising magma or produced by leaching of rocks within hydrothermal systems, generally carry low REE contents. In a system with low fluid/rock ratios, a high pH and abundant chloride ions in solution, magmatic-hydrothermal fluids will produce early-stage assemblages with some REE mobility. These early stage alterations include K-feldspathisation, albitisation, biotisation and chloritisation. The development of late-stage hydrothermal fluids and the production of sericitisation, argillisation, tourmalinisation, epidotisation, silicification and chloritisation is characterised by increasing fluid/rock ratios, abundant REE complexing agents (CO_3^{-2} , F^- , Cl^- , PO_4^{-3}), decreasing temperature and pH conditions and pronounced REE mobility. These fluids either produce a progressive leaching of all REE or an enrichment of all REE with increasing alteration intensity (Lottermoser, 1992).

5.2.5 The Volcanic-Hosted Epithermal System

Epithermal gold deposits are positioned at shallow levels above or marginal to the volcanic breccia complexes. However, telescoping, which is commonly caused by rapid erosion and collapse of these hydrothermal systems, may result in juxtaposition of epithermal and intrusion-related mineralisation types.

Sillitoe and Bonham (1984) have modelled volcanic-related mineralised systems (mostly of the epithermal range) in terms of their relationship to volcanic systems and related landforms. They distinguish deposit types related to andesitic strato-volcanoes, Valles-type calderas, high-silica rhyolite domes and maar-diatreme complexes.

In terms of alteration mineral assemblages, as well as the nature of the volcanic environment, epithermal systems have been considered as follows :

1. Quartz-adularia, adularia-sericite, or low-sulphur types; and
2. Quartz-alunite, acid-sulphate, or high-sulphur types.

Quartz-adularia, adularia-sericite or low-sulphur types refer to epithermal systems that are generally associated with caldera structures of acid volcanic terranes in which hydrothermal activity is characterised by deep meteoric circulation of predominantly chloride-rich fluids, with a pH ranging from 5.5 to 6.5, and temperatures of 250-350°C (Hedenquist and Lindqvist, 1985). Near the surface, in the hot spring zone, the host rocks are silicified and contain adularia, albite, calcite and dolomite. This grades into argillic-type alteration with kaolinite, illite, sericite and/or chlorite, illite, smectite, calcite and zeolites. Propylitic alteration follows and affects fairly wide areas. The alteration mineralogy in or adjacent to veins, stockworks and fractures include quartz, adularia, calcite, dolomite, Mn-bearing carbonates and silicates, minor fluorite and barite. Ore minerals include native Au, electrum, As, Sb and Hg sulphides, Ag sulphosalts, selenides and base metal sulphides.

Quartz-alunite, acid-sulphate or high-sulphur types may occur in caldera settings, but appear to be more characteristic of strato-volcanoes related to calc-alkaline magmatism. Near-surface hydrothermal circulation is characterised by acid-sulphate-rich, or mixed acid-sulphate-chloride-rich fluids, with pH values ranging from 2 to 5, and temperatures between 100 and 180°C. The origin of the acid nature of these fluids is essentially due to the inability, in places, of deep chloride-rich fluids to discharge at the surface. However, when they reach the boiling level, volatiles such as CO₂ and S compounds (SO₂ and H₂S) are partitioned into vapour phase. The steam produced will heat levels of aquifers forming acid-sulphate and/or CO₂-rich (bicarbonate) waters. Localised mixing of chloride-rich with acid-sulphate or bicarbonate waters occurs. Oxidation of H₂S results in the development of H₂SO₄ and native S (Hedenquist and Browne, 1989). Figure 5.5 schematically illustrates the various types and nature of the geothermal fluids in volcanic areas and the associated dominant alteration (acid-sulphate and adularia-sericite).

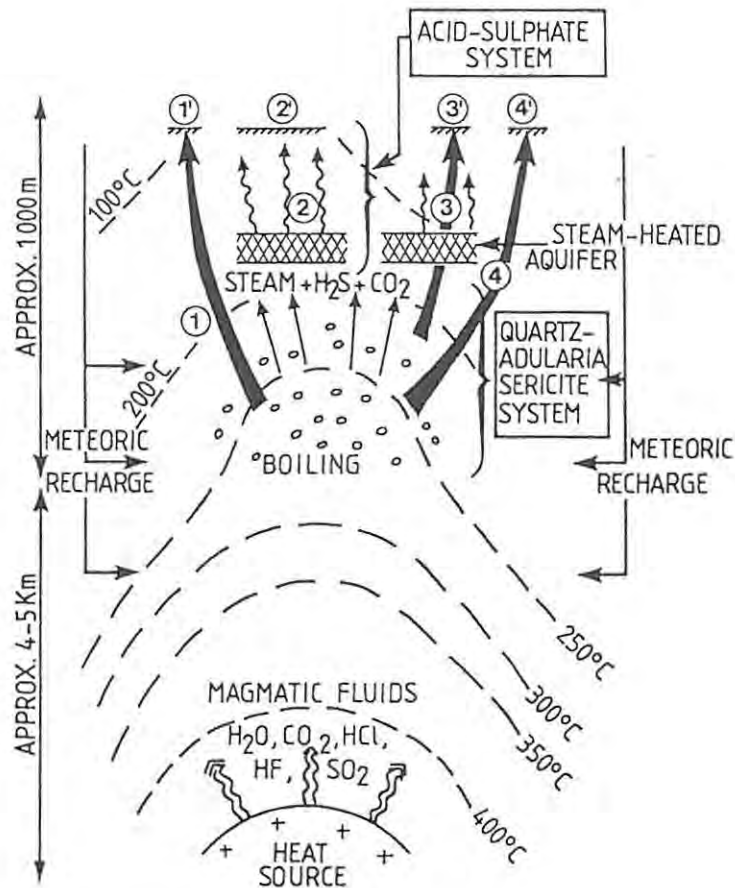


Figure 5.5 : Idealised representation of the main types and nature of geothermal fluids. Note that the upper sector is expanded with respect to the lower one. The types of geothermal fluids are: (1) chloride-rich fluids, (1') near-neutral chloride boiling spring; (2) acid-sulphate fluids, (2') acid-sulphate springs, fumaroles and mud pools; (3) CO₂-rich fluids, (3') bicarbonate hot springs; (4) chloride-rich fluids, (4') dilute chloride warm springs. Chloride-rich fluids are usually associated with quartz-adularia-sericite systems and with siliceous sinters; acid-sulphate fluids are associated with varying degrees of acid leaching (argillic alteration); bicarbonate waters are commonly responsible for the precipitation of extensive deposits of carbonate material such as travertine. In this case the CO₂ may have been acquired from the surrounding lithologies. The magmatic fluids component is assumed, but the actual measure of its input is not known and is isotopically difficult to detect once the incursion of large quantities of meteoric waters has taken place (Pirajno, 1992).

The main effects of the circulation of predominantly acid-sulphate fluids, is the intensive acid leaching of wall rocks leading to various stages of intermediate to advanced argillic alteration, and the deposition higher up (usually in the crater of the volcanic edifice) of native S, the presence of boiling mud pools, warm to hot springs, and abundance of kaolinite and alunite (Pirajno, 1992).

Bonham (1986) also considers an alkalic subtype of the epithermal system which is characterised by Au-tellurides and associated with alkaline igneous rocks such as syenite, trachytes and phonolites. The alkali subtype occurs in a variety of volcanic environments, including maar-diatremes and calderas. The main mineralogical features of this subtype are: quartz + fluorite + adularia + carbonates + roscoelite vein assemblages surrounded by a narrow alteration envelope of adularia + carbonate + sericite + pyrite + smectite + illite + roscoelite, and followed by a zone of propylitic alteration with disseminated pyrite.

The dominant epithermal system within the Kidston and Mount Leyshon breccia complexes is the quartz-adularia-sericite-type. However, the acid-sulphate system appears to have been present in the upper portions of the Mount Leyshon breccia complex. Overprint of the magmatic-hydrothermal alteration assemblages by epithermal alteration systems are dominant in both breccia complexes.

5.2.6 Model for Volcanic Breccia Complexes

The development of volcanic breccia complexes in north Queensland occurred in the Permo-Carboniferous evolution of the Thomson Fold Belt and Georgetown Inlier. The type of exploration ore genesis model that could be used to search for a gold-related volcanic breccia complex deposit, can be described as the following sequence of events :

1. Cambrian deposition of a sequence of fine-grained sedimentary rocks with or without intrusive Cambrian I-type granitoids. At a later stage, these rocks were deformed and metamorphosed to produce greenschist to amphibolite facies lithologies.
2. The development of an extensional environment that allowed the introduction of various Ordovician to Devonian I-type granitoid intrusives. Various vein-type gold deposits should be related to this type of granitoid emplacement. Sericite-pyrite alteration was associated with these granitoids.
3. Permo-Carboniferous development of a back-arc environment with subsequent folding and faulting. Deposition of shallow marine and continental sedimentary sequences as the sea transgressed.
4. Further extension of the crust allowed emplacement of alkaline magmas during the Permo-Carboniferous time. These magmas were mainly dominated by porphyries and porphyry breccias intruding into zones of weakness. The lithological contacts between the Cambrian sedimentary/igneous rocks and the Ordovician to Devonian granitoids were ideal structural weaknesses for the intrusion of these porphyries.

5. Early magmatic-hydrothermal alteration of the porphyries and breccias formed massive low-grade gold deposits with minor molybdenum-quartz stockwork. The hydrothermal fluids, mainly being of chloride complexes, that mobilised and deposited the gold and base metals. The porphyry systems at this stage were probably a closed-system with no venting at surface. However, dyke swarms related to the porphyry systems were developed. Early-stage hydrothermal alteration appears to have been similar to the 'Lowell-Guilbert Model' as explained in section 5.2.4.

6. Further porphyry intrusions caused the brittle fracture and brecciation of earlier porphyritic bodies and possible exposure to the surface to form an open system. Meteoric water was introduced into the system as sea water while the marine transgression proceeded. Meteoric-magmatic hydrothermal processes began and the metals were further distributed throughout the breccia complex systems. The mineralisation of gold being within clast supported breccias that allowed deposition of metals to occur as cavity-fill, vein-type deposits and mainly as homogenous disseminated mineralisation.

7. Epithermal deposits formed at the top of the breccia complexes that were dominantly quartz-adularia-sericite-type. The erosion, collapse and further intrusion of later porphyry phases allowed the upper parts of the breccia complexes to mix with the lower hydrothermal systems. The mixing phase was especially evident by the development of pebble-type breccias. Overprinting of hydrothermal alteration is a common feature, with the phyllic alteration being the most dominant.

8. A final stage of intrusive basic dykes is the last stage of igneous activity within the breccia complexes.

5.3 Exploration in the Thomson Fold Belt and Georgetown Inlier

5.3.1 Geomorphology and Structure

The Kidston, Mount Leyshon and Mount Wright breccia complexes exist as prominent topographic highs with radiating drainage. This dominant feature is mainly a result of the quartz-sericite-type alteration associated with the complexes. Aerial photograph interpretation would be a useful tool for finding topographic highs within the Thomson Fold Belt and the Georgetown Inlier. Vegetation anomalies will generally stand out because the hydrothermal alteration generally produces an acidic environment in which vegetation finds difficult to grow on.

Historically, the drainage systems of the breccia complexes have been mined for alluvial gold. The identification of alluvial working around an area may help to build a picture to interpret the source of gold.

The possibility of other breccia complexes being covered by later sedimentary basins, or not venting at the surface to produce topographic highs, must be considered. The structural setting then becomes a very important tool to interpret porphyries at depth. Radiating structural features and structural corridors are important features to explore.

Recognising regional structural corridors and detailed structural mapping of these corridors, is necessary to interpret the extent of crustal weakness that might accommodate a breccia complex. The structural directions of faults, joints, and dykes at Kidston and Mount Leyshon suggest that synchronous dextral northeast and sinistral north-northwest faults displacing each other may be a possible model for breccia complex/porphyry development.

5.3.2 Remote Sensing

At the regional and district scales, remote sensing methods can provide information on structure and lithology. Spatial and spectral data processing techniques are needed to enhance subtle features and responses. Especially such characteristics as circular features possibly related to calderas and lineaments, which are possible indications of extensional tectonics.

Spectral remote sensing has become an important tool for the detection of hydrothermal alteration. Details of spectral reflectance of rocks and minerals in the visible to thermal infrared wavelength region are known from field and laboratory work, by recording data with a spectrophotometer. The detection of spectral reflectance is also obtained by aircraft and spacecraft. The spectral features of altered rocks are a function of electronic and vibrational processes involving Fe and OH groups respectively. Each displays curves with characteristic slopes and absorption bands that are diagnostic of the surface materials.

Spectral features due to vibrational processes are especially useful, as they report OH-bearing minerals that are normally present in hydrothermally altered rocks. For this reason, the short wavelength region between 1.0 and 2.5 μm is ideal for the detection of clays and zones of acid-sulphate alteration with alunite present.

Figure 5.6 shows the spectral ranges of six visible and reflected thermal infrared (IR) thematic-mapper (TM) bands together with spectral reflectance curves of vegetation, hydrothermally altered rock, and unaltered rock. Table 5.2 summarises the characteristics of TM spectral bands.

Clay and iron minerals of the altered rock, within the breccia complexes, have distinctive spectral characteristics that can be recognisable in multispectral images from the Landsat thematic-mapper. Absorption caused by alunite and clay minerals results in low reflectance at 2.2 μm , which corresponds to TM band 7. Altered rocks have high reflectance at 1.6 μm , which corresponds to TM band 5. A ratio of bands 5/7 has bright signatures for altered rocks because the lower reflectance values of band 7 are in the denominator, which results in higher ratio values of approximately 1.5. The unaltered rocks, with a band ratio of 5/7, will have ratio values of approximately 1.0 (Sabins, 1987). Therefore, brighter signatures are present from altered rocks rather than unaltered rocks. The best combination of bands to use when using TM remote sensing for hydrothermally altered rocks is 3/5/7 or 4/5/7.

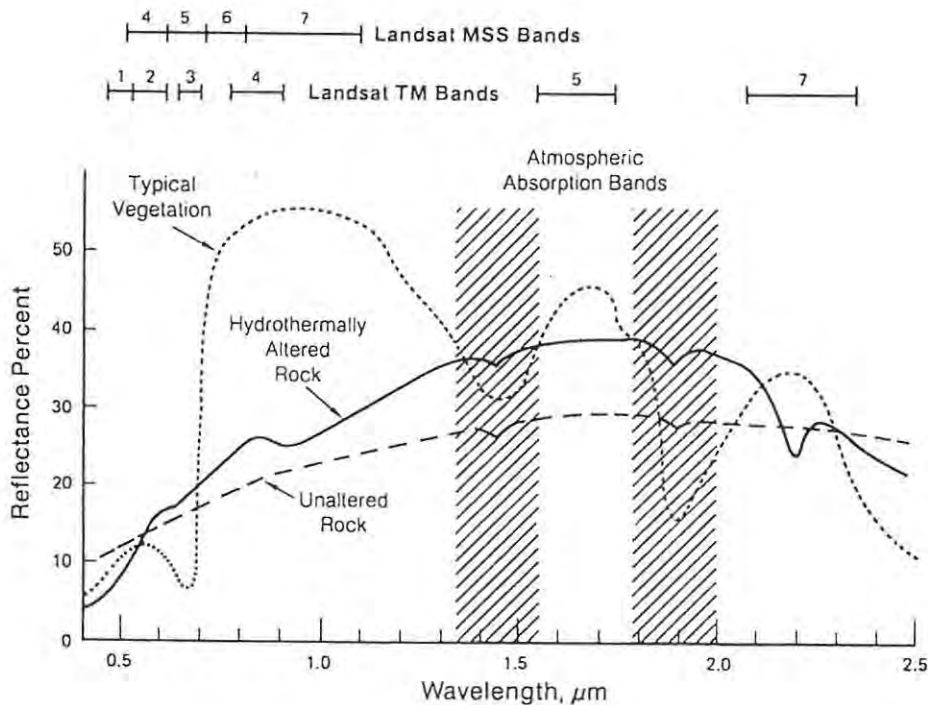


Figure 5.6 : Spectral bands for TM and MSS systems. Reflectance curves for vegetation, unaltered rocks, and hydrothermally altered rocks (Sabins, 1983).

Band	Wavelength, μm	Characteristics
1	0.45 to 0.52	Blue-green—no MSS equivalent. Maximum penetration of water, which is useful for bathymetric mapping in shallow water. Useful for distinguishing soil from vegetation and deciduous from coniferous plants.
2	0.52 to 0.60	Green—coincident with MSS band 4. Matches green reflectance peak of vegetation, which is useful for assessing plant vigor.
3	0.63 to 0.69	Red—coincident with MSS band 5. Matches a chlorophyll absorption band that is important for discriminating vegetation types.
4	0.76 to 0.90	Reflected IR—coincident with portions of MSS bands 6 and 7. Useful for determining biomass content and for mapping shorelines.
5	1.55 to 1.75	Reflected IR. Indicates moisture content of soil and vegetation. Penetrates thin clouds. Good contrast between vegetation types.
6	10.40 to 12.50	Thermal IR. Nighttime images are useful for thermal mapping and for estimating soil moisture.
7	2.08 to 2.35	Reflected IR. Coincides with an absorption band caused by hydroxyl ions in minerals. Ratios of bands 5 and 7 are potentially useful for mapping hydrothermally altered rocks associated with mineral deposits.

Table 5.2 : Thematic-mapper spectral bands (Sabins, 1987).

5.3.3 Geophysics

Regional geophysical surveys are normally those designated to locate environments of regional scale (e.g. intracratonic basin margins, rift zones, plate boundaries and regional fault patterns). Aeromagnetic and gravity surveys are most useful at this stage.

The geophysical exploration for gold-related volcanic breccia complexes, centres on the regional identification and detailed delineation of the porphyries and associated granitoids, usually by magnetics or a combination of magnetics, gravity, and gamma-ray spectrometry. The orebodies are usually found as breccia and fissure systems, often related to contacts of granitic intrusions with older sedimentary rocks. Magnetite may be depleted through the conversion to pyrite, ankerite or hematite, or it may have been introduced with the mineralising solutions.

The use of combining magnetic and EM (electromagnetic) survey equipment, within a regional survey, will assist in geological mapping of structure and lithology. VLF EM (very-low frequency electromagnetic) systems, both fixed-wing and helicopter-mounted, are now used routinely to locate conductive features such as major shears and zones of hydrothermal alteration (mainly argillic alteration). Local potassium concentrations have been found by gamma-ray spectrometry.

The frequent association of gold with sulphides, in the volcanic breccia complexes, allows induced polarisation (IP) and resistivity methods to be favoured in detailed exploration surveys.

Studying magnetic, gravity, gamma-ray spectrometry and IP signatures of known gold-related volcanic breccia complex deposits may provide essential information in exploring for other exposed and hidden (covered) breccia complexes.

5.3.4 Geochemistry

Geochemical exploration for gold-related volcanic breccia complexes would generally be an attractive exploration tool. This is especially true if the breccia complexes form a topographical high allowing metals to be easily leached and dispersed into the surrounding tributaries. However, hidden, or complexes that have not vented, could cause problems, as the dispersion patterns would be more localised. Generally, the most common mineral association of the gold-related breccia complexes is sericite - k-feldspar - pyrite. This mineral association should be carefully geologically sampled and mapped in the field.

Regional and detailed scale exploration makes extensive use of stream sediment, soil and rock-chip sampling with multi-element analyses. The advantage of these geochemical methods is that they may still be highly effective even in the case of exploration being constrained by a low budget, because of the usual wide dispersion of metals and the nearly ever present Au, Cu, Pb, Zn, anomalies associated with the mineralisation. Multi-element analyses should include, first of all the elements of the ores sought, aided by the numerous pathfinders such as Bi, Te, As, Mo, with minor W, Sb, Tl, and Hg. However, Tl and Te may be useful as discriminates, but are generally precluded by the difficulties and cost of analysis. It is a common error to pursue by detailed ground work, for example, a Tl or As anomaly in soils or rocks, in the belief that somewhere there must be associated Au. However, the opposite situation of a Au anomaly associated with anomalous concentrations of Tl or As, is far more worthy of a closer scrutiny.

In the semi-arid terrains of the Thomson Fold Belt and Georgetown Inlier, the pre-existing lateritic weathering profiles are truncated or lacking. In such environments, the pedogenic activity, mostly physical, is not sufficient to develop a mature soil profile. The material resulting from degradation of rocks or mineralisation is mechanically dispersed, either by water or by the wind. Under these conditions, the fine size fraction (<80 μm) of soil and

stream sediment samples would give the best contrast and the longest dispersion train for gold. Samples should be collected in medium size tributaries, under the upper, sandy, aeolian layer. However, orientation surveys are strongly recommended in arid to semi-arid environments to ensure selection of the optimum procedures. A summary of geochemical exploration for gold is shown in Table 5.3.

Ref.	Climate	Relief	Stage of exploration	Sampling media	Sampling Interval	Size fraction	Au response	Pathfinders
(1)	Temperate	Low	REGIO	SS	2-3/km ²	<125 µm	None	(+)As, Li, B
(1)	Temperate	Low	REGIO	HC	1/km ²	-	Good	
(1)	Temperate	Low	DETAIL	SO	50x100 m, 50x200 m,...	<125 µm	Good	(+) As, Pb, Sb, W
(1)	Temperate	Low	PRE-D	WR, RO	5, 10, 20 m	Total	Good	
(2)	Temperate	Moderate	DETAIL	SO	100x25 m	<125 µm	Good	(+)As, Li, B
(3)	Temperate	Moderate	REGIO	HC	1/km ²		Good	
(3)	Temperate	Moderate	DETAIL	SO		<63 µm	Good	(+)As, Hg
(4)	Temperate	Moderate	DETAIL	SO	10 m		Good	(+)As, Ag, Hg, Sb, W, (-)Ca, Mg
(5)	Arid	Low	REGIO	SS	2/km ²	<80 µm	Good	
(5)	Arid	Low	DETAIL	SO	50, 100 m	<80 µm	Good	
(6)	Arid	Low	REGIO	PL	1/km ²	Total	Good	(+)As, Bi, Sb, Mo, Ag, Sn, Ge, W, Se
(7)	Savanna	Low	REGIO	SO, SS	1600x500 m	<125 µm	Good	(+)B
(8)	Savanna	Low	REGIO	SO	300x500 m	Total	Good	(+)Cu, Zn, Mo
(9)	Rainforest	Moderate	REGIO	SS	1.5/km ²	<125 µm	Good	
(9)	Rainforest	Moderate	REGIO	HC	0.5/km ²		Good	
(10)	Rainforest	Moderate	DETAIL	SO	100x200 m	>125 µm	Poor	
(10)	Rainforest	Moderate	PRE-D	SA	10 m	Total	Good	
(11)	Rainforest	Moderate	PRE-D	SA	5, 10 m	Total	Good	(+)Ag, Mo, Pb, Si, (-)Fe, Ti, Sr
(12)	Rainforest	Moderate	PRE-D	SA	10, 20 m	Total	Good	(+)As, B, Sb, Cu, K, Mg

Exploration stage: REGIO, regional; DETAIL, detailed; PRE-D, pre-drilling.

Sampling media: SS, stream-sediments; HC, heavy concentrates (with determination of visible gold); SO, soils; PL, pisolitic laterite; SA, saprolite; WB, weathered bedrock; RO, bedrock.

Pathfinder elements: (+) enriched; (-) depleted.

Reference: (1) Vasquez-Lopez *et al.* (1987); (2) Braux *et al.* (1989); (3) Janatka and Moravek (1987); (4) Chaffee and Hill (1989); (5) Salpéteur and Sabir (1989); (6) Smith *et al.* (1989); (7) Dommanget *et al.* (1987); (8) Ouedraogo (1988); (9) Barthélémy *et al.* (1987); (10) Colin and Lecomte (1988); (11) Zeegers (1987); (12) Taylor *et al.* (1989).

Table 5.3 : Geochemical exploration for gold: summary of different sampling media and intervals, size fractions retained for analysis, Au geochemical responses obtained, and significant pathfinder elements, in relation to various climatic and morphological environments (Zeegers and Leduc, 1991).

The highest mobility of gold seems to be achieved during dry climatic periods, when saline ground waters may mobilise gold as chloride complexes. Gold may thus be mobilised and leached from some horizons of the weathering profile and further redistributed in the saprolite, forming wide dispersion haloes (Figure 5.7). It can also be mechanically dispersed, either free or associated for instance with Fe-rich pisoliths.

Ishihara (1981) pointed out that magnetite-series magmas tend to be enriched in S and Cl, components which, like the ore metals, may have been derived, at least in part, from dehydration of subducted lithospheric slabs. This mechanism, involving incorporation of seawater sulphate (and chloride), accounts for both the positive $\delta^{34}\text{S}$ values and relatively high oxygen fugacities of magnetite-series magmas. It also explains the localisation of the volcanic breccia complexes at sites of ancient or modern subduction (Sillitoe, 1991). This type of analysis could be useful in the determination of the tectonic environment at which these deposits occur.

REE, as immobile elements, have been used for the classification of basic igneous rocks in order to determine the magmatic affinity of igneous lithologies (Floyd and Winchester, 1978) and as qualitative evaluation of geochemical alteration processes. Magmatic affinity can be confirmed (Figure 5.8) using changes in La/Yb and Zr/Yb ratios, as the heavy REE are geochemically similar to Y. Slopes of Zr versus Nb plots coincide in some tholeiitic to mildly calc-alkaline suites, but diverge in others. The Zr/Nb ratio is distinctly higher in anorogenic (rift-related) than in orogenic (subduction-related) alkaline rocks, and provides a reliable discriminate for magmatic suites and tectonic setting (MacLean and Barrett, 1993).

Factors favouring REE mobility upon fluid/rock interactions appear to be long fluid residence times, high fluid/rock ratios and abundant REE complexing agents in solutions. The REE content of the incoming fluid, REE adsorption during alteration and the pH conditions during alteration can influence the transport of REE groups away from their original locations, whereas changing Eh and temperature conditions may especially determine the mobility of Eu and Ce (Lottermoser, 1992).

Hydrothermal alteration profiles may exhibit distinct vertical zonations, whereby leached rare earth elements from the lower part of the profile are redeposited at the top of the alteration sequence. Thereby, mobility of rare earth elements appears to increase with the change from early-magmatic to late-stage hydrothermal fluids. The analysis of REE in a

geochemical exploration survey may provide vital information on the magmatic affinity of igneous lithologies. The use of REE in soil geochemistry surveys could produce profiles to accurately locate a hydrothermal system.

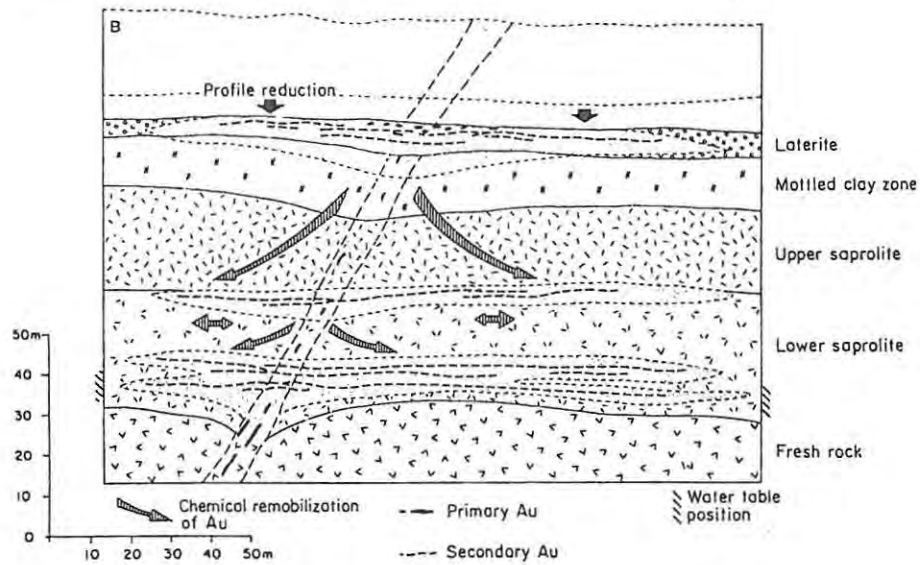


Figure 5.7 : Schematic representation of chemical and physical remobilisation of gold with increasing aridity (Lawrance, 1988).

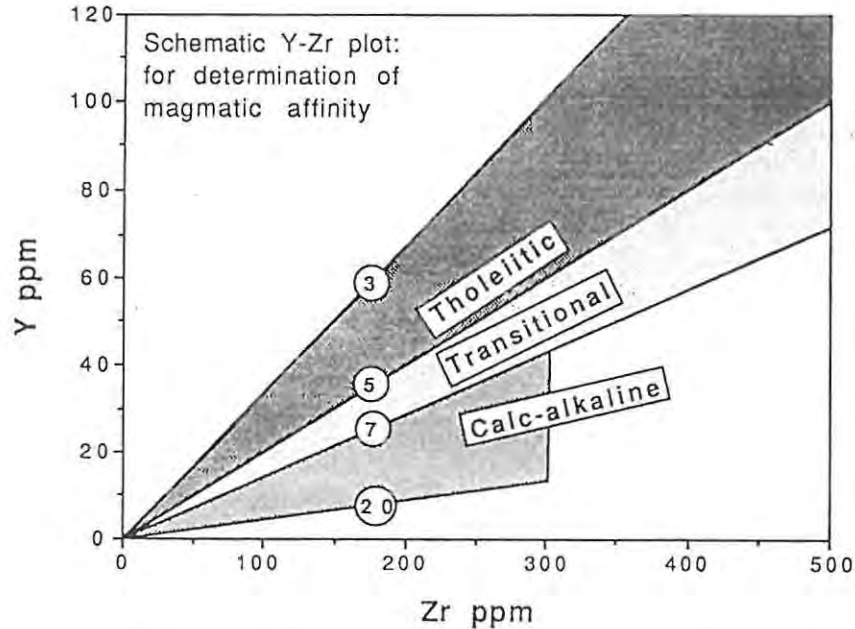


Figure 5.8 : Schematic Y-Zr plot used for the determination of magmatic affinity (MacLean and Barrett, 1993).

5.3.5 Isotopes and Fluid Inclusions

Light stable isotopic studies conducted on hydrothermal material from Mount Leyshon (Morrison *et al.*, 1988) and Kidston (Baker and Andrew, 1988) have demonstrated the importance of magmatic-hydrothermal fluids at the initial development of the breccia complexes. At Kidston, the deuterium-depleted δD values for the main gold stage are interpreted by Baker and Andrew (1988) in terms of condensation of late magmatic volatiles rather than meteoric-hydrothermal dilution (Taylor, 1988). This type of study may provide essential criteria for examining the type of mineralising hydrothermal fluids within a breccia complex.

Detailed oxygen isotope exploration of a volcanic breccia complex can assist in the mapping of hydrothermal alteration associated with the complexes. Using rock samples, the $\delta^{18}O$ values can be measured, and the results contoured to accurately determine the extent of hydrothermal alteration. However, the number of samples needed to put together a workable data base, and the cost of analysing the samples, may prove to be an expensive exploration tool.

Fluid inclusions can assist in determining the number and type of magma episodes in a breccia complex system. In terms of morphology and contents, several important types of fluid inclusions have been described. The classification scheme reported by Shepherd *et al.* (1985) is summarised below, and diagrammatically shown in Figure 5.9.

1. Monophase inclusions: entirely filled with liquid (L).
2. Two-phase inclusions: filled with a liquid phase and a small vapour bubble (L + V).
3. Two-phase inclusions: in which the vapour phase is dominant and occupies more than 50% of the volume (V + L).
4. Monophase vapour inclusion (V): entirely filled with a low density vapour phase (generally mixtures of H_2O , CH_4 , CO_2).
5. Multiphase inclusions containing solids (S + L \pm L): contain solid crystalline phases known as daughter minerals. These are commonly halite (NaCl) and sylvite (KCl), but many other minerals may occur including sulphides.
6. Immiscible liquid inclusions: contain two liquids, usually one H_2O -rich and the other CO_2 -rich ($L_1 + L_2 \pm V$).

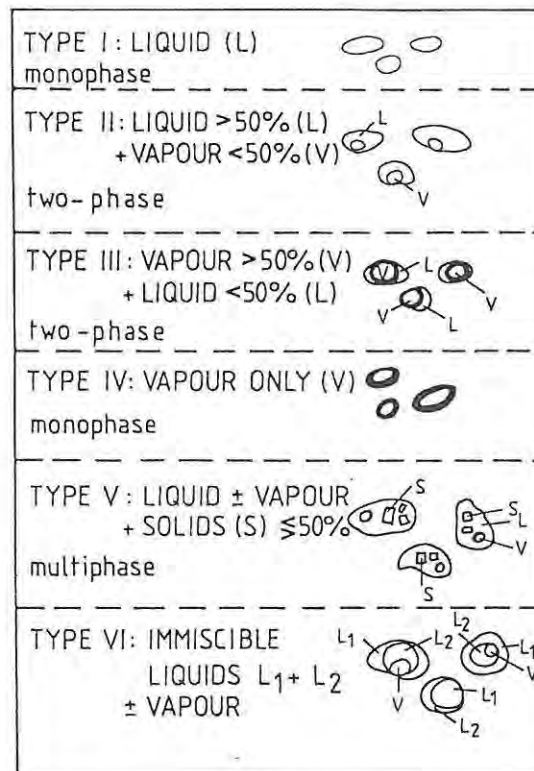


Figure 5.9 : Classification of fluid inclusions observed at room temperature (Shepherd *et al.*, 1985).

In general, the coexistence of type II (L + V) and III (V + L) may indicate that the fluid was boiling at the time of entrapment.

The study of fluid inclusions in porphyry systems indicates that there are, broadly speaking, three classes of fluids (Beane and Titley, 1981) : (1) hypersaline fluids with up to 40 wt. % NaCl equivalent and homogenisation temperatures of 750°C or greater; (2) high salinity fluids, with approximately 10 to 25 wt. % NaCl equivalent and homogenisation temperatures of between 600 and 250°C; and (3) low salinity fluids with less than 10 wt. % NaCl equivalent and homogenisation temperatures of between 400 and 200°C. Integration of isotopic, fluid inclusion, petrological and field data suggest that the hypersaline fluids are largely magmatic-derived. Fluid inclusion data also suggests that boiling and condensation occurred within these hypersaline magmatic fluids.

Fluid inclusion studies at Kidston and Mount Leyshon indicate that there were essentially at least two episodes of hydrothermal fluid activity. The initial hydrothermal fluids were largely magmatic-derived followed by possibly several episodes of meteoric-magmatic fluids. Determining the types and episodes of hydrothermal fluids in a volcanic breccia complex system, may indicate possibilities of a mineralised episode within the system.

5.3.6 Petrology

The identification of alteration, through a series of rock samples collected from a hydrothermal system, will provide essential information to the types of hydrothermal processes involved. Usually, a line traverse, when geologically mapping in the field, should consist of a sequence of lithology and alteration suites to enable petrological studies to be carried out. In most circumstances, this would probably be the most cost effective tool in determining the hydrothermal alteration processes in the breccia complex.

The volcanic breccia complex ore deposits result from hydrothermal fluids which are channelled through zones of permeability, with the various ore-related components being formed either by precipitation in void space, or by interaction with the wall rocks. The permeability controls (channel ways) vary widely in detail ranging from primary permeability in unconsolidated sediments through to secondary permeability imposed by various styles of fracturing.

Cavities formed by breaking rocks will take on a variety of shapes depending on the angularity of the rocks, the amount of rock matrix, the range in size of rock fragments etc. The formation of these cavities are described as large-scale triangular textures. They are particularly common in the volcanic breccia complexes of north Queensland, and represent void spaces between rock fragments. These may be partially infilled when they are relatively easy to recognise, or completely infilled, which renders their observation a little more difficult. The passage of hydrothermal fluids also completely alters the host fragments which presents a major barrier to field recognition. This problem is further exacerbated when the alteration minerals are very similar to the infilling minerals (e.g. silica infill accompanied by silica alteration).

Infill recognition in brecciated rocks is difficult, particularly where wall rock alteration is intense. All breccia host rocks contain three major structural components. These include rocks (fragments), finer-scale rock fragments and powders (matrix), and void space

(potential infill sites). The amount of void space varies enormously from around 20-50% in collapse breccias to very minor milled breccias. Although the void spaces within a breccia may exhibit a wide range of size and shape, they tend to be vaguely triangular in cross section with sharp acute angles existing between fragments. This triangular texture is a prime criterion enabling breccia and infill recognition even within very altered rocks.

6.0 Conclusions

The gold-bearing volcanic breccia complexes, in the Thomson Fold Belt and Georgetown Inlier, are major low-grade, high tonnage deposits that are restricted to Permo-Carboniferous magmatism. This magmatism occurred within an active-marginal basin to remnant arc environment, resulting from the subduction-related tectonic activity in northern Queensland.

The formation of the volcanic breccia complexes was by several episodes of intrusive porphyries and breccia development. The breccia complexes were emplaced into structural corridors and lithological contacts between Ordovician to Devonian granitoids and Precambrian sedimentary or granitic rocks.

Gold mineralisation exists as a late-stage episode in the breccia complexes. Hydrothermal fluids transported the gold and base metals as chloride complexes before being deposited into cavities and fractures. The dominant epithermal system within the Kidston and Mount Leyshon breccia complexes is the quartz-adularia-sericite-type.

An exploration ore genesis model for gold-related volcanic breccia complexes appears in section 5.2.6. The most important features of this model, are the relationships of the breccia complexes with a porphyry-type system and a Permo-Carboniferous age limit. The hydrothermal alteration and mineralisation characteristics are similar to the 'Lowell-Guilbert Model' (Lowell and Guilbert, 1970). Successful exploration for volcanic breccia complexes will depend on the accuracy of the ore genesis model. Testing the model, and updating the geological parameters that control the model, are important functions in perfecting exploration programs.

An initial target selection for a volcanic breccia complex environment, can be rapidly obtained by using remote sensing technology for the detection of volcanic arc terrains, calderas, fracture analyses, and areas of hydrothermal alteration. Fieldwork is then undertaken to check on the areas selected, by using geological reconnaissance mapping and preliminary igneous petrological and hydrothermal alteration studies.

The exploration for hydrothermal mineral deposits, formed in subduction-related settings, follows a common trend. This is essentially due to the fact that most of these deposits are characterised by intense and/or wide haloes of hydrothermal alteration. These characteristics provide the exploration geologist with a signature that is relatively easy to detect.

The recent discovery of the Mount Wright (section 4.4) gold mineralisation, in the Thomson Fold Belt, has revealed the importance for exploration of gold-bearing volcanic breccia complex deposits. Their dominant occurrence in the Thomson Fold Belt and Georgetown Inlier would make the deposits one of the most prime exploration targets in north Queensland.

Acknowledgments

I would like to thank the Normandy-Poseidon Group of Australia for allowing me the opportunity to further my education in geology at Rhodes University, South Africa. The support and understanding by the Australian Exploration Manager, Mr Bruce Kay, throughout the year have been much appreciated. Thankyou to Mrs Chris Drew, for putting up with my never ending questions through facsimiles during the year, and to Ms Helen Challen for her efficient literature research of my dissertation topic.

The Exploration Geology course at Rhodes University has supplied me with a great wealth of information. It has enhanced my exploration skills to search for a vast variety of mineral deposits. This has been achieved through the efforts of the course supervisor, Professor John Moore. I would like to sincerely thank John Moore and the visiting lecturers for their contribution towards the course during the year. The organisation of the exploration geology students would not have been possible without the support of Mrs Sue Brooks, Exploration Geology course secretary. I would like to thank Sue for always being there to answer my endless list of questions and for always having time to lend a helping hand.

The communication and companionship between students during the course work, field trips, and general leisure have been fantastic. I would like to thank Robert Boelema, Karl Hartmann, Ian Gendall, Peter Mann, Chimwemwe Chikusa, Mike Skead, Phillo Schoeman, Brian Coxan, Harilaos Tsikos, and Sue Frost for their individual contributions to keeping me sane throughout the year. I wish them all the best with their future endeavours.

The completion of this course and dissertation would never have been possible without the support and guidance of my girlfriend and best mate, Cathy Murphy. Thankyou for your assistance with proof-reading and production of figures for this dissertation, and for being there when the times got tough. I would also like to thank my good friends, John and Kerri Fry, for looking after Cathy in Australia during the year.

South Africa and Namibia have a vast resource of mineral deposits and incredible geology that any geologist would be proud to visit. These aspects combined with the friendliness and hospitalities of the people have made the course, and my stay in South Africa, an invaluable experience.

References

- Andrew, A. S. and Baker, E. M., 1987. The nature and origin of the ore-forming fluid in the Kidston gold deposit, north Queensland, in *Proceedings Pacific Rim Congress 87*, 13-16 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Arnold, G. O. and Fawckner, J. F., 1980. The Broken River and Hodgkinson Provinces, in *The Geology and Geophysics of Northeastern Australia* (Eds. Henderson, R. A. and Stephenson, P. J.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 175-189.
- Bailey, J. C., Morgan, W. R. and Black, L. P., 1982. Geochemical and isotopic evidence for the age, orogenic setting and petrogenesis of the Nychum volcanic association, north Queensland. *J. Geol. Soc. Aust.*, 29, 375-393.
- Bain, J. H. C. and Withnall, I. W., 1980. Mineral deposits of the Georgetown region, northeast Queensland, in *The Geology and Geophysics of Northeastern Australia* (Eds. Henderson, R. A. and Stephenson, P. J.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 129-148.
- Bain, J. H. C., Black, L. P., Mackenzie, D. E., Oversby, B. S., Withnall, I. W. and Holmes, R. D., 1985. Tectonic evolution of the Georgetown Inlier, Queensland, in *Tectonics and Geochemistry of Early to Middle Proterozoic Fold Belts, Programme and Abstracts, Combined IGCP Meeting on the Proterozoic Fold Belts (215) and Proterozoic Geochemistry (217), Darwin, 7-14 August 1985*. *Aust.*, Bur. Miner. Resour., Rec. 1985/28, unpublished, 5-7.
- Bain, J. H. C., Withnall, I. W., Black, L. P., Etminan, H., Golding, S. D. and Sun, S. S., 1988. Geologic, isotopic, and metallogenic aspects of gold mineralisation in the Georgetown region, Queensland, in *Bicentennial Gold '88: Extended Abstracts Poster Programme* (Eds. Goode, A. D. T., Smyth, E. L., Birch, W. D. and Bosma, L. I.). *Geol. Soc. Aust. Abstr.*, 23, 246-248.
- Bain, J. H. C., Withnall, I. W., Oversby, B. S. and Mackenzie, D. E., 1990. North Queensland Proterozoic Inliers and Palaeozoic Igneous Provinces-Regional geology and mineral deposits, in *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. Hughs, F. E.), 963-978 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Baker, E. M., 1974. Geology of the Cape River-Gorge Creek area. *Unpubl. Hons. Thesis, Dep. Geol., James Cook University*.

- Baker, E. M., 1987. Brecciation, mineralization and alteration of the Kidston gold deposit, in *Proceedings Pacific Rim Congress 87*, 29-33 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Baker, E. M., 1988. The Kidston gold deposit, in *Bicentennial Gold 88 Excursion No. 8 Guide, Epithermal and Porphyry Style Gold Deposits in North Queensland, Contribution 29* (Ed. Morrison, G. W.), 61-74 (Economic Geology Research Unit, James Cook University of North Queensland: Townsville).
- Baker, E. M., Kirwin, D. J., and Taylor, R. G., 1986. *Hydrothermal Breccia Pipes, Contribution 12* (Economic Geology Research Unit, James Cook University of North Queensland: Townsville).
- Baker, E. M., and Andrew, A. S., 1988. Processes associated with gold mineralization within the Kidston breccia pipe, north Queensland, in *Bicentennial Gold 88, Extended Abstracts Oral Programme* (Comps Goode, A. D. T. and Bosma, L. I.). *Geol. Soc. Aust. Abstr.*, 22, 102-109.
- Baker, E. M. and Tullemans, F. J., 1990. Kidston gold deposit, in *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. Hughs, F. E.), 1461-1465 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Barthélémy, F., Kassa Momobo, M. and Labbé, J. F., 1987. Inventaire minier transgabonais: campagnes géochimiques régionales et détaillées 1979-1986. Acquisition des données sur le terrain, in *Abstracts of the 12th IGES*, Orléans, France, April 23-26.
- Beane, R. E. and Titley, S. R., 1981. Porphyry copper deposits. Part II. Hydrothermal alteration and mineralisation. *Econ. Geol.*, 75th Anniv. Vol., 235-269.
- Bell, T. H. and Rubenach, M. J., 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. *Tectonophysics*, 92, 171-194.
- Bonham, H. F., 1986. Models for volcanic-hosted epithermal precious metal deposits: a review, in *Proc. Symp. 5 Int. Volcanol. Congr.*, Auckland, NZ, 13-17.
- Bosworth, W., 1985. Geometry of prograding continental rifts. *Nature*, 316, 625-627.
- Braux, C., Bonnemaïson, M., Prévot, J. C., Maurin, G. and Zeegers, H., 1989. Le Châtelet gold deposit, France, Creuse: geology and geochemical exploration. *Gold '89 in Europe*, Toulouse, France, May 23-25 Terra Abstracts 1, 19.
- Chaffee, M. A. and Hills, R. H., 1989. Soil geochemistry of Mother Lode-type deposits in the Hodson mining district, central California, USA (extended abstract). *J. Geochem. Explor.*, 32, 53-55.

- Clarke, D. E., 1969. Geology of the Ravenswood 1-mile sheet area, Queensland, *Geol. Surv. Queensl. Rep.* 53.
- Colin, F. and Lecomte, P., 1988. Etude minéralogique et chimique du profil d'altération de Mébaga Mvomo (Gabon). *Chron. Rech. Min.*, 491, 55-65.
- Day, R. W., Murray, C. G. and Whitaker, W. G., 1978. The eastern part of the Tasman Orogenic Zone. *Tectonophysics*, 48, 327-364.
- Dommanget, A., Traore, H. and Zeegers, H., 1987. Discovery of the Loulo gold deposit (Mali), in *Abstracts of the 12th IGES*, Orléans, France, April 23-26.
- Etheridge, M. A., Rutland, R. W. R. and Wyborn, L. A. I., 1987. Orogenesis and tectonic process in the Early to Middle Proterozoic of Northern Australia. *Geodynamics Series*, 17, Am. Geophys. Union, Washington, DC, 131-147.
- Floyd, P. A. and Winchester, J. A., 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chem. Geol.*, 21, 291-306.
- Fordham, B. G., 1976. Geology and Lower-Middle Devonian coral conodont biostratigraphy of the Nogoia Anticline, Springsure district, central Queensland. *Proc. R. Soc. Queensl.*, 87, 63-76.
- Franklin, J. M., Lydon, J. W. and Sangster, D. F., 1981. Volcanic-associated massive sulphide deposits, in *Economic Geology Seventy-Fifth Anniversary Volume* (Ed. Skinner, B. J.), 485-627 (The Economic Geology Publishing Company: El Paso, Texas).
- Graylin, R. K., 1981. The geology of the Kidston breccia complex. *Unpubl. M.Sc. thesis*, James Cook University of North Queensland.
- Harrison, P. L., Anfiloff, W. and Moss, F. J., 1975. Galilee Basin seismic and gravity survey, Queensland 1971. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 175.
- Hedenquist, J. W., and Lindqvist, W. P., 1985. *Aspects of gold geology and geochemistry, Contribution 23* (Economic Geology Research Unit, James Cook University of North Queensland: Townsville).
- Hedenquist, J. W. and Browne, P. R. L., 1989. The evolution of the Waiotapu geothermal system, New Zealand, based on the chemical and isotopic composition of its fluids, minerals and rocks. *Geochim. Cosmochim. Acta.*, 53, 2235-2257.
- Heidecker, E., 1974. A review of major Palaeozoic tectonometallogenic events, northern part of the Tasman Orogenic Zone, in *The Tasman Geosyncline* (Eds. Denmead, A. K., Tweedale, G. W. and Wilson, A. F.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 99-126.

References

- Heidecker, E. J. and Rynn, J. M. W., 1984. The role of lineament interpretation with seismicity: resource implications in northern Queensland. *Qld. Gov. Min. J.*, Vol. 85, 388-392.
- Henderson, R. A., 1980. Structural outline and summary geological history for northeastern Australia, in *The Geology and Geophysics of Northeastern Australia* (Eds. Henderson, R. A. and Stephenson, P. J.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 1-26.
- Henderson, R. A., 1986. Geology of the Mt Windsor Subprovince—a Lower Palaeozoic volcano-sedimentary terrane in the northern Tasman Orogenic Zone. *Aust. J. Earth Sci.*, 33, 343-364.
- Henderson, R. A., 1987. An oblique subduction and transform faulting model for the evolution of the Broken River Province, northern Tasman Orogenic Zone. *Aust. J. Earth Sci.*, 34, 237-249.
- Hodkinson, I., 1990. Mount Leyshon Mine: Then and Now. *Australian Science Magazine*, Issue 1, 31-38.
- Horton, D. J., 1987. Framework of acid volcanic-hosted bulk tonnage gold mineralization in eastern Australia, in *Gold in Queensland* (ed. Herbert, H. K.). *Dep. Geol. Univ. Queensl. Pap.*, 12(1), 17-33.
- Ishihara, S., 1981. The granitoid series and mineralisation. *Econ. Geol.*, 75th Anniv. Vol., 458-484.
- Janatka, J. and Moravek, P., 1987. Geochemical exploration in the Céline Mokrsko gold district in the Jilove Belt, Bohemian massif, Czechoslovakia, in *Abstracts of the 12th IGES*, Orléans, France, April 23-26.
- Jell, J. S. and Hill, D., 1969. Devonian corals from the Ukalunda District, north Queensland. *Publ. Geol. Surv. Queensl.*, 340.
- Karig, D. E., 1974. Evolution of arc systems in the western Pacific. *Earth Planet. Sci.*, 2, 51-75.
- Kirkegaard, A. G., Shaw, R. D., and Murray, C. G., 1970. Geology of the Rockhampton and Port Clinton 1 : 250000 Sheet area. *Rep. Geol. Surv. Queensl.*, 38.
- Kirkegaard, A. G., 1974. Structural elements of the northern part of the Tasman Geosyncline, in *The Tasman Geosyncline* (Eds. Denmead, A. K., Tweedale, G. W. and Wilson, A. F.), 47-62 (Geological Society of Australia, Queensland Division: Brisbane).

- Lacy, W. C., 1980. Mineralization along the extension of the New England and Lachlan-Thomson Fold Belts into north Queensland, in *The Geology and Geophysics of Northeastern Australia* (Eds R. A. Henderson and P. J. Stephenson). *Geol. Soc. Aust.*, Qld Division, 269-277.
- Lawrance, L. M., 1988. Behaviour of gold within the weathering profile in the Yilgarn block, Western Australia, in *Advances in Understanding Precambrian Gold Deposits*, Vol. II (Eds. Ho, S. E. and Groves, D. I.). *Geol. Dept. Univ. Extension*, Univ. of W. Aust., Pub. 12, 335-351.
- Laznika, P., 1988. *Breccias and coarse fragments: petrology, environments, associations and ores*. Elsevier, p. 832.
- Levingston, K. R., 1981. Geological evolution and economic geology of the Burdekin River region, Queensland. *Bur. Miner. Resour. Geol. Geophys. Aust. Bull.* 208.
- Lottermoser, B. G., 1992. Rare earth elements and hydrothermal ore formation processes. *Ore Geology Reviews*, 7, 25-41.
- Lowell, J. D. and Guilbert, J. M., 1970. Lateral and vertical alteration-mineralisation zoning in porphyry ore deposits. *Econ. Geol.*, 65, 373-408.
- Mackenzie, D. E., Henderson, G. A. M., Warnick, J. V. and Bain, J. H. C., 1985. Geology of the Croydon region, Queensland, 1 : 250000 scale map. *Bur. Miner. Resour. Geol. Geophys. Aust.*
- MacLean, W. H. and Barrett, T. J., 1993. Lithogeochemical techniques using immobile elements. *J. Geochem. Explor.*, 48, 109-133.
- Malone, E. J., 1967. Devonian of the Anakie High area, in *International Symposium on the Devonian System, II* (Oswald, D. H.). *Alberta Soc. Pet. Geol.*, Calgary, 93-97.
- Malone, E. J., Corbett, D. W. P. and Jensen, A. R., 1964. Geology of the Mount Coolon 1 : 250000 Sheet area. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 64.
- Malone, E. J., Jensen, A. R., Gregory, C. M. and Forbes, V. R., 1966. Geology of the southern half of the Bowen 1 : 250000 Sheet area, Queensland. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 100.
- Malone, E. J., Olgers, F. and Kirkegaard, A. G., 1969. The geology of the Duaringa and Saint Lawrence 1 : 250000 Sheet areas, Queensland. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 121.
- Marsden, M. A. H., 1972. The Devonian history of northeastern Australia. *J. Geol. Soc. Aust.*, 19, 125-162.
- McMillan, W. J. and Panteleyev, A., 1980. Ore deposits models-1 Porphyry copper deposits. *Geosci. Can.*, 7, 52-63.

- Miller, R. McG., 1983. The Pan African Damara orogen of South West Africa/Namibia. *Spec. Pub. Geol. Soc. S. Afr.*, 11, 431-515.
- Mining Magazine, 1986. Kidston Gold Mine, in *Mining Magazine, January 1986*. Mining Journal Limited: London, 16-21.
- Morrison, G. W., 1987. Styles of bulk tonnage gold mineralization in north Queensland, in *Gold in Queensland* (Ed. Herbert, H. K.). *Dep. Geol. Univ. Queensl. Pap.*, 12(1), p. 34.
- Morrison, G. W., 1988. Palaeozoic gold deposits of northeast Queensland, in *Bicentennial Gold 88*, Melbourne (Ed. Morrison, G. W.). *Geol. Soc. Aust. Abstr.*, 22, 91-101.
- Morrison, G. W., Teale, G. S. and Hodkinson, I., 1987. Geology and gold mineralisation at Mount Leyshon, North Queensland, in *Proceedings Pacific Rim Congress 87*, 777-780 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Morrison, G. W., Teale, G. S., and Hodkinson, I., 1988. The Mount Leyshon gold deposit, in *Bicentennial Gold 88 Excursion No. 8 Guide, Epithermal and Porphyry Style Gold Deposits in North Queensland, Contribution 29* (Ed. Morrison, G. W.), 43-56 (Economic Geology Research Unit, James Cook University of North Queensland: Townsville).
- Murray, C. G., 1974. Alpine-type ultramafics in the northern part of the Tasman Geosyncline - possible remnants of Palaeozoic ocean floor, in *The Tasman Geosyncline - A Symposium* (Eds. Denmead, A. K., Tweedale, G. W., and Wilson, A. F.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 161-181.
- Murray, C. G., 1986. Metallogeny and tectonic development of the Tasman Fold Belt System in Queensland, in *Metallogeny and tectonic development of eastern Australia* (Ed. Scheibner, E.). *Ore Geology Reviews*, Vol. 1, 315-400.
- Murray, C. G., 1990. Tasman Fold Belt in Queensland, in *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. Hughes, F. E.), 1431-1450 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Murray, C. G. and Kirkegaard, A. G., 1978. The Thomson Orogen of the Tasman Orogenic Zone. *Tectonophys.*, 48, 299-325.
- Murray, C. G., Fergusson, C. L., Flood, P. G., Whitaker, W. G. and Korsch, R. J., 1987. Plate Tectonic model for the Carboniferous evolution of the New England Fold Belt. *Aust. J. E. Sci.*, 34, 213-236.
- Mustard, H., 1986. Geology and genesis of the Kidston gold deposit, Australia, in *Gold '86, An International Symposium on the Geology of Gold Deposits* (Ed. Macdonald, A. J.), Toronto, 404-415.

- Ohmoto, H., 1972. Systematics of sulphur and carbon isotopes in hydrothermal ore deposits. *Econ. Geol.*, 67, 551-578.
- Olgers, F., 1972. Geology of the Drummond Basin, Queensland. *Bull. Bur. Miner. Resour. Geol. Geophys. Aust.*, 132.
- Ouedraogo, M. F., 1988. The Kwademen gold deposit: a polymorphic mineralisation within a Precambrian (Birimian) greenstone belt in Burkina Faso, West Africa: a case history (Abstract), in *The 2nd Int. Conf. on Prospecting in Arid Terrain*, Perth, Western Australia. Aust. IMM, Symposia Series 57, 105.
- Paine, A. G. L., Clarke, D. E. and Gregory, C. M., 1974. Geology of the northern half of the Bowen 1 : 250000 Sheet area, Queensland (with additions to the geology of the southern half). *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 145.
- Paull, P. L., Hodkinson, I. P., Morrison, G. W. and Teale, G. S., 1990. Mount Leyshon gold deposit, in *Geology of the Mineral Deposits of Australia and Papua New Guinea* (Ed. Hughes, F. E.), 1471-1481 (The Australasian Institute of Mining and Metallurgy: Melbourne).
- Pelham, D. A., 1983. The geological evolution and mineralised environments of the Tasman Geosyncline. *Unpubl. M.Sc. Dissertation, Rhodes University, Grahamstown, South Africa*, p. 200.
- Peters, S. G., 1987. Geology and lode controls on the Charters Towers Goldfield, north eastern Queensland. *Contributions of the Economic Geology Research Unit* 19, p. 117.
- Peters, S. G. and Golding, S. D., 1987. Relationship of gold quartz mineralisation to granodioritic phases and mylonites at Charters Towers goldfield, northeastern Queensland, in *Proceedings Pacific Rim Congress '87*, 363-367 (The Australian Institute of Mining and Metallurgy: Melbourne).
- Pirajno, F., 1992. *Hydrothermal Mineral Deposits : Principles and Fundamental Concepts for the Exploration Geologist*. Springer-Verlag, New York, p. 709.
- Sabins, F. F., 1983. *Remote sensing laboratory manual, second edition*. Remote Sensing Enterprises, La Habra, Calif.
- Sabins, F. F., 1987. *Remote Sensing: Principles and interpretation*. W. H. Freeman and Company: New York.
- Salpéteur, I. and Sabir, H., 1989. Orientation studies for gold in the central piedplain of the Saudi Arabian shield. *J. Geochem. Explor.*, 25, 129-137.
- Seward, T. M., 1984. The transport and deposition of gold in hydrothermal systems, in *Gold '82: The Geology, Geochemistry and Genesis of Gold Deposits* (Ed. Foster, R. P.). Balkema Press, Rotterdam, 165-181.

- Seward, T. M., 1991. The hydrothermal geochemistry of gold, in *Gold Metallogeny and Exploration* (Ed. Foster, R. P.). Blackie and Son Limited, London, 37-62.
- Shepherd, T., Rankin, A. H. and Alderton, D. H. M., 1985. *A practical guide to fluid inclusion studies*. Chapman & Hall, New York, pp. 239.
- Sillitoe, R. H., 1983. Styles of low grade gold mineralisation in volcano-plutonic arcs. *Nev. Bur. Mines & Geol.*, Rept 36, 52-68.
- Sillitoe, R. H., 1985. Ore-related breccias in volcano-plutonic arcs. *Econ. Geol.*, 80, 1467-1514.
- Sillitoe, R. H., 1991. Intrusion-related gold deposits, in *Gold Metallogeny and Exploration* (Ed. Foster, R. P.). Blackie and Son Limited, London, 165-209.
- Sillitoe, R. H., and Bonham, H. F., Jr., 1984. Volcanic landforms and ore deposits. *Econ. Geol.*, 79, 1286-1298.
- Smith, R. E., Birrell, R. D. and Bigden, J. F., 1989. The implications to exploration of chalcophile corridors in the Archaean Yilgarn Block, Western Australia, as revealed by laterite geochemistry. *J. Geochem. Explor.*, 32, 169-184.
- Streckeisen, A., 1979. Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites and melilitic rocks: recommendations and suggestions of the IUGS Subcommission on the Systematics of Igneous Rocks. *Geology*, 7, 331-335.
- Taylor, B. E., 1988. Degassing of rhyolitic magmas: Hydrogen isotope evidence and implications for magmatic-hydrothermal ore deposits, in *Recent Advances in the Geology of Granite-related Mineral Deposits* (Eds. Taylor, R. P. and Strong, D. F.). *Can. Inst. Min. Metal.*, Special Vol. 39, 33-49.
- Taylor, G. H., Coste, B., Lambert, A. and Zeegers, H., 1989. Geochemical signature (bedrock and saprolite) of gold mineralisation and associated hydrothermal alteration at Dorlin, French Guyana (extended abstract). *J. Geochem. Explor.*, 32, 59-60.
- Taylor, R. G., 1992. *Ore Textures : Recognition and Interpretation. Volume 1 : Infill Textures*. James Cook University of North Queensland, p. 24.
- Thompson, R. W., 1975. Tidal flat sediments of the Colorado River delta, northwestern Gulf of California, in *Tidal Deposits* (Ed. Ginsburg, R. N.). Springer-Verlag, Berlin, 57-65.
- Uematsu, M. and Franck, E. U., 1980. The static dielectric constant of water and steam. *J. Phys. Chem. Ref. Data* 9, 1291-1301.

References

- Vasquez-Lopez, R., Lefur, Y., Chevance, H., Bellivier, F., Brosset, R., Callier, L. and Kerjean, M., 1987. La recherche de l'or primaire dans le massif Armoricaïn (France): approches géochimiques et minéralogiques combinées, in *Abstracts of the 12th IGES*, Orléans, France, April 23-26.
- Vine, R. R., 1972. Relationship between the Adavale and Drummond Basins. *APEA J.*, 12, 58-61.
- Vogt, P. R., 1974. Volcano spacing, fractures, and thickness of the lithosphere. *Earth Planet. Sci. Lett.*, 21, 235-252.
- Warnick, J. V., 1985. Mines and mineral deposits of the Croydon region. *Geol. Surv. Queensl. Rec.* 1985/42 (unpublished).
- Webb, A. W. and McDougall, I., 1968. The geochronology of the igneous rocks of eastern Queensland. *J. Geol. Soc. Aust.*, 15, 313-346.
- Whitaker, W. G., Murphy, P. R. and Rollason, R., 1974. Geology of the Mundubbera 1 : 250000 Sheet area. *Rep. Geol. Surv. Queensl.*, 84.
- White, D. A., 1965. The geology of the Georgetown/Clarke River area, Queensland. *Bull. Bur. Miner. Resour. Geol. Geophys. Aust.*, 71.
- Willmott, W. F., Whitaker, W. G., Palfreyman, W. D. and Trail, D. S., 1973. Igneous and metamorphic rocks of Cape York Peninsula and Torres Strait. *Bull. Bur. Miner. Resour. Geol. Geophys. Aust.*, p. 135.
- Wilson, G. I., Lewis, R. W., Gallo, J. B. and Tullemans, F. J., 1986. The geology of the Kidston gold mine, in *Publications of the 13th CMMI Congress, Vol. 2, Geology and Exploration* (Ed. Berkman, D. A.), 235-242 (13th Congress of the Council of Mining and Metallurgical Institutions: Melbourne; and the Australian Institute of Mining and Metallurgy: Melbourne).
- Withnall, I. W., 1984. Stratigraphy, structure, and metamorphism of the Proterozoic Etheridge and Langlovale Groups, central Georgetown Inlier, north Queensland. *Geol. Surv. Queensl.*, Rec. 1984/59, unpublished, p. 175.
- Withnall, I. W., 1985. Geochemistry and tectonic significance of Proterozoic mafic rocks from the Georgetown Inlier, north Queensland. *BMR J. Aust. Geol. Geophys.*, 9, 339-351.
- Withnall, I. W., Bain, J. H. C. and Rubenach, M. J., 1980. The Precambrian geology of northeastern Queensland, in *The Geology and Geophysics of Northeastern Australia* (Eds. Henderson, R. A. and Stephenson, P. J.). *Geol. Soc. Aust.*, Qld Division, Brisbane, 109-127.

- Withnall, I. W., Bain, J. H. C., Draper, J. J., Mackenzie, D. E. and Oversby, B. S., 1988a. Proterozoic stratigraphy and tectonic history of the Georgetown Inlier, northeastern Queensland. *Precambrian Research*, 40/41, 429-466.
- Withnall, I. W., Lang, S. C., Jell, J. S., McLennan, T. P. T., Talent, J. A., Mawson, R., Fleming, P. J. G., Law, S. R., Macansh, J. D., Savory, P., Kay, J. R. and Draper, J. J., 1988b. Stratigraphy, sedimentology, biostratigraphy and tectonics of the Ordovician to Carboniferous Broken River Province, north Queensland. *Geol. Soc. Aust. Australas. Sedimentol. Group Field Guide Series 5*.
- Wormald, P. J., Orr, T. O. and Hodgkinson, I. P., 1991. The Mount Leyshon Gold Mine (NE Queensland), an Intrusive Breccia and Igneous Complex. *World Gold '91*. Cairns, Qld, 21-25.
- Wyatt, D. H. and Jell, J. S., 1967. Devonian of the Townsville hinterland, Queensland, Australia, in *International Symposium on the Devonian System, II* (Ed. Oswald, D. H.). *Alberta Soc. Pet. Geol.*, Calgary, 99-105.
- Wyatt, D. H., Paine, A. G. L., Clarke, D. E. and Harding, R. R., 1970. Geology of the Townsville 1 : 250 000 Sheet area, Queensland. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 127.
- Wyatt, D. H., Paine, A. G. L., Clarke, D. E., Gregory, C. M. and Harding, R. R., 1971. Geology of Charters Towers 1 : 250000 Sheet area, Queensland. *Rep. Bur. Miner. Resour. Geol. Geophys. Aust.*, 137.
- Wyborn, L. A. I., 1981. Aspects of the geochemistry and economic potential of the felsic igneous rocks of the Mt Isa region, in *Tenth BMR Symposium, Abstr.*, *BMR J. Aust. Geol. Geophys.*, 6, 276.
- Zeegers, H., 1987. Remaniements de surface et prospection géochimique de l'or. *Chron. Rech. Min.*, 488, 55-61.
- Zeegers, H. and Leduc, C., 1991. Geochemical exploration for gold in temperate, arid, semi-arid, and rain-forest terrains, in *Gold Metallogeny and Exploration* (Ed. Foster, R. P.). Blackie and Son Limited, London, 309-335.