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A review of the geology, mineralisation, and geothermal energy potential of the Thomson Orogen in Queensland

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SUMMARY

The Thomson Orogen is the largest but least understood element of Queensland's geology. Only a small proportion crops out at the surface, the remainder being covered by a series of sedimentary basins. The outcropping rocks include Neoproterozoic to Devonian metasedimentary and metavolcanic sequences and several major batholiths. These have undergone multiple compressional and extensional deformation events and several major phases of magmatism. This long history is reflected in the abundance and wide variety of mineralisation styles represented in the outcropping area and bodes well for the greenfield potential of covered areas. The tectonic evolution of the Thomson Orogen is traditionally interpreted in terms of major deformation events (defined in southern Australia) associated with a convergent plate boundary. However, several issues, including the relationship between the Thomson Orogen and surrounding crustal domains, remain unknown.

SCOPE OF REPORT

This review is a component of the Geological Survey of Queensland's 'Geology of the Thomson Orogen' project which aims to increase knowledge of this large but poorly understood and potentially economically important element of Queensland geology. The report is a synthesis of published and unpublished geological data for the Thomson Orogen and represents the current state of knowledge regarding the geology (lithology, geochronology, structure), mineralisation (style, age, production), and geothermal energy potential (exploration and research). Additionally, hypotheses for the distribution and tectonic evolution of the Thomson Orogen are summarised here and placed within the context of the development of eastern Australia. Key knowledge gaps are identified and these form the basis of an outline for future research.

INTRODUCTION

The Thomson Orogen is a component of the Tasmanides of eastern Australia (see Glen, 2005 for summary) which also includes the Delamerian Orogen, Lachlan Orogen, Mossman Orogen and New England Orogen (Figure 1). Together, these tectonic elements record the break-up of Rodinia, followed by the growth of orogenic belts along the eastern margin of Gondwana.

In Queensland, the Thomson Orogen is enormous. According to the currently defined distribution (Figure 2), it extends through much of central to southern and south-western Queensland and occupies ~810 000km^2 (approximately one third of the state). However, only a small proportion (~22 000km^2) crops out (Figure 2). The remainder is buried to depths of up to 4km below a sequence of younger sedimentary basins (Figure 3) and remains poorly understood. Outcrop occurs in central to northern Queensland across several tectonic provinces and includes extensive metasedimentary

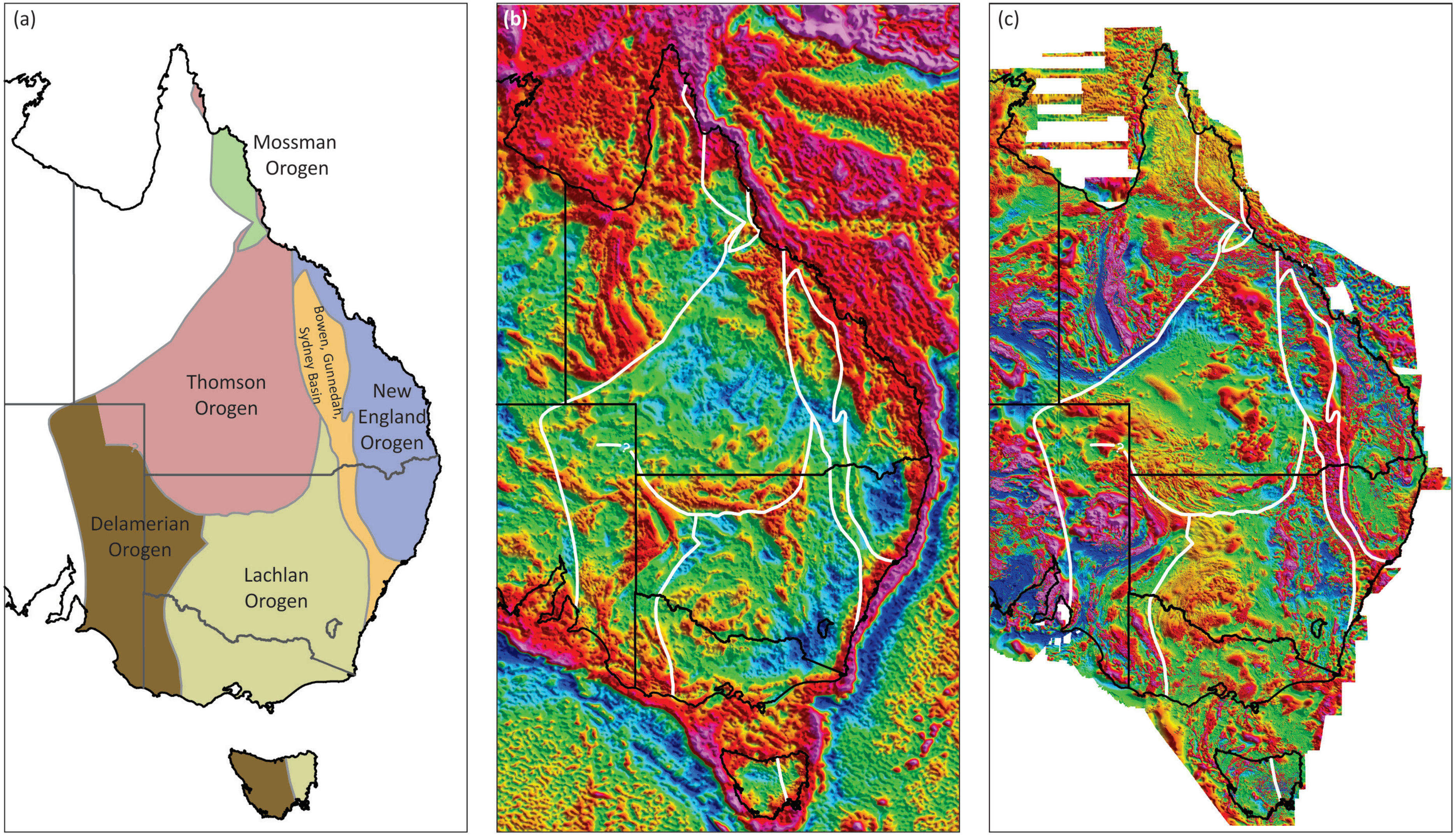


Figure 1. Distribution and division of the Tasmanides in eastern Australia as defined by Glen (2005) with the addition of the Iron Range Province after GSQ (2012). a) tectonic elements that comprise the Tasmanides, b) boundaries of the Tasmanides relative to gravity and c) total magnetic intensity images. Note the sharp boundary defining the north-western boundary of the Thomson Orogen and the curved gravity and magnetic trends that define the southern boundary of the Thomson Orogen.

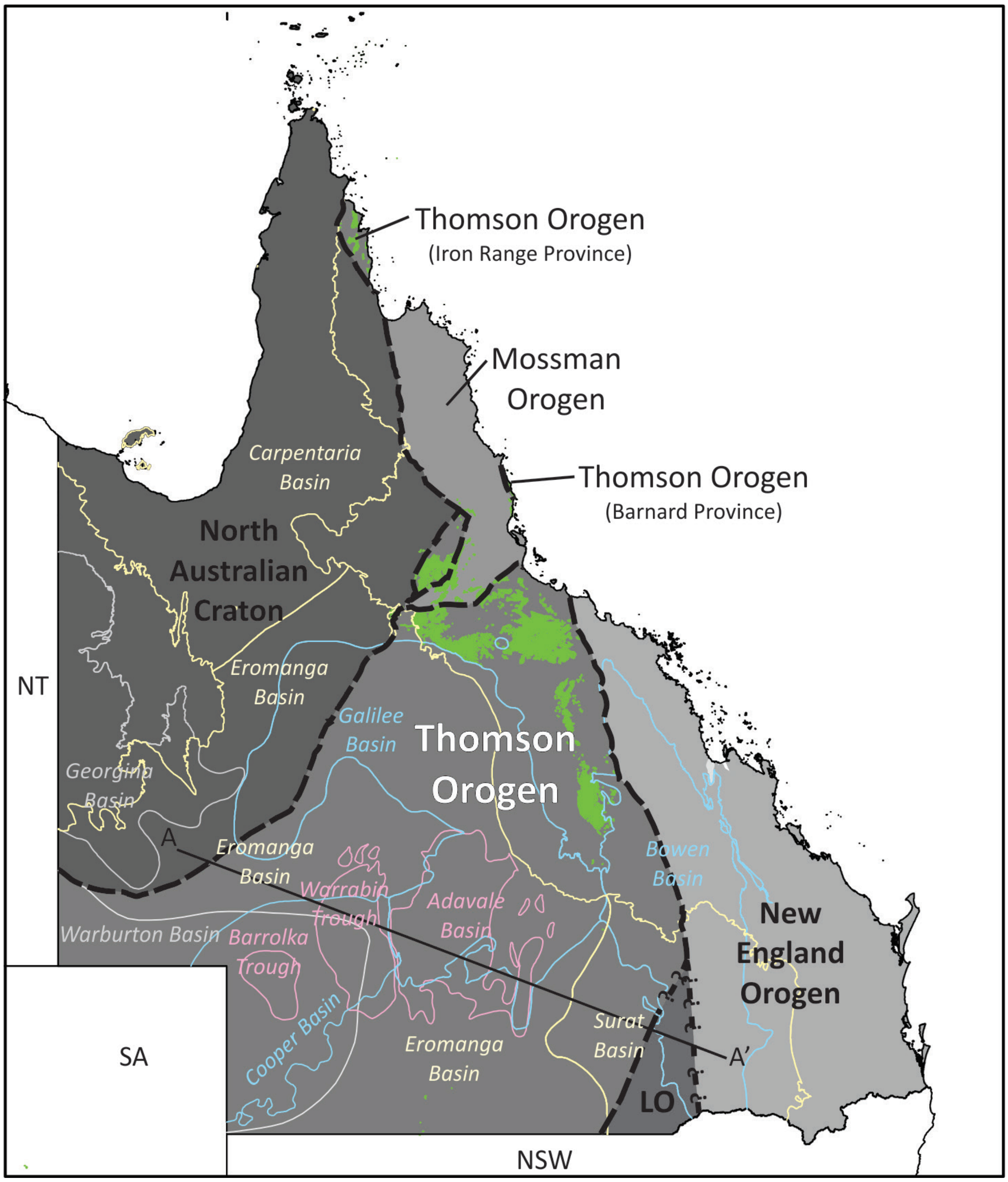


Figure 2. Major basement tectonic elements of Queensland overlain by distribution of major basins. Green indicates areas of Thomson Orogen outcrop, the remainder of the Thomson Orogen is inferred below a series of basins.

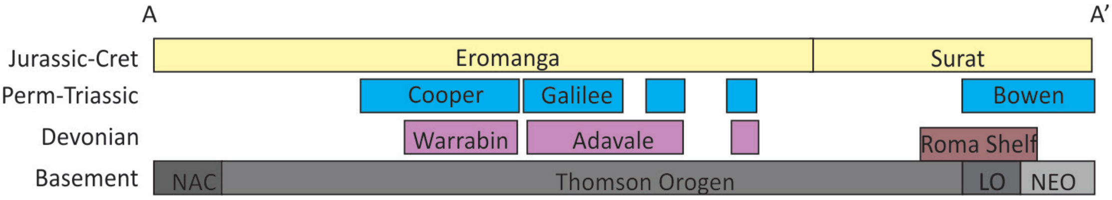


Figure 3. Schematic arrangement of basement terranes and overlying basins through southern Queensland. The Thomson Orogen is overlain by elements of the Devonian basin system (Adavale Basin, Warrabin Trough etc.), Permian to Triassic basins (Bowen, Galilee, Cooper), and Jurassic to Cretaceous Basins (Surat in the east and Eromanga in the west).

and metavolcanic sequences and voluminous granitic batholiths. The metasediments and metavolcanics can be broadly divided into Neoproterozoic to Cambrian and Cambrian to Ordovician age groups whereas batholiths are Ordovician to Permian. Very small areas of outcrop also occur in the far southern Thomson Orogen along the Eulo Ridge where small granitoid bodies are exposed.

The outcropping Thomson Orogen rocks are rich in mineralisation and include some of Queensland's most economically important deposits (e.g. Charters Towers Goldfield). Several different mineralisation styles are represented including orogenic gold, VHMS, and porphyry-related styles. Although age constraints are generally poor, these appear to span the Neoproterozoic to Carboniferous history of the orogen. The variety and abundance of mineralisation in the outcropping Thomson Orogen of Queensland and New South Wales make shallowly covered areas attractive as greenfields exploration targets and worthy of further investigation.

The isolation of outcropping Thomson Orogen rocks in Queensland relative to the better-defined Delamerian and Lachlan Orogens further south makes development of tectonic models difficult. Most tectonic models are severely limited by lack of knowledge of the lithology, age ranges and deformational history of the undercover Thomson Orogen. The Geological Survey of Queensland has commenced work on a new project to overcome some of these issues and to investigate the economic potential of the Thomson Orogen. This report forms an initial part of that project and is a summary of what is known about the Thomson Orogen and key areas of future work.

In addition to a review of the geology, mineralisation, geothermal energy potential and tectonics, we also include a glossary of terms commonly associated with the Thomson Orogen (Appendix 1) as well as compilations of geochemistry (Appendix 2), geochronology (Appendix 3) and known resources and production (Appendix 4).

EXTENT OF THE THOMSON OROGEN

The Thomson Orogen occupies ~1 000 000km^2 between the Proterozoic North Australian Craton in the west and north, and the Devonian to Triassic New England Orogen in the east (Figure 2). It extends into northern New South Wales where it is bounded by the Delamerian Orogen and Lachlan Orogen.

The north-western boundary of the Thomson Orogen is generally considered to be marked by a change from broadly north–south trending gravity and magnetic features in the Mount Isa Inlier to broadly north-east trending features in the Thomson Orogen (Murray & Kirkegaard, 1978). The boundary is concealed but appears as a strikingly obvious contrast in modern geophysical images (Figure 1c). The boundary trends east-north-east and is known as the Cork Fault or Dimantina Lineament (Kirkegaard 1974). This boundary corresponds to the Tasman Line which was initially proposed significantly eastward (Hill, 1951). Unlike regions to the south, the Tasman Line is Queensland is well defined as separating Proterozoic and Paleozoic rocks (see Direen

& Crawford, 2003a). Further north the line coincides with the north-south trending Palmerville Fault System; a major west-dipping Devonian Carboniferous thrust system (Shaw & others, 1987). However in central-northern Queensland geophysical contrasts between the North Australian Craton and Thomson Orogen become less apparent. The steeply dipping Lynd Mylonite Zone, separating Paleoproterozoic to Mesoproterozoic rocks of the Einasleigh Metamorphics from the Early Paleozoic rocks of the Greenvale Province may represent an exposed section of the Tasman Line (Fergusson & others, 2007c).

The north-eastern boundary of the Thomson Orogen is marked by faults between the Greenvale Province and Broken River Province (Burdekin River Fault, Halls Reward Fault, Teddy Mount Fault) (Withnall & Lang, 1993). Further to the south, the eastern boundary with the New England Orogen, is either obscured by granitoid intrusion (Townsville region) or covered by the Bowen Basin (through central and southern Queensland). In southern Queensland, the Thomson and New England Orogens may be separated by a wedge of Lachlan Orogen (Figure 1). The eastern boundary of the Thomson Orogen here may be imaged in deep seismic associated with the Brisbane–Eromanga geoscience transect (Finlayson & others, 1990). The Thomson/Lachlan interface is described as a shallow-dipping structure (which corresponds to a gravity boundary) characterised by upwardly convex reflectors (Finlayson & others 1990; Wellman 1990).

Despite good geophysical data coverage including a deep crustal seismic profile, the nature of the southern boundary of the Thomson Orogen is contentious. In early models the Darling River Lineament (Figure 4) (a persistent crustal-scale feature) was used as the southern boundary (e.g. Kirkegaard, 1974; Scheibner, 1978). The notion that curved gravity trends in northern New South Wales are related to the boundary was proposed by Murray & Kierkegaard (1978), and this has persisted in more recent interpretations (Figure 4). More specifically, the exact boundary has been interpreted as the Olepoloko Fault (Stevens, 1991; Glen, 2005; Glen & others, 2007). Some interpretations from deep seismic data (e.g. Glen & others, 2007) suggest that this fault is a major north-dipping crustal suture which offsets the Moho and separates thinner (32km) lower crust of the Lachlan Orogen from thicker crust of the Thomson Orogen (~48km) (Glen & others, 2007). An alternative hypothesis (Burton, 2010) suggests that there is no boundary between the Thomson and Lachlan Orogens.

The south-western boundary of the Thomson Orogen, along the Queensland – South Australia border is more problematic and cannot be defined until the relationship between the Thomson Orogen and Warburton Basin is resolved.

In the far north, the Barnard Province and more tentatively the Iron Range Province (Figure 2) are included as discrete elements of the Thomson Orogen due to age and lithology similarities. The Barnard Province is restricted to coastal areas between Cairns and Tully and has a faulted contact to the west with the Hodgkinson Province (Russell-Mulgrave Shear Zone) (Bultitude & others, 1997). The relationship between the Sefton Metamorphics (Iron Range Province) and the adjacent Savannah and Etheridge Provinces to the west is uncertain (Blewett & others, 1997).

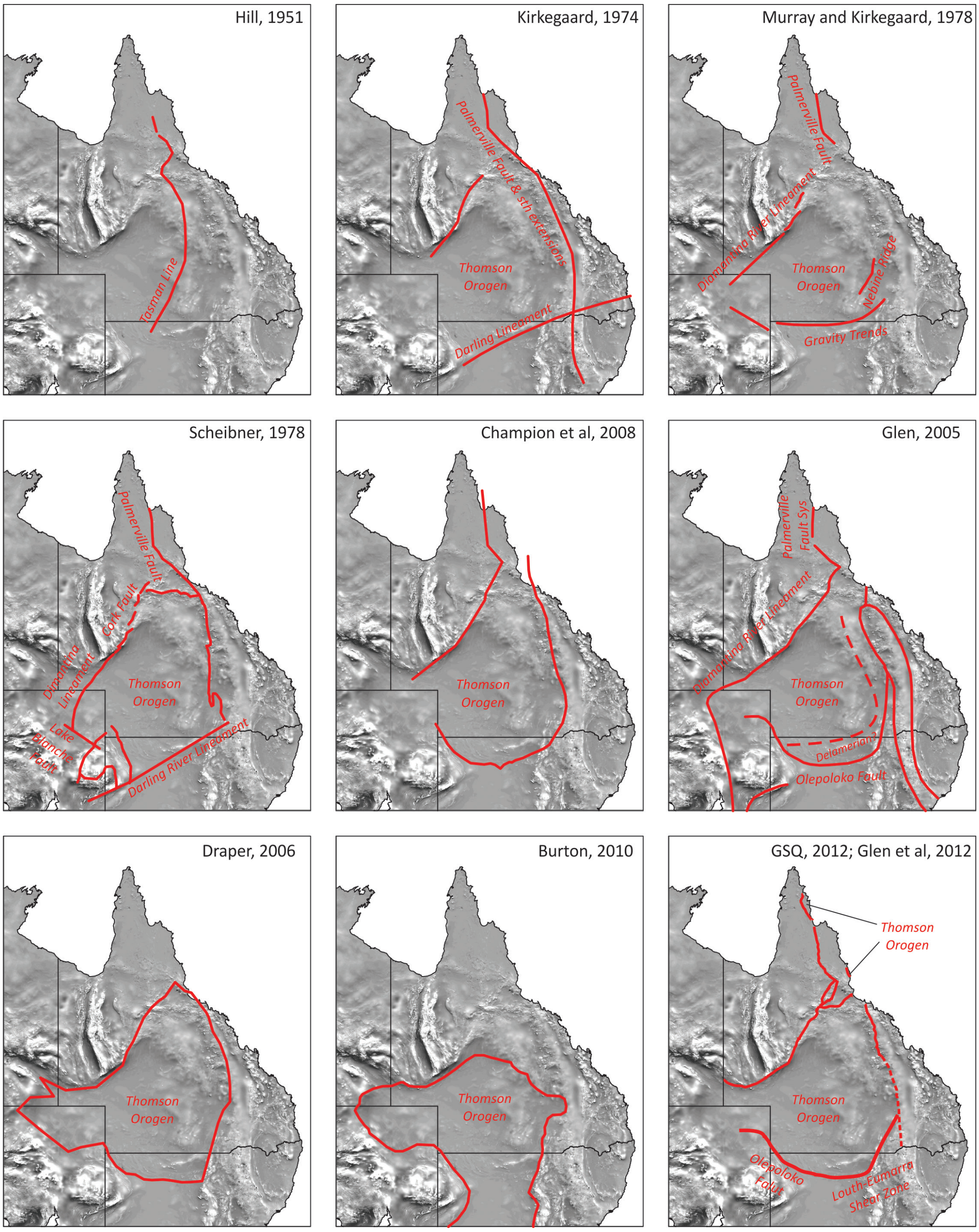


Figure 4. Different interpretations for the distribution of the Thomson Orogen. Murray & Kirkegaard (1978) were the first to use regional trends in geophysical data to define boundaries. Recent interpretations include the Barnard and Iron Range Provinces in north Queensland, and define the southern boundary as the Olepoloko Fault.

OUTCROPPING GEOLOGY

Outcrop of the Thomson Orogen is rare and predominantly restricted to the north-eastern margin where it occurs within several tectonic provinces: Anakie Province, Charters Towers Province, Greenvale Province, Barnard Province and possibly the Iron Range Province (Figure 5). The outcropping Thomson Orogen rocks are divided into numerous metamorphic complexes generally composed of metasedimentary schist and gneiss, mafic and ultramafic rocks, and deformed granite and migmatite

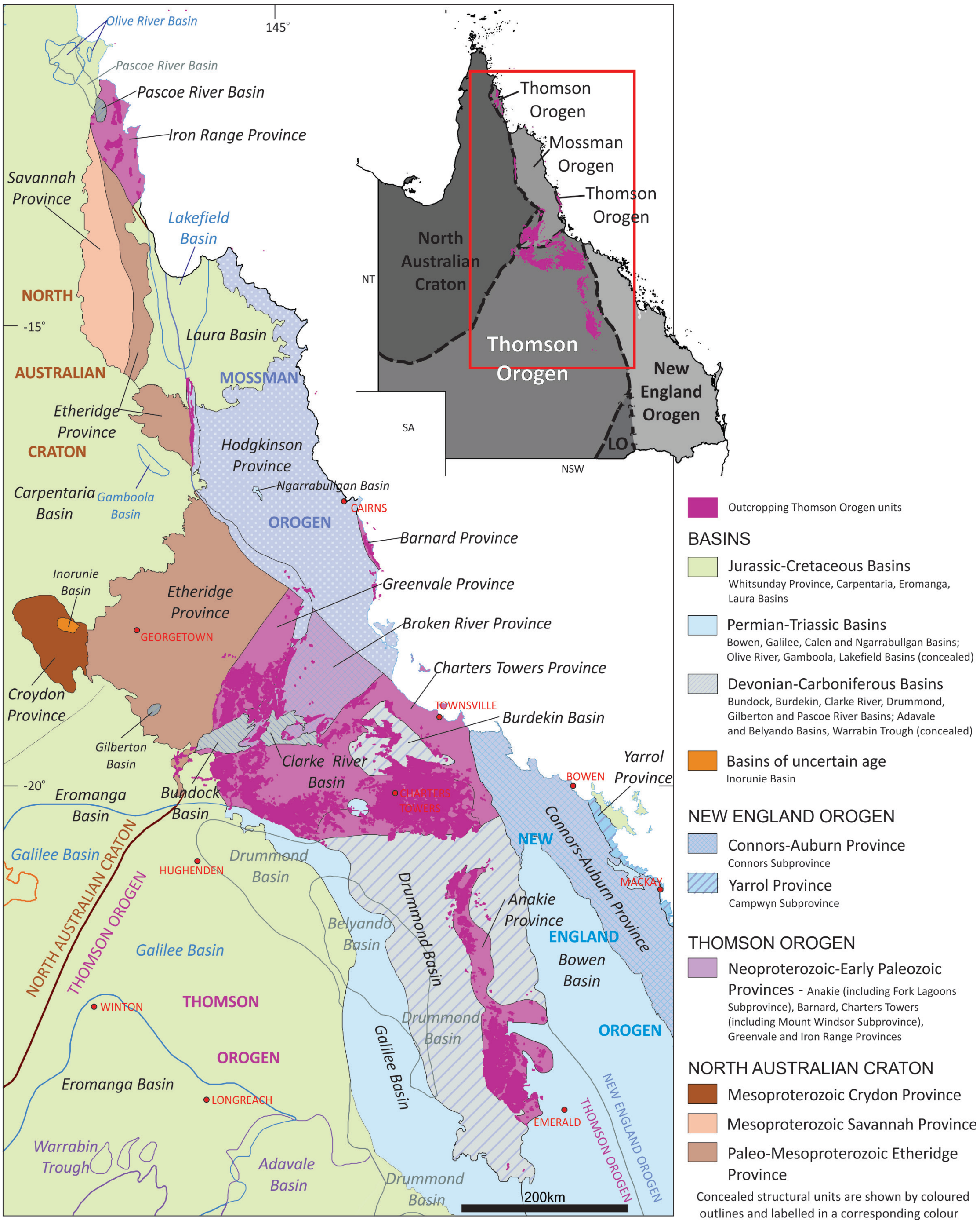


Figure 5. Distribution of outcropping Thomson Orogen rocks relative to geological provinces defined in central and north Queensland (Geological Survey of Queensland, 2012). Outcrop occurs in the Anakie, Barnard, Charters Towers, Greenvale, and Iron Range Provinces.

(Withnall & others, 1995; 1997b; Bultitude & others, 1999; Hutton, 2004: Fergusson & others, 2007b; Fergusson & others, 2007c). Rocks of comparable age also occur along the western margins of the Broken River Province (the Judea Formation, Carriers Well Formation and Everetts Creek Volcanics) and Hodgkinson Province (the Mountain View Conglomerate, the Mulgrave Formation, and the Quadroy Conglomerate) of the Mossman Orogen, and are described here.

Below, we describe the geology of outcropping Thomson Orogen rocks divided into tectonic province and age.

ANAKIE PROVINCE

The Anakie Province is an elongate (300km by 60km) body of Neoproterozoic to Ordovician metasediments and metavolcanics, sparsely intruded by rocks of Ordovician to Devonian age (Figure 6). It is unconformably overlain by the Bowen Basin to the east, and the Drummond Basin to the west. The province is believed to continue subsurface southwards, forming a basement high known as the Nebine Ridge.

The province is dominated by the Neoproterozoic to Cambrian Anakie Metamorphic Group which is predominantly metamorphosed fine- to medium-grained sedimentary rocks, with minor greenstone and calc-silicate units. These are in fault contact with late Cambrian to Early Ordovician metasediments of Les Jumelles beds in the north, and Ordovician metasediments with minor metavolcanics of the Fork Lagoon beds in the south. Intrusive rocks comprise the Middle Ordovician Coquelicot Tonalite and Mooramin Granite, the Early Silurian Gem Park Granite and the voluminous Late Devonian Retreat and Taroborah Batholiths, which have possible extrusive equivalents in the Theresa Creek Volcanics.

Neoproterozoic–Cambrian

Anakie Metamorphic Group

The Anakie Metamorphic Group crops out as a predominantly linear belt of intermingled meta-igneous and meta-sedimentary rocks. The belt extends 250km north from Anakie, and reaches a maximum width of 80km. The northern section is deeply weathered and poorly exposed (Hutton & others, 1998). Within the southern section Withnall & others (1995) defined six units and their structures (summarised in Table 1), although intense metamorphism and deformation has prevented the establishment of a complete stratigraphic succession. Withnall & others (1995) noted a consistent westerly dip of foliation and lithological layers, creating an apparent stratigraphic sequence with the Bathampton Metamorphics forming the basal layer overlain by the Rolfe Creek Schist, Monteagle Quartzite and Wynyard Metamorphics. The position of the Scurvy Creek Meta-arenite and the Hurleys Metamorphics within this sequence is unknown, but it is speculated that they are equivalents of the Wynyard Metamorphics and the Monteagle Quartzite respectively.

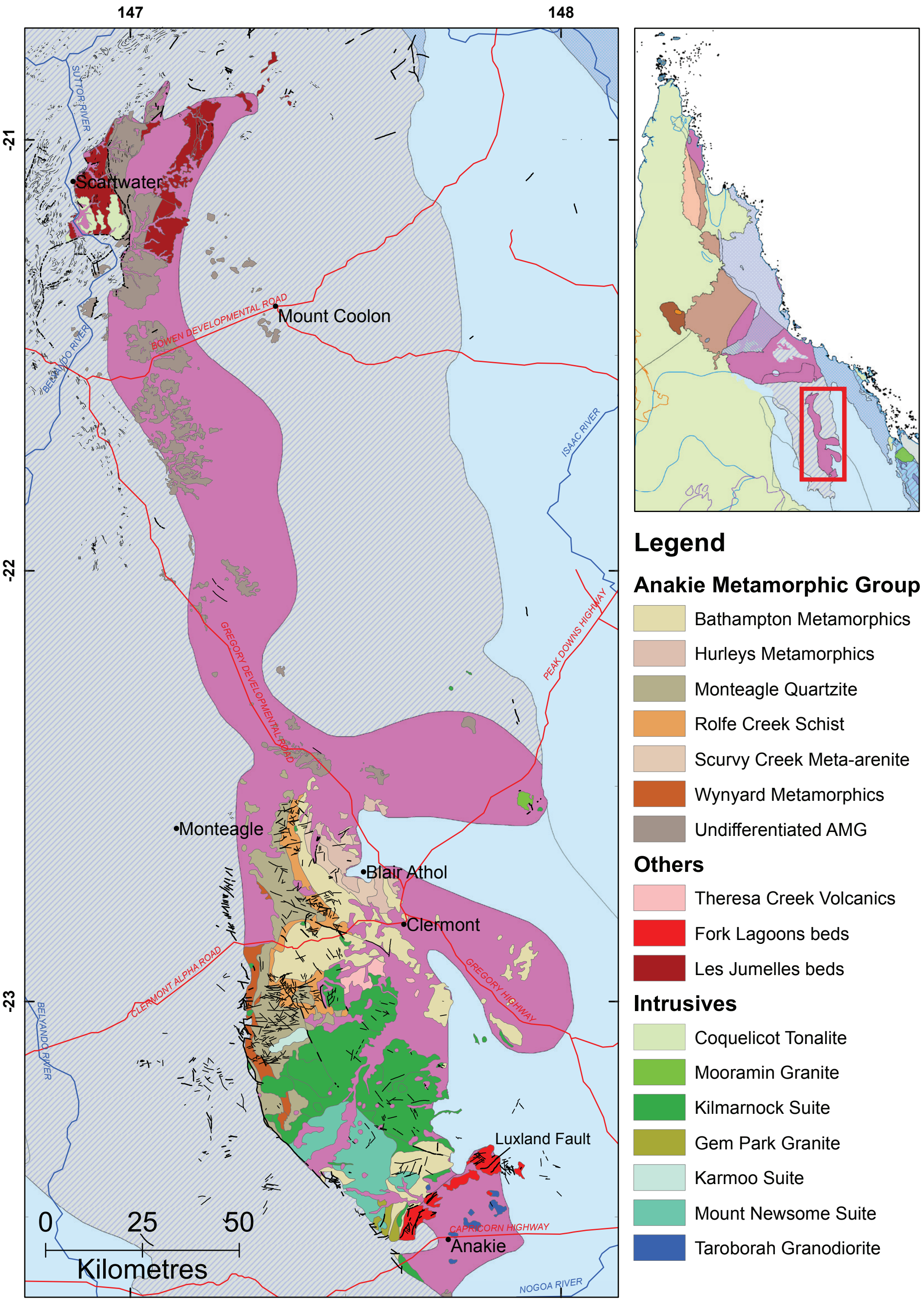


Figure 6. Outcropping geology of the Anakie Province. Inset shows location of the Anakie Province relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

Table 1. Geology of the Anakie Metamorphic Group, modified from Withnall & others (1995)

Unit	Lithology	Structure	Age constraints
Bathampton Metamorphics	Pb: mica schist and quartzite, neither of which is particularly dominant.	Dominant micaceous and quartzose S_2 foliation and isoclinal F_2. Minor S_1 crenulation.	>500Ma (K–Ar; Withnall & others, 1996), < ~615Ma (U-Pb detrital zircon; Fergusson & others, 2001).
	Pbp: pelitic lithofacies consisting dominantly of fine-grained mica schist (grading to phyllite) and subordinate quartzite.		
	Pbq: more psammitic lithofacies consisting of abundant to dominant quartzite interlayered with mica schist and phyllite.		
	Pbg: commonly laminated greenstone or calc-silicate rocks, and interbedded mica schist and phyllite.		
	Psp: minor serpentinite bodies.		
	Yan Can Greenstone: similar lithology to Pbg but generally not as strongly laminated.		
	Pba: massive to foliated metagabbro, laminated amphibolite and calc-silicate rocks (Figure 7a).		
Rolfe Creek Schist	Single homogenous pelitic unit, strongly foliated, mostly fine-grained, dominant mineralogy including quartz and muscovite, minor chlorite and/or biotite, iron oxides, tourmaline, magnetite and graphite.	Dominant micaceous and quartzose S_2 foliation and isoclinal F_2. Minor S_1 crenulation.	None
Monteagle Quartzite	Fine- to very coarse-grained, medium- to very thick-bedded, well foliated quartzite interlayered with thin to thick mica schist.	S_0 locally preserved. S_1 commonly folded by tight F_2 folds with associated S_2 fabric.	None
Wynyard Metamorphics	Fine- to medium-grained meta-arenite and medium-grained muscovite-biotite schist with local calc-silicate lenses (including hornblende, garnet and zoisite).	Micaceous non-domainal S_1 which is parallel to S_0. Deformed by F_2 folds and crosscut by slightly domainal S_2 micaceous foliation.	< ~510Ma (U-Pb detrital zircon; Fergusson & others, 2001).
Hurleys Metamorphics	Fine- to medium-grained and locally coarse-grained quartzite, phyllite or fine-grained mica schist. Ranges in thickness to tens of meters. Minor quartzose metasiltstones to quartz-rich phyllites.	Crenulated micaceous S_1 foliation and domainal muscovite S_2 foliation	>495Ma (whole rock K–Ar; Withnall & others, 1996).
Scurvy Creek Meta-arenite	Very fine- to medium-grained meta-arenite with subordinate phyllite and fine-grained mica schist (Figure 7b).	Strongly differentiated S_1 layering with anastomosing mica-rich layers. Deformed by F_2 folds and cross cut by a locally crenulated but generally domainal S_2 foliation.	None

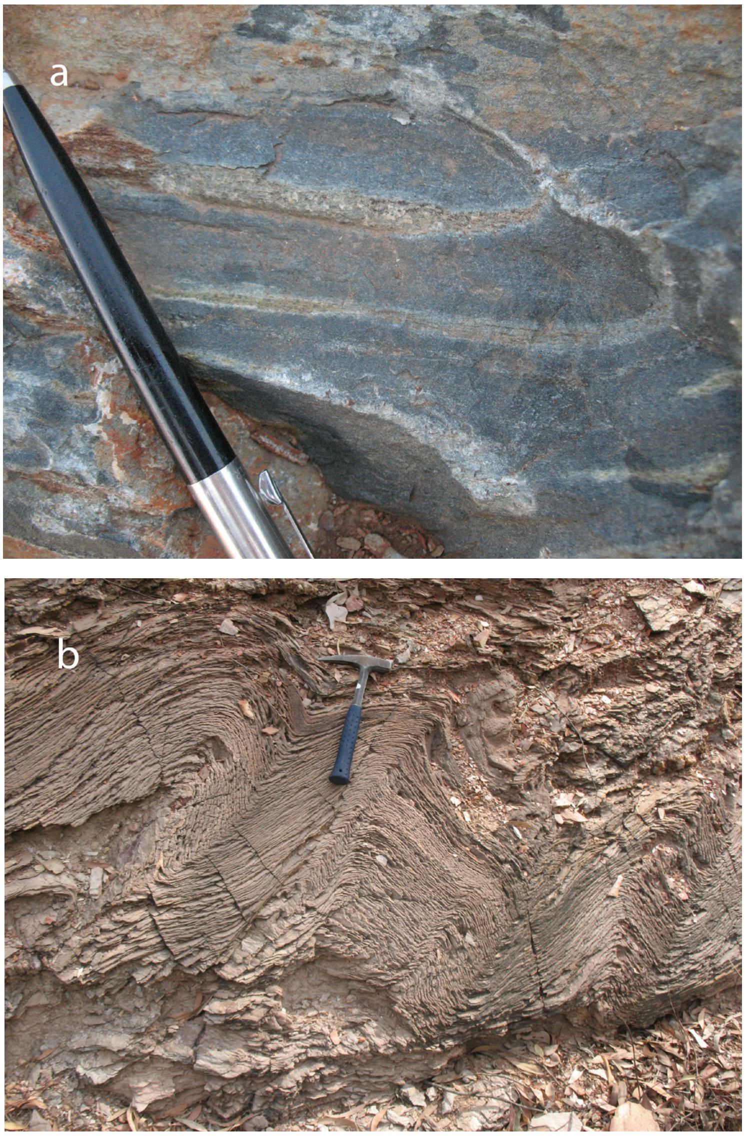


Figure 7. Outcrops of the Anakie Metamorphic Group: a) banded amphibolite with a strong foliation of the Bathampton Metamorphics (GR E568086 N7414740); b) at least two deformations within a phyllitic to schistose meta-arenite of the Scurvy Creek Meta-arenite (GR E557436 N7486686).

Geochemistry

Geochemical analyses of igneous rocks within the Bathampton Metamorphics have been presented by Withnall & others (1995) and Fergusson & others (2009). Due to significant alteration, protolith interpretations are based largely on immobile elements.

The igneous rocks surrounding Clermont are geochemically different to those at Rubyvale. At Clermont, the Yan Can Greenstone Member (interpreted as basaltic lava) and an unnamed laminated greenstone (interpreted as dolerite or gabbroic sills) are andesite to basalt in composition (Figure 8) and display similar immobile and incompatible element concentrations indicative of a magmatic affinity (Withnall & others, 1995; Fergusson & others, 2009). Geochemically the protolith appears subalkaline (Figure 8), resembling MORB-like, low-Ti basalts (Figure 9a,b; Withnall & others, 1995; Fergusson & others, 2009).

Metabasalt, metagabbro and amphibolite surrounding Rubyvale are distinct from Clermont samples in that they are alkaline (Figure 8), more enriched in high field strength elements (HFSE) and large-ion lithophile elements (LILE) compared

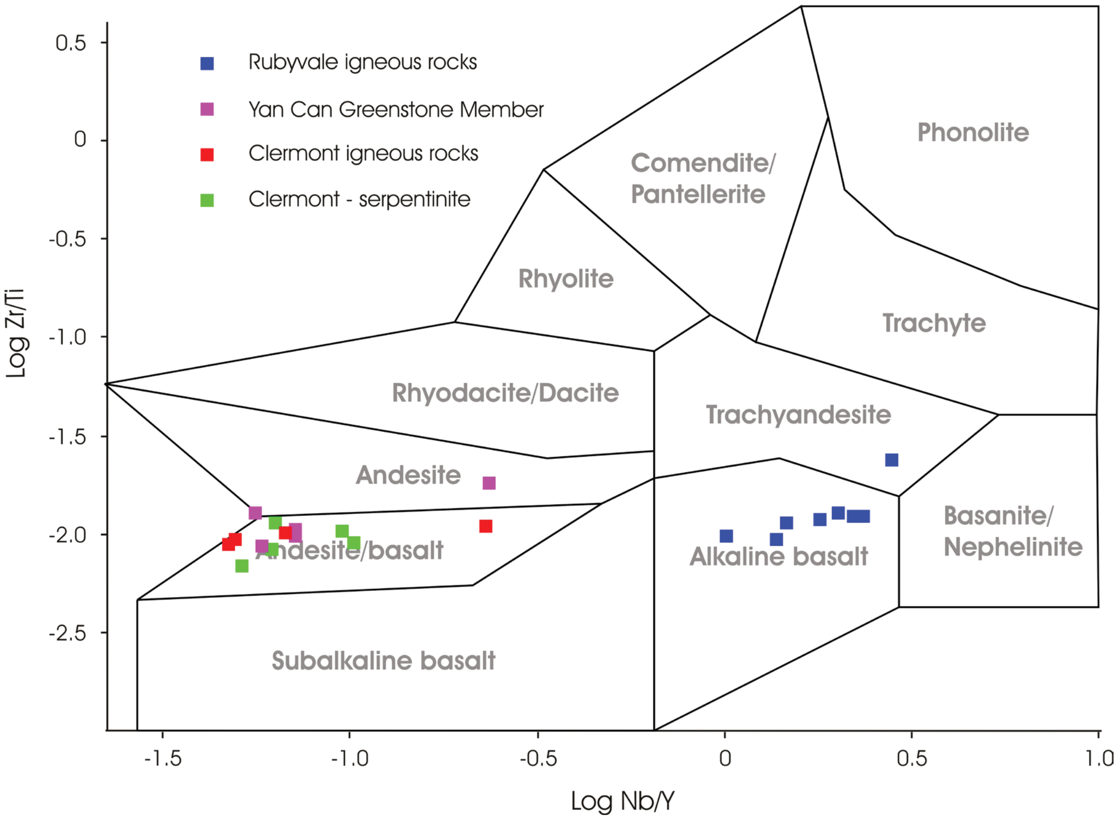


Figure 8. Geochemistry of the mafic rocks within the Bathampton Metamorphics; Winchester & Floyd (1977) classification diagram showing much more alkaline rocks surrounding Rubyvale than those surrounding Clermont.

to the Clermont samples. Numerous bivariate plots (not shown) indicate that all samples from Rubyvale form part of a single fractionation series. The metagabbros at Rubyvale are the least fractionated with high Mg-numbers (72–82), Cr (up to 2500ppm) and Ni (up to 750ppm), indicating minor degrees of fractionation of a primary magma. More fractionated rocks, represented by laminated amphibolite, show increasing alkaline compositions. Tectonic discrimination diagrams are suggestive of a “within-plate” basalt affinity (Figure 9a,b; Pearce & Cann, 1973; Meschede, 1986).

Metamorphism and deformation

Atleast three deformation events (D_1, D_2 and D_3) with associated metamorphism are identified within the southern Anakie Inlier (Withnall & others, 1995; Green & others, 1998; Offler & others, 2011) with a possible six suggested (Wood, 2006).

Wood (2006) inferred the presence of a deformation and metamorphic event pre-dating D_1. This inference is not based on any observations, rather the predication that spaced cleavages (S_1) require the presence of an earlier fabric (Passchier & Trouw, 1998, page 70).

D_1 formed an S_1 foliation defined by micaceous and elongate quartzose layers within psammitic, pelitic and greenstone units (Green & others 1998). Upright F_1 folds are identified in two areas and have been subsequently complexly refolded. In the Oaky

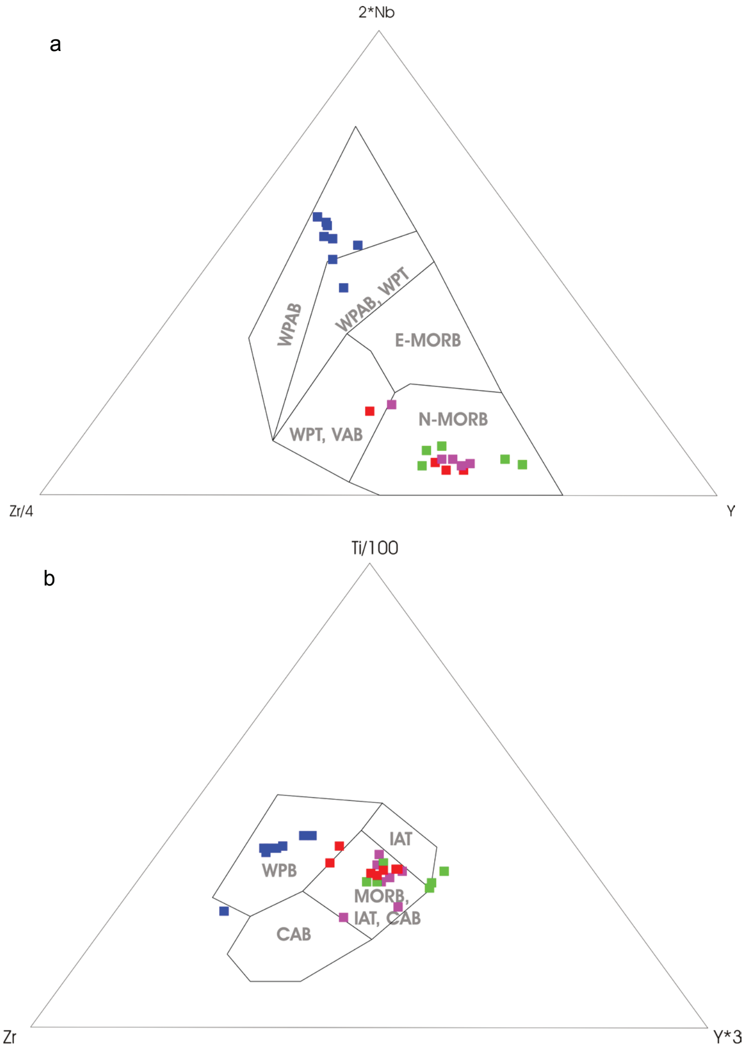


Figure 9. Tectonic discrimination diagrams for the igneous rocks of the Anakie Metamorphic Group, Anakie Inlier:
a) Meschede, 1986;
b) Pearce & Cann, 1973.
Data from Withnall & others (1995) and Fergusson & others (2009). See Figure 8 for symbol definitions.

Dam area, metamorphic mineral assemblages of magnetite, garnet, biotite, muscovite, quartz and aluminosilicates (probably andalusite and staurolite) are thought to be associated with this event and represent medium grade, low-P/moderate-T amphibolite facies metamorphism (Wood, 2006).

D_2, a more intense deformation event, created a gently dipping S_2 foliation that defines the main structural fabric within the Anakie Metamorphic Group (Figure 7b). This foliation is generally defined by closely packed muscovite ± biotite ± chlorite ± carbonaceous aggregates ± ilmenite (Withnall & others, 1995; Offler & others, 2011). Staurolite also occurs locally in the Eastern Creek area (Wood, 2006). S_2 is commonly a crenulation cleavage resulting in long amplitude folding of S_1. D_2 also resulted in the development of tight to isoclinal micro–mesoscopic folds (F_2). Elongate biotite/chlorite in metasedimentary rocks and actinolite in the greenstones, as well as pressure fringes surrounding magnetite porphyroblasts define a west–south-west stretching lineation (L_m; Green & others, 1998).

D_3 lead to the regional reorientation of S_2 through north-east trending upright folds (Withnall & others, 1995; Green & others, 1998). North-west to south-west faulting was contemporaneous with this event, interpreted as accommodation faults during F_3 folding (Green & others, 1998). Wood (2006) suggested that this event was a series of three separate deformational events with the initial folding and associated shearing (F_3; as defined previously) followed by two minor events which resulted in minor crenulations, kinks and reorientation of the dominant S_2 foliation.

Age

U–Pb dating of detrital zircon yields maximum depositional ages of *ca* 580Ma for the Bathampton Metamorphics and *ca* 510Ma for the Wynyard Metamorphics (Fergusson & others, 2001). Detrital monazite from the Wynyard Metamorphics yielded similar U–Th–Pb ages of *ca* 540Ma (Fergusson & others, 2001). Metamorphic cooling of the Anakie Metamorphic Group is constrained by whole rock K–Ar dating of phyllite units near Blair Athol (south of Clermont) which cluster between *ca* 510–504Ma (Withnall & others, 1996) and ^{40}Ar/^{39}Ar ages from D_1 and D_2 micas which ranged from between 483–458Ma (Wood, 2006).

Two detrital provenance signatures are apparent in the limited data available. The Bathampton Metamorphics are dominated by populations between 1100–1300Ma and minor contributions from 1500–1800Ma aged zircons (Fergusson & others, 2001). Conversely the Wynyard Metamorphics have major peaks between 850–1000Ma and 600–680Ma, with a minor peak at 1100–1350Ma (Fergusson & others, 2001).

Northern Anakie Metamorphic Group

Deeply weathered and poorly exposed rocks in the northern Anakie Inlier are identified as Anakie Metamorphic Group (Figure 6; Hutton & others, 1998; Purdy & others, in preparation; Blake & others, 2012). The rocks occur as north–south trending belt on the western boundary of the Anakie Inlier, abutting the Drummond Basin.

Lithologically they are comparable with the Scurvy Creek Meta-arenite, being pale green, chloritic, phyllitic to schistose, characterised by a well-developed layer-differentiated foliation, consisting of quartzose microlithons up to 1cm across, separated by narrower micaceous domains. The rocks are fine-grained and interpreted to represent a siltstone to very fine-grained sandstone protolith (Blake & others, 2013; Purdy & others, in preparation*).* A prominent white quartzite unit similar to the Bathampton Metamorphics forms discontinuous ridges, and contains minor feldspar and interstitial mica and is extensively quartz veined. On its western margin the unit is separated from Les Jumelles beds by a shear zone. Although the eastern margin is concealed, Purdy & others (in preparation) suggest that it could be a series of horses within a thrust duplex.

The foliation is gently dipping and folded by open upright folds that plunge north to north-east and have an axial planar crenulation cleavage. Unlike in the southern Anakie Metamorphic Group, this main foliation appears to be D_1 (Blake & others, 2013; Purdy & others, in preparation), suggesting that D_1 in the southern Anakie Metamorphic Group did not affect the northern rocks, or it has been completely overprinted.

Age constraints are poor for the northern Anakie Metamorphic Group. However, they appear to be older than Les Jumelles beds which are intruded by a ~471Ma tonalite (Coquelicot Tonalite — below).

Cambrian–Ordovician

Fork Lagoon Beds

The Fork Lagoon beds (Withnall & others, 1995) form a 35km north-east trending belt of slate, phyllite and interbedded, thin to thick, brown to grey, quartzose sandstone, siltstone and mudstone with minor (predominantly mafic) igneous rocks (Figure 6). These are juxtaposed against the Anakie Metamorphic Group by a series of north-east–south-west trending thrust faults with associated mylonitic zones. Serpentinite units, up to 200m wide and 2km long, are commonly associated with these faults. The unit was first defined and described by Anderson & Palmieri (1977) and later by Withnall & others (1995).

The sandstone is predominantly fine- to medium-grained containing 70–80% subangular to subrounded, subequant, strained monocrystalline quartz grains and various amounts of felsic volcanic clasts, feldspar, chert and mudstone (Withnall & others, 1995). In the north-east, unstrained and embayed quartz is interpreted as volcanogenic (Withnall & others, 1995). Interbeds of quartzose siltstone and mudstone with a single slaty cleavage are generally subordinate except in central and south-west areas where they are the dominant lithology. Limestone occurs in the Fork Lagoons area and hosts numerous fossils including crinoid stem ossicles, corals, brachiopods, molluscs, ostracodes, stromatoporoids, gastropods, foraminifera and nautiloids of Late Ordovician age (Palmieri, 1978) and shallow-marine deposition. Fine-grained marble, forming thin (<10m), elongate (up to 800m) bodies occurs in the south-west area, but primary features have been destroyed by intense shearing and foliation. Despite this, sedimentary structures are preserved in the siliciclastic rocks in most areas and include graded bedding, ripple cross laminae and load casts (Withnall & others, 1995).

Mafic–intermediate volcanics form topographically recessive belts and commonly comprise fine-grained, dark-green, aphyric basalt to andesite. Associated altered dolerite or gabbro in the north-eastern area is interpreted to represent the plumbing system to these volcanics (Withnall & others, 1995). They are mostly unfoliated, despite minor sheared examples (Withnall & others, 1995). The dominant mineralogy of the basalt includes elongate laths of plagioclase amongst a network of skeletal to sub-ophitic clinopyroxene which alters to amphibole (Withnall & others, 1995).

Elongate gabbroic units have intruded mudstones west of the Luxland Fault (Figure 6), but it is unknown whether they represent relatively low grade Anakie Metamorphic Group equivalents or, syn-Fork Lagoons beds igneous activity. Geochemically this gabbro is comparable with the basalt, representing subalkaline, K-poor magmas (Withnall & others, 1995). Immobile element ratios (Zr/Y, Ti/Y and

MnO/P_2O_5), and spidergram patterns contrast with the mafic rocks of the Bathampton Metamorphics.

Metamorphism and deformation

The south-western margin of the Fork Lagoon beds is controlled by a series of north-east to north-north-east trending faults (including the Ruby Creek Mylonite Zone and the Graves Hill Fault). Withnall & others (1995) interpreted these as thrust faults juxtaposing metasediments of the Bathampton Metamorphics against the younger Fork Lagoon beds and causing stratigraphic repetition throughout the unit. Further north, east of the Fork Lagoons area, this boundary is concealed by Permian sedimentary units of the Bowen Basin and Cenozoic cover, but the Luxland Fault (an extension of the north-east to north-north-east trending thrust faults) continues within the Fork Lagoons beds. These faults are commonly associated with mylonitic zones with subequant to elongate quartz and aligned muscovite and chlorite up to 0.1mm with minor biotite.

The general structural fabric of the unit is north-east; defined by lithologically resistant topographical ridges of sandstone and mudstone. The quartzose sandstone displays anatomising spaced cleavage planes but is generally unfoliated in the north-east. Quartz grains are generally monocrystalline and typically strained, but in places they are unstrained. The mudstones and siltstones are regularly cleaved, typically defined by subequant to elongate quartz and aligned fine-grained muscovite, chlorite and minor biotite. In the central and north-eastern areas this is oblique to $S_{0.}$

Intrusions associated with the Retreat and Taroborah batholiths have caused localised hornfelsing resulting in the formation of cordierite porphyroblasts and increased abundance and size of micas (particularly biotite). Within these contact metamorphic aureoles, mica is randomly orientated and up to 0.3mm across, but in more distal areas it conforms to the dominant foliation.

Age

Coral and conodont fossils hosted in limestone within the north-eastern area are interpreted as Gisbornian–Bolindian (approximately 460–443Ma) age (Palmieri, 1978). This is in agreement with the youngest age cluster from detrital zircon U–Pb dating which falls between 445–453Ma and 457–467Ma from quartz and quartz-lithic sandstones in the central and south-western areas (Fergusson & others, 2007a).

Les Jumelles beds

Les Jumelles beds occur as two parallel north-north-east trending belts at the northern tip of the Anakie Province (Figure 6). They have been described on three separate mapping programs of the GSQ (Hutton & others, 1998; Fitzell & others, 2006; Blake & others, 2013; Purdy & others, in preparation). In the north-east area they are very fine- to medium-grained, medium- to very thick-bedded quartzose to feldspathic sandstone and cleaved mudstone (Figure 10a). Petrographic analysis of a sandstone identified subangular to subrounded quartz and feldspars up to 0.25mm with minor lithic fragments (siltstone or chert and mica aggregates) and detrital mica. The sandstone is generally massive with minor planar laminae and rare rip-up clasts. In the western area, Les Jumelles beds are in fault contact with the Anakie Metamorphic Group which is inferred as an easterly dipping thrust fault (Withnall, 2013). Here they are fine- to coarse-grained, medium- to very thick-bedded quartzose meta-arenite and cleaved mudstone or phyllite. In the southern area the beds are intruded by three bodies of the Middle Ordovician Coquelicot Tonalite causing a contact metamorphic aureole with andalusite porphyroblasts up to 2.5mm in a groundmass of fine-grained muscovite, biotite and quartz.

Metamorphism and deformation

Deformation is evidenced by tight upright north-north-east trending folds (F_1), predominantly identified within the Scartwater area. Associated mica-defined cleavage planes within mudstones and flattened quartz in sandstones form S_1. S_1 is typically oblique to bedding in the sandstone and locally forms a pencil cleavage (Figure 10b),

Figure 10. Outcrops of Les Jumelles beds:
a) interbedded and cleaved sandstone and mudstone (photo by Ian Withnall);
b) pencil cleavage

and in places is axial planar to F_1 folds. The S_1 cleavage within Les Jumelles beds is parallel to the S_2 crenulation within the Anakie Metamorphic Group.

Age

Les Jumelles beds are unconformably overlain by the Early Devonian Ukalunda Formation and are intruded by the Middle Ordovician Coquelicot Tonalite. They appear to post-date D_1 of the Anakie Metamorphic Group which coincides with the regional Cambrian Ross-Delamerian Orogeny (Cawood, 2005). The most likely correlatives are rocks of the Puddler Creek Formation, the basal unit of the Cambrian – Early Ordovician Seventy Mile Range Group near Charters Towers.

Theresa Creek Volcanics

The Theresa Creek Volcanics occur 15km south-west of Clermont (Figure 6) and include basaltic to andesitic, aphyric to porphyritic lavas with minor breccia, conglomerate, tuff and volcaniclastic sandstone (Withnall & others, 1995). The lavas are probably subaerial and exhibit phenocrystic plagioclase and minor clinopyroxene and orthopyroxene. Rare granitic xenoliths occur locally. The breccias and conglomerates contain mafic clasts with minor quartz and rare feldspar. The tuff contains feldspar crystals amongst a fine grained matrix. The sandstone contains subangular to subrounded mafic volcanics and feldspars. Zeolitisation is present within all units, forming during diagenesis (Withnall & others, 1995). Preliminary U–Pb dating, based on a limited number of zircons suggests a Middle to Late Devonian age (A.J. Cross & D. Dunkley, GA, preliminary unpublished data, 2012). Additionally, Withnall & others (1995) showed that major and trace element data of the Theresa Creek Volcanics and the 366–385Ma Retreat Batholith are comparable, suggesting comagmatic affinities.

Intrusive units

Coquelicot Tonalite

The Coquelicot Tonalite intrudes the southern part of Les Jumelles beds (Figure 6). It comprises four northerly trending elongate plutons of which the largest is 10km long and 4km wide (Fitzell & others, 2006). It is described by Purdy & others (in preparation) as a medium- to coarse-grained, equigranular, biotite-hornblende tonalite. Fine-grained enclaves are common and contain up to 40% mafic minerals. The tonalite exhibits a north to north-easterly trending weak foliation defined by the elongation of quartz. SHRIMP U–Pb dating of zircon yielded a crystallisation age of 471 ± 3.6Ma (OZCHRON, 2007) which places it within the late Cambrian to Middle Ordovician Macrossan Igneous Association (Bain & Draper, 1997).

Mooramin Granite

The Mooramin Granite is a single equidimensional pluton east-north-east of the Mooramin homestead (Figure 6). This unit was described and mapped originally by Hayward (1993), and later by Withnall & others (1995) and Richards & others (2013). It is cordierite-bearing muscovite-biotite granite displaying foliation and local mylonitisation. The intrusive hosts numerous meta-sedimentary xenoliths of biotite schists and quartzite. These, along with former cordierite pseudomorphed by fine phyllosilicate aggregates indicate S-type compositions (Withnall & others (1995). The tectonic foliation is weak to very strong and is defined by quartz and biotite concentrations within layers. Quartz grains display undulose extinction and recrystallised boundaries. U–Pb dating of zircon (via LA-ICP-MS) yielded a crystallisation age of 463 ± 15Ma (Richards & others, 2013) which places it within the Macrossan Igneous Association.

Gem Park Granite

The Gem Park Granite (Withnall & others, 1995) consists of numerous elongate plutons intruding the Bathampton Metamorphics (Figure 6) parallel to the dominant structural trend (D_2). They were subsequently intruded by components of the Retreat Batholith, and are unconformably overlain by the Late Devonian to early Carboniferous Silver Hills Volcanics and Drummond Basin sedimentary rocks. They consist of biotite, muscovite, quartz, plagioclase, alkali feldspar, and minor garnet (Figure 11). Geochemically the Gem Park Granite is peraluminous, with some authors suggesting it formed from the melting of the Anakie Metamorphic Group (Fergusson & Withnall, 2013). The granite is strongly foliated (Figure 11) and commonly has a stretching lineation that plunges shallowly to moderately to the north. The easternmost intrusives also display strong mylonitisation with clearly developed S and C planes. Wood (2006) reported a U–Pb monazite age of 443.3 ± 6.2Ma and suggested that this represented crystallisation of the unit.

Figure 11. Strongly foliated biotite–muscovite granite of the Gem Park Granite (GR E568894 N7408544).

Retreat and Taroborah Batholiths

The Retreat and Taroborah Batholiths (Table 2) represent Late Devonian igneous activity within the Anakie Province (Figure 6) and form components of the Silurian-Devonian Pama Igneous Association. The Retreat Batholith includes 18 units of diorite, monzodiorite, monzonite, quartz diorite, tonalite, granodiorite and granite intruding the southern Anakie Inlier (Withnall & others, 1995; Crouch & others, 1995a). Outcrop of the Retreat Batholith is restricted to areas south of Clermont, but its subsurface extent is likely to be much greater. The Taroborah Batholith has only a single mapped unit of isolated outcrops, but a broad magnetic high suggests a more extensive, concealed batholith (Crouch & others, 1995a).

In general the Retreat and Taroborah Batholiths comprise medium- to high-K, calc-alkaline, and metaluminous to mildly peraluminous I-type granitoids (Crouch & others, 1995b). Crouch & others (1995b) identified three suites based on minor variations in geochemical trends; the Kilmarnock, Karmoo and Mount Newsome suites. For example, the Karmoo Suite displays a negative correlation between P_2O_5 with increasing SiO_2 whilst the other two suites are the opposite.

Webb & McDougall (1968) reported K–Ar biotite ages between 379–352Ma for the Retreat Batholith. A personal communication by P. Carr in Withnall & others (1995) reported similar ages using Rb–Sr dating of a biotite-whole rock pair, between 384–369Ma. More recently, Wood (2006) reported a U–Pb zircon age of 392.4 ± 10.2Ma from the Mount Newsome Granodiorite of the Retreat Batholith.

The tectonic environment for the genesis of the Retreat Batholith is subject to debate. Crouch & others (1995b) suggested a continental back-arc environment whilst Fergusson (2013) suggested a more direct subduction related setting.

Table 2. General characteristics of the Retreat and Taborah Batholiths after Withnall & others (1995) and Crouch & others (1995a)

Suite/Unit	Age constraints	Lithology
Retreat Batholith		
Kilmarnock Suite	382–375Ma (Rb-Sr biotite-wholerock; Withnall & others, 1995)	Grey, fine- to coarse-grained, equigranular to porphyritic biotite, hornblende granodiorite to granite and monzonite to diorite, minor gabbro. Metasedimentary xenoliths are common.
Karmoo Suite	384 ± 3Ma (Rb-Sr biotite-wholerock; Withnall & others, 1995)	Grey, fine- to medium-grained, equigranular, biotite-hornblende quartz diorite and tonalite with subordinate hornblende-biotite granodiorite and hornblende gabbro.
Mount Newsome Suite	372–382Ma (Rb-Sr biotite-wholerock; Withnall & others, 1995)	Grey, fine- to coarse-grained, equigranular to porphyryitic biotite-hornblende granodiorite.
Taroborah Batholith		
Taroborah Granodiorite	372Ma (K–Ar biotite; Webb & others, 1963).	Medium-grained, equigranular to seriate with hornblende phenocrysts.

CHARTERS TOWERS PROVINCE

The Charters Towers Province is a large (300km by 200km) tectonic province of Neoproterozoic to early Paleozoic metasediments extensively intruded during a period of prolonged igneous activity (Ordovician to Permian) within three major batholiths (Ravenswood Batholith, Lolworth Batholith and Reedy Springs Batholith) (Figure 12). The province is bounded to the north by the Broken River Province of the Mossman Orogen at the Clarke River Fault and to the east by the New England Orogen. The remaining boundaries are concealed by the Drummond Basin in the

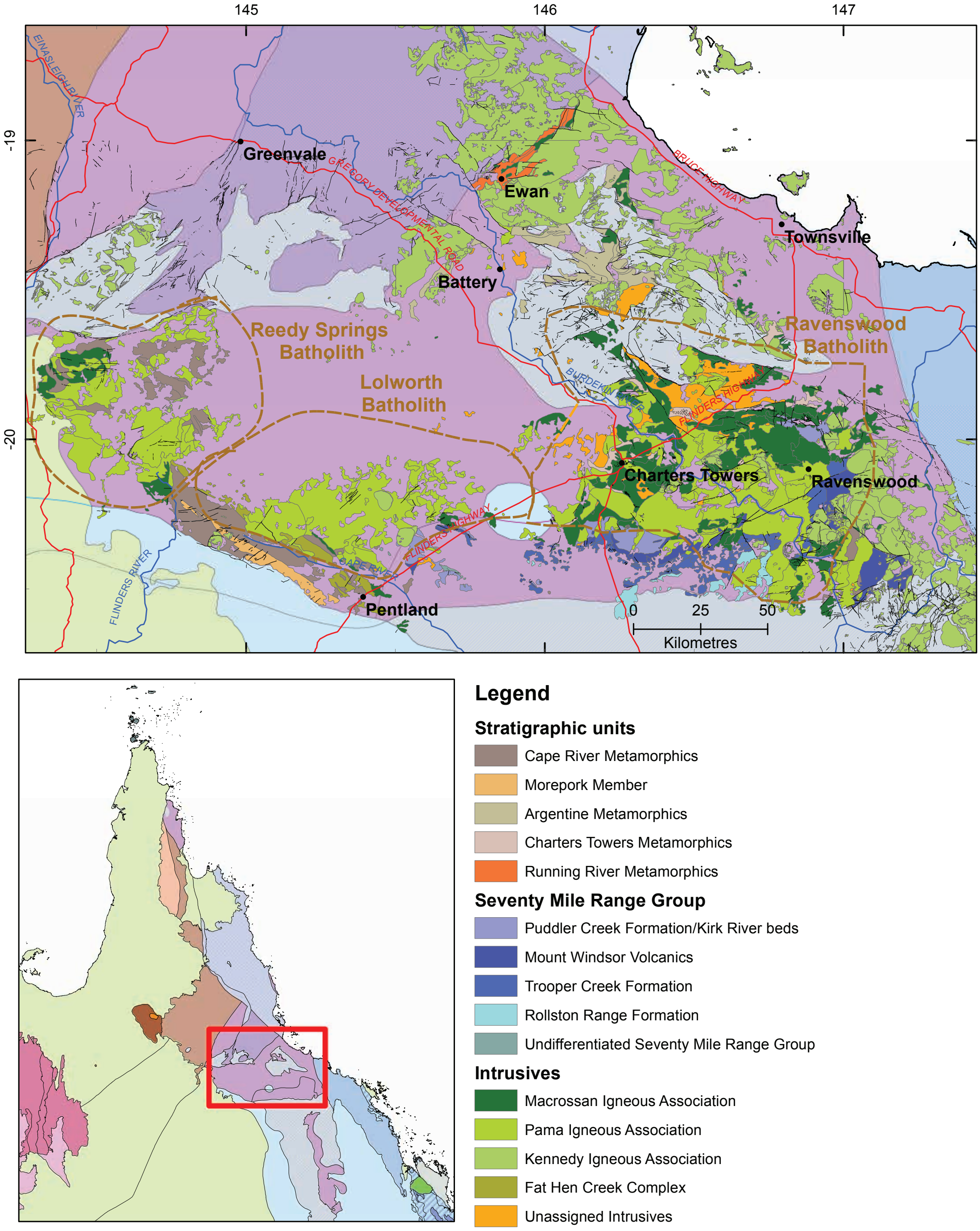


Figure 12. Outcropping geology of the Charters Towers Province. Inset shows location of the Charters Towers Province relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

south, and the Galilee Basin and Eromanga Basin to the west. Sedimentary and volcanic cover is common throughout the province.

In the south-western area of the Charters Towers Province, Neoproterozoic to Cambrian metasediments and metamafic rocks of the Cape River Metamorphics predominate. This unit passes into the Fat Hen Creek Complex, an *in situ* orthogneiss formed during the Early Ordovician (Hutton, 2004). The predominantly Silurian to Devonian Lolworth Batholith in the south, and the Ordovician to Devonian Reedy Springs Batholith in the north, intrude these rocks. Metasediments and metamafic rocks in the north of the Province are mapped as the Cambrian to Ordovician Running River Metamorphics and Argentine Metamorphics, which are extensively intruded by igneous rocks of predominantly Carboniferous to Permian age, but also by probable Ordovician plutons. In the south-east, metasediments and metavolcanics of the Cambrian to Ordovician Charters Towers Metamorphics and Seventy Mile Range Group are intruded by plutonic rocks of the Ordovician to Permian Ravenswood Batholith.

Neoproterozoic–Cambrian

Cape River Metamorphics

The Cape River Metamorphics crop out in the western part of the Charters Towers Province (Figure 12). The rocks were described by Withnall & others (1997a) and dominantly comprise thick- to very thick-bedded and fine- to medium-grained, feldspathic meta-arenite and fine-grained mica schist that grade into various types of gneiss (Figure 13a). An easily mappable subunit which forms prominent topographical ridges, the Morepork Member, is fine- to medium-grained, feldspathic to quartzose, locally calcareous meta-arenite forming beds 5cm to tens of meters thick (Figure 13b). It defines a 65km north-west trending belt, up to 6km wide in the south and tapering out to the north in a fold closure.

Three mafic igneous rock types are observed in the Cape River Metamorphics (Withnall & others, 1997a; Strachotta, 1998). These outcrop poorly but comprise 1) bedding-parallel amphibolite which locally preserves relict pillow structures, 2) numerous fine-grained amphibolite dykes 5–10m thick with minor scapolite porphyroblasts intruding the Fat Hen Creek Complex and other Cape River Metamorphics, and 3) a well foliated, porphyroblastic amphibolite which contains prismatic hornblende up to 3mm long, and interstitial granoblastic plagioclase with subordinate quartz that typically occurs in higher grade rocks near the contact with the Fat Hen Creek Complex.

Geochemistry

Geochemical analyses of amphibolite units (Rienks & Withnall, 1996; Strachotta, 1998) indicates basaltic to andesitic, and generally subalkaline compositions (Figure 14a). Of the three amphibolite units, the dykes show unique geochemical characteristics, including fractionated REEs and enrichment in LILEs (Figure 14b).

Figure 13. Outcrops of the Cape River Metamorphics:
a) gneiss with folded calc-silicate bands (Photo by Ian Withnall);
b) thick bed of diffusely cleaved quartzite of the Morepork Member.

The heavy rare earth elements (HREEs) and HFSEs are comparable to MORB-like sources. Strachotta (1998) noted that discrimination diagrams are very ambiguous for the amphibolite units, and suggested a back-arc basin environment with elevated light rare earth elements (LREEs) and LILEs possibly resulting from input of slab-derived fluids.

The amphibolite flow unit containing pillow structures has much flatter REE (not shown) and trace element patterns which are more closely comparable with MORB (Figure 14b). Overall the geochemistry shows characteristics of both MORBs and arc related basalts. Rienks & Withnall (1996) favoured a plume related continental setting because of their similarities with mafic rocks of the Etheridge Group. However, these rocks are now known to be significantly older.

Deformation and metamorphism

The Cape River Metamorphics have undergone three phases of deformation (Withnall & others, 1997a; Fergusson & others, 2005). Metamorphic grade ranges from greenschist (typically near the Reedy Springs Batholith) to amphibolite facies (Withnall & others, 1997a; Fergusson & others, 2005). Migmatites are increasingly common approaching the intrusive Fat Hen Creek Complex.

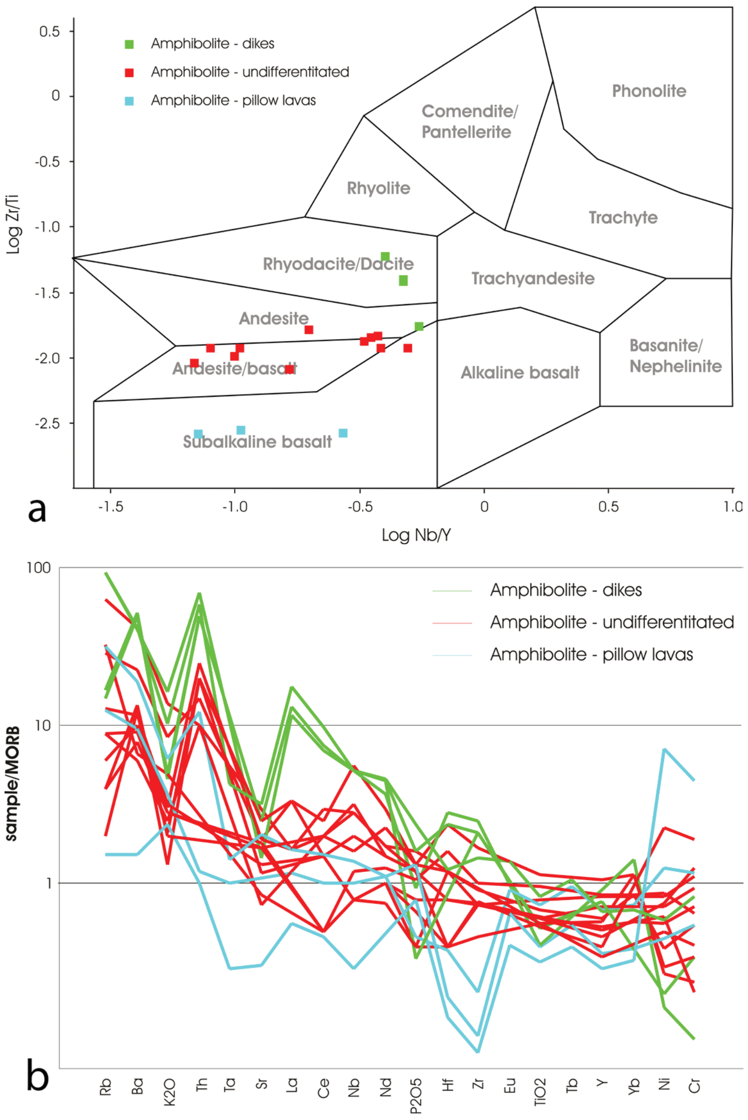


Figure 14. Geochemistry of the igneous rocks, Cape River Metamorphics:
a) Geochemical classification diagram (Winchester & Floyd 1977) of the igneous rocks in the Cape River Metamorphics, Charters Towers Province;
b) MORB normalised multielement spidergram. Data from Rienks & Withnall (1996) and Strachotta (1998).

Very little is known about D_1 due to poor preservation. However a steeply dipping south-east striking foliation was found within microlithons in lower grade rocks (Withnall & others, 1997a; Fergusson & others, 2005). D_2 is evidenced by S_2 defined by biotite, muscovite and quartz, with parallel isoclinal folds (F_2), interpreted to have occurred after significant S_2 development, and within significant shortening regimes (creating high amplitude-to-wavelength ratios) (Fergusson & others, 2005). Strachotta (1998) used thermobarometry calculations to indicate that peak metamorphism occurred at 690 ± 25°C at 4.78 ± 0.6kbars which resulted in the partial melting of the Fat Hen Creek Complex. The D_3 event involved open to locally tight folds with related axial planar S_3 crenulation cleavages developed from the S_2 foliation (Withnall & others, 1997a). Folding created an east-south-east trending synclinorium, with the Morepork Member at its core. Metamorphic grade increases from upper greenschist facies in the Oxley Creek area (near the headwaters of the Flinders River) and the Morepork Member to amphibolite facies adjacent to the Fat Hen Creek Complex. Near the Fat Hen Creek Complex high-grade gneiss and migmatite are common. $^{40}Ar/^{39}Ar$ mica dating of biotite schists and biotite orthogneiss in the Oxley Creek and Gorge Creek – Oak Vale areas suggest cooling ages (~350–310°C) of 409–423Ma (Fergusson & others, 2005).

Age

A maximum depositional age is provided by SHRIMP U–Pb dating of detrital zircon from a quartzo-feldspathic-biotite metasandstone, and is in the range 1000–1300Ma (Fergusson & others, 2007a). Metamorphic cooling ages derived from $^{40}Ar/^{39}Ar$ mica analysis provide a minimum age of 409Ma (Fergusson & others, 2005). Granites of the Fat Hen Creek Complex (part of the Lolworth Batholith) intrude the Cape River Metamorphics. SHRIMP U–Pb zircon ages for this intrusive are 455–493Ma (Hutton & others, 1997a).

Cambrian–Ordovician

Argentine Metamorphics

The Argentine Metamorphics (Wyatt & others, 1970) crop out in the northern part of the Charters Towers Province. Most recently they have been described by Withnall & McLennan (1991) and revised by Fergusson & others (2007b). Low and high metamorphic grade subunits are mapped. The lower grade rocks occur in the southern area and predominantly comprise quartzite, mica schist, amphibolite and calc-silicate rocks (Figure 15a). Foliation in the schist is defined by elongation of mica and quartz and differentiated layers up to 5mm wide. Rare sillimanite and andalusite porphyroblasts are replaced by fine-grained mica. The schist grades into quartzite layers which form prominent ridges. The quartzite is well foliated and preserves S and C planes. Within the quartzite, finely laminated hematite forms laminations 1 to 10mm thick.

The high grade unit occurs in the central and northern parts of the Argentine Metamorphics and consist of amphibolite facies migmatite, gneiss, schist, and amphibolite (Figure 15b). The gneiss and schist are interlayered and composed of quartz, feldspar (predominantly plagioclase with minor microcline), biotite, muscovite, sillimanite and local porphyroblasts of garnet. Foliation in the schist is defined by muscovite, biotite and sillimanite and is generally parallel to layering.

Amphibolite is commonly laminated and forms thin layers intercalated with schist and marble. Depending on metamorphic grade the dominant mineral assemblage of the amphibolite includes hornblende-actinolite, clinozoisite-epidote and plagioclase. Withnall & McLennan (1991) suggested that these represent para-amphibolites, but that thicker units could represent lava or dolerite protoliths. Calc-silicate rocks are interlayered with the amphibolite and include quartz, garnet, clinozoisite and amphibole.

Withnall & Blight (2005) divided the lower grade part of the Argentine Metamorphics into the Paynes Lagoon Amphibolite and Brinagee Schist (Figure 12). The Paynes Lagoon Amphibolite is described as laminated amphibolite, quartzite, banded-iron-formation and subordinate mica schist. The Brinagee Schist includes fine-grained schist, quartzite and subordinate amphibolite.

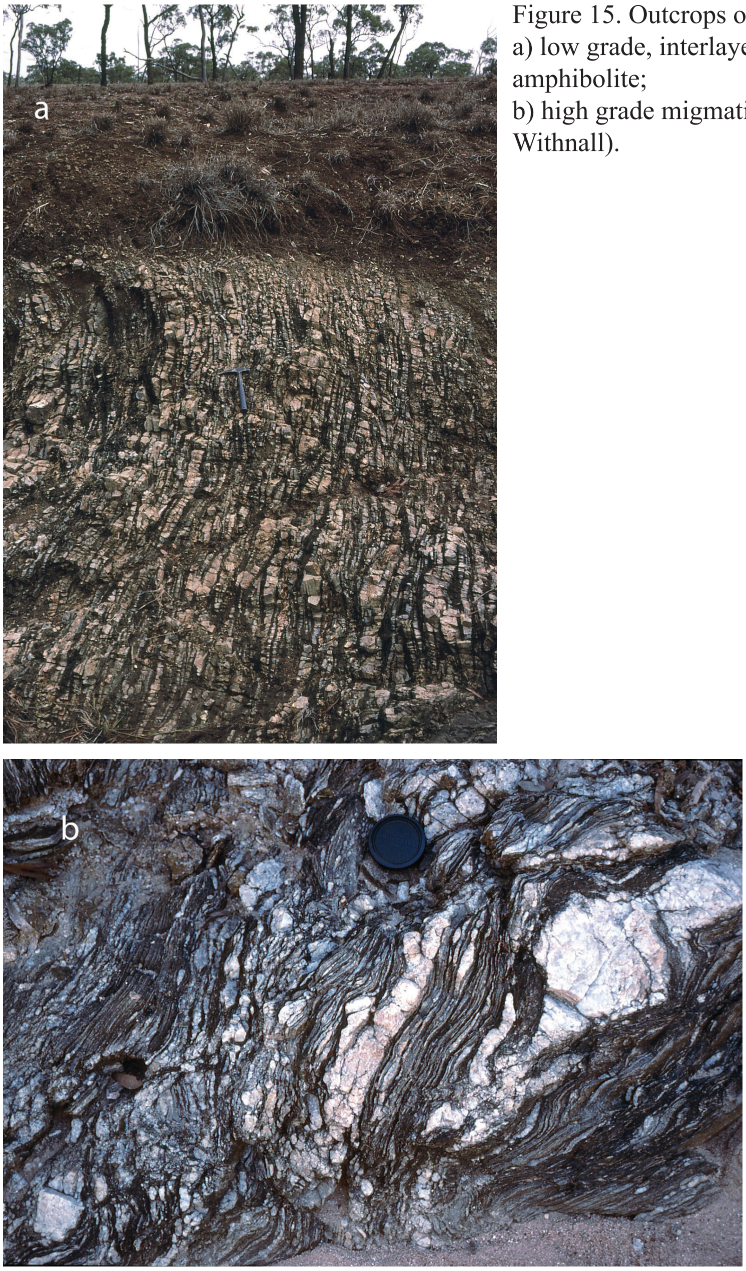


Figure 15. Outcrops of the Argentine Metamorphics:
a) low grade, interlayered calc-silicate rock and amphibolite;
b) high grade migmatite and gneiss (photos by Ian Withnall).

Deformation and metamorphism

Fergusson & others (2007b) identified four deformation events within the Argentine Metamorphics. D_1 is commonly overprinted, but produced a north-west to south-east S_1 foliation and an F_1 of unknown geometry. The foliation is defined by alignment of biotite, muscovite, actinolite and hornblende indicating that greenschist to amphibolite facies metamorphism accompanied deformation. It is interpreted as a contractional regime. The D_2 event created the regional foliation (S_2) that mainly dips moderately to gently southward. Associated tight mesoscopic F_2 folds and L_2 fabrics have been identified and plunge moderately to the east-south-east. It is interpreted as an extensional regime. Like D_1, metamorphism and deformation were synchronous with $D_{2,}$ and S_2 is defined by aligned biotite, muscovite, actinolite and hornblende indicative of greenschist to amphibolite facies. This event was accompanied by the emplacement of numerous intrusive bodies. The distribution of D_3 is restricted to the higher grade rocks in the southern area. It resulted in west-north-west to east-south-east trending, close to tight, recumbent to gently inclined folds verging towards the south. This is also interpreted as an extensional regime. D_4 resulted in abundant north–south trending, broad to tight, mesoscopic folds with S_4 foliations developed in the limbs. Folded and cross-cutting leucogranite veins indicate high grade metamorphism and melting occurred during this event. This event is interpreted as an east–west shortening regime (Fergusson & others, 2007b).

In the southern area a domal feature is defined by S_2. Within the core of this feature are low grade retrogressed rocks dominated by phyllite with some mafic schist. The phyllite displays textures indicative of shearing including folded lineations within the plane of foliation, S and C planes, shear bands and dynamic recrystallisation, and could be termed a phyllonite. Shear sense is top to the north and north-east.

Age

The Argentine Metamorphics are nonconformably overlain by, and faulted against, volcanic and sedimentary rocks of the Devonian–Carboniferous Burdekin Basin. SHRIMP U–Pb zircon ages of granites intruding the Argentine Metamorphics also provide a minimum age of 480 ± 4Ma. D_2 was constrained by two granites dated at 480 ± 4Ma and 461 ± 4Ma that display pre- and post-D_2 features (Fergusson & others, 2007b).

Detrital zircon inheritance spectra distinguish two separate sources for the Argentine Metamorphics (Fergusson & others, 2007a,b). Quartzite beds yielded a maximum depositional age of 999–1012Ma, whilst in the lower grade rocks a felsic meta-igneous clast within a breccia in the Paynes Lagoon Amphibolite yielded an age of 500 ± 4Ma.

Charters Towers Metamorphics

The Charters Towers Metamorphics crop out in a discontinuous, generally east–west trending, 150km-long, sublinear belt of quartz-biotite-plagioclase schist, cordierite-quartz-biotite-schist, quartzite and minor calc-silicate rocks (Figure 12; Peters, 1987). The schists are fine-grained and interlayered with quartzites that include minor biotite and local sillimanite. The calc-silicates are dark and banded containing quartz, tremolite and clinozoisite with secondary feldspar, titanite and calcite. Peak metamorphic conditions are indicated by upper amphibolite facies assemblages including the presence of sillimanite in the quartzite, and migmatite. Minor upper greenschist facies rocks also occur. An absence of garnet has been inferred to represent low pressure/high temperature conditions (Hutton & others, 1997a). Middle Ordovician S-type granites of the Ravenswood Batholith parallel the trend of the high grade metamorphism and have therefore been inferred to have hornfelsed their host rocks (Hutton & others, 1997a). Structurally the rocks display a well-developed foliation, which trends north-west and dips steeply to the north-east, as well as localised tight isoclinal folding defined by quartz veining (Peters, 1987). A minimum age constraint of 508 ± 7Ma (Fanning, cited in Hutton & others, 1997a) is provided by the Bucklands Hill Diorite which intrudes the Charters Towers Metamorphics (Hutton & Crouch, 1993a; 1993b). Lithologically the Charters Towers Metamorphics are comparable with the Cape River Metamorphics (Hutton & others, 1997a).

Running River Metamorphics

The Running River Metamorphics (Wyatt & others, 1970) outcrop is restricted to areas incised by the Running River in the northern Charters Towers Province (Figure 12). Withnall & McLennan (1991) described them as comprising muscovite-biotite schist and amphibolite with minor quartzite and serpentinite. Migmatite occurs in the east within the highest metamorphic grade rocks (Figure 16a). The Running River Metamorphics are considered equivalent to the Argentine Metamorphics due to lithological similarity.

Amphibolites were inferred by Withnall & McLennan (1991) to have both igneous and sedimentary protoliths, but by comparison with the laminated amphibolites in the Anakie Metamorphic Group (Withnall & others, 1995), it is possible that much of the layering is a tectonic feature. Amphibolite, north-east of Ewan, exhibits well-developed layering defined by hornblende and diopside concentrations (Figure 16b). Garnet occurs locally. Ortho-amphibolite preserves igneous textures, including randomly oriented, euhedral and twinned plagioclase, hornblende and minor opaque minerals. Fine-grained equivalents may represent lavas and some relict pillows and hyaloclastite have been observed (Withnall & McLennan, 1991).

Most of the ortho-amphibolites of the Running River Metamorphics and the Argentine Metamorphics display both MORB and low-K tholeiite compositions. Conversely a metabasalt from the Running River Metamorphics and the layered amphibolite from the Argentine Metamorphics are more similar to alkali basalt compositions in the Bathampton Metamorphics in the Rubyvale area. This suggests that at least two suites are present.

Small pods of serpentinite straddle the Endeavour Fault and are believed to have been emplaced during later movement of this fault.

Deformation and metamorphism

Metamorphic grade ranges from middle to upper amphibolite facies, with localised hornfelsing adjacent to Carboniferous granite batholiths. Open to isoclinal folding resulted in a dominant S_2 foliation. Mylonitisation occurred adjacent to the Endeavour Fault.

Age

A minimum age constraint is provided by the intrusion of the Ordovician Falls Creek Tonalite.

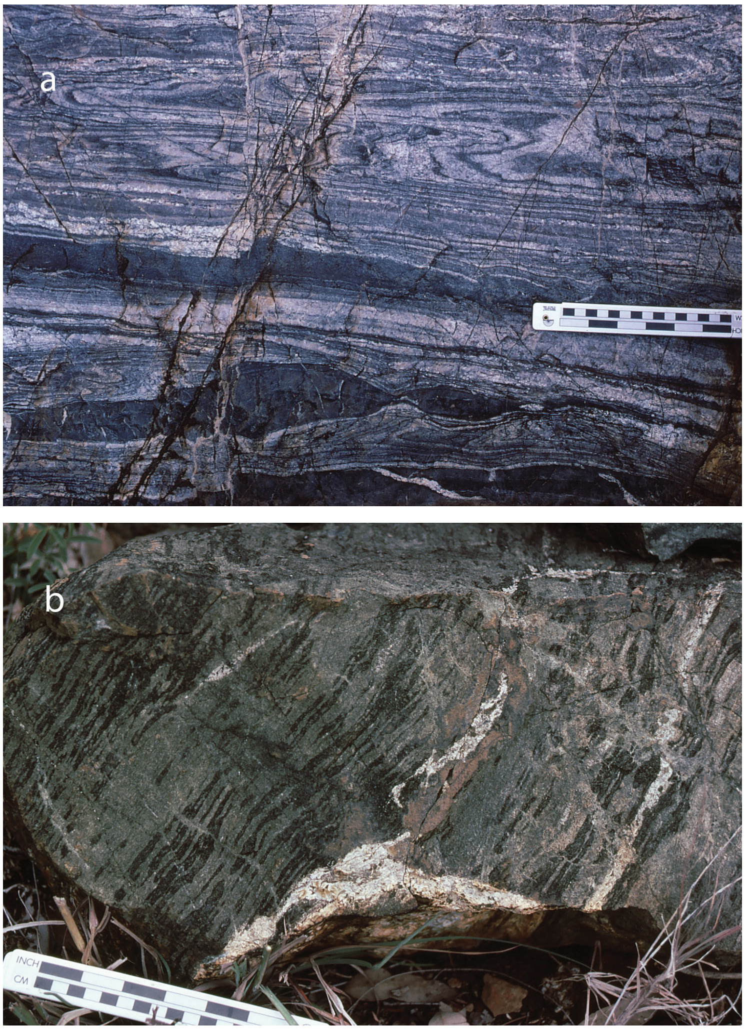


Figure 16. Outcrops of the Running River Metamorphics: a) high grade folded gneiss; b) layered amphibolite (photos by Ian Withnall)

Seventy Mile Range Group

The Seventy Mile Range Group is a 14km thick conformable sequence of subaqueous sedimentary deposits and intermediate to felsic lavas and dykes on the southern margin of the Charters Towers Province (Figure 12). The east–west distribution is marked by relative gravity highs truncated to the north by the Ravenswood and Lolworth Batholiths (Kreuzer & others, 2007). The group hosts numerous VMS style deposits including Thalanga (see Paulick & McPhie, 1999) and Highway Reward (see Doyle & McPhie, 1999). In stratigraphic order from the base it is divided into the Puddler Creek Formation, Mount Windsor Volcanics, Trooper Creek Formation and Rollston Range Formation as described by Henderson (1986) and Berry & others (1992) and summarised in Table 3.

The sedimentary record within the Seventy Mile Range Group is inferred to represent a subaqueous environment ranging from relatively deep, low energy (Henderson, 1986) to shallow water (Doyle & McPhie, 1997; Paulick & McPhie, 1999). Berry & others (1992) suggested that this was in an active extensional regime.

The basal Puddler Creek Formation is up to 9km thick and constitutes over half the overall thickness of the group. The sediments are largely continentally derived. In

Table 3. Geology of the Seventy Mile Range Group after Henderson (1986) and Berry & others (1992)

Formation	Lithology	Age	Depositional environment
Rollston Range Formation	Thinly bedded siltstone and sandstone with minor vitric tuff. The sediments are largely volcaniclastic with a minor basement component. Abundant graptolites and trilobites.	Early Ordovician	Relatively deep, low energy (Henderson, 1986)
Trooper Creek Formation	Andesitic to rhylotic tuffs, siltstones and mudstones with minor basaltic andesite to andesite flows, andesitic lapilli tuff and volcaniclastic sandstone and fine conglomerate. The sediments are largely volcaniclastic with minor basement-derived muscovite and phyllite.	Cambro-Ordovician boundary	Deep to shallow marine (e.g. Doyle & McPhie, 1999)
Mount Windsor Volcanics	Massive rhyolite porphyry lavas with phenocrysts of quartz and albite amongst finely crystalline quartz-feldspar-chlorite groundmass. Rhyolitic dykes are common in upper section, rare dacite and andesite.	479 ± 5Ma (U-Pb; Perkins & others, 1993)	Marine; below storm wave base (Paulick & McPhie, 1999)
Puddler Creek Formation	Fine- to medium-grained lithic sandstone and greywacke interbedded with siltstone.	Late Cambrian	Unknown
Kirk River Beds	Thin to thick bedded arenite, fissile micaceous mudstone, volcanic rudite, and rare quartzite, shale and chert.	Unknown	Unknown

the upper section mafic dykes and sills become dominant. These are geochemically comparable to andesitic flows at the top of the formation, and are likely part of the feeder system for the overlying Mount Windsor Volcanics and Trooper Creek Formation (Berry & others, 1992).

Although not formally included in the Seventy Mile Range Group, the Kirk River beds are considered to be a small outlier of the Puddler Creek Formation (Henderson, 1986) and comprise micaceous shales, sandstones and siltstones (Wyatt & others, 1965).

The overlying Mount Windsor Volcanics and Trooper Creek Formation show considerable thickening eastward. Henderson (1986) suggested that this represents the primary geometry of the unit with the volcanic source in the east. However Berry & others (1992) suggested syn-depositional faults have caused structural repetition.

Geochemistry

Geochemical analyses of igneous rocks from the Seventy Mile Range have been completed by Henderson (1986), Berry & others (1992), Hutton & others (1994) and Stolz (1995), with the last author also contributing Sm-Nd isotopic data. Considerable alteration and secondary mobilisation of elements has meant primary geochemical interpretations rely largely on immobile elements (e.g. HFSEs).

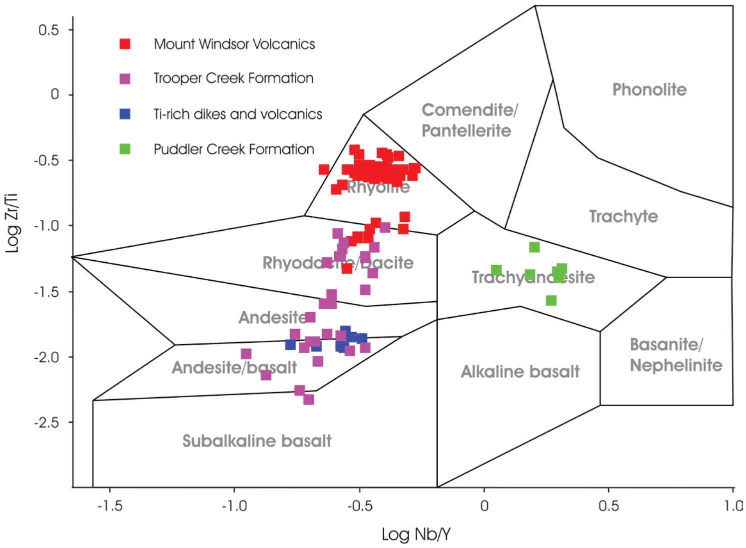


Figure 17. Geochemical classification diagram (Winchester and Floyd 1977) of the igneous rocks in the Seventy Mile Range Group, Charters Towers Province. Data from Berry & others (1992), Stolz (1995) and Paulick & others (2001).

Samples from the Trooper Creek Formation and Mount Windsor Volcanics show geochemical similarities, and may only differ due to fractionation processes. Samples from the Puddler Creek Formation are distinctly more alkaline and display different geochemical characteristics (Figure 17).

The Mount Windsor Volcanics are rhyolitic (71–79 wt% SiO_2) with very low P_2O_5 (<0.02 wt.%), TiO_2 (0.04–0.23 wt.%), CaO (0.04–1.75 wt.%) and MgO (0.07–1.12 wt.%) and enriched in incompatible elements (Stolz, 1995). Pronounced negative Eu anomalies implicate the role of plagioclase within their formation.

Basalts and andesites of the Trooper Creek Formation have low TiO_2 (<1 wt%), low incompatible element concentrations, high Zr/Nb and La/Nb values and low Nb/Y values. These features are characteristic of subduction-related magmatism (Stolz, 1995). Basalts have moderately high MgO (6.70–10.06 wt.%), Cr (66–478ppm) and Ni (28–80ppm), and MORB like immobile element concentrations (Stolz, 1995).

Mafic dykes and sills intruding the upper section of the Puddler Creek Formation are trachyandesite in composition (Figure 17; Berry & others, 1992; Stolz, 1995). They have moderate TiO_2 (>1.2 wt %), high P_2O_5 (>0.60 wt %), enriched incompatible element concentrations, high Nb/Y, and low Zr/Nb and La/Nb values. $\varepsilon Nd_{(480Ma)}$ values are within a restricted range from -0.2 – -2.7 (Stolz, 1995). These rocks are widely inferred to represent alkaline intraplate magmatism (Henderson, 1986; Hutton & others, 1994; Berry & others, 1992; Stolz, 1995).

Deformation and metamorphism

Berry & others (1992) defined three deformation events in the Seventy Mile Range Group. D_1 involved open south-plunging folding and associated faulting. Faulting kinematics suggest sub-horizontal thrust movements. A rare S_1 occurs in narrow zones along faults.

The entire Seventy Mile Range Group forms a near-continuous south-facing limb of an F_2 fold (Berry & others, 1992). The D_2 event had a regional extent and produced the dominant S_2 fabric. Regional metamorphism associated with D_2 increases from east to west from prehnite-pumpellyite to greenschist facies (Berry & others, 1992). S_2 is defined by andalusite, biotite and muscovite in pelitic rocks, and hornblende in mafic rocks.

D_3 is represented by a sporadic, but well developed F_3 folding and S_3 foliation. The deformation is spatially associated with north-west to west trending faults and unfoliated granites of the Lolworth and Ravenswood Batholiths (see below). The emplacement of these batholiths developed aureoles of cordierite-biotite and biotite-muscovite hornfels for up to 600m from the contact (Henderson, 1986).

Intrusive units

Fat Hen Creek Complex

The Fat Hen Creek Complex is a 5km-wide linear belt trending west-north-west for nearly 100km along the south-western boundary of the Charters Towers Province (Figure 12). It comprises biotite orthogneiss, foliated S-type granitoid and migmatite, with minor biotite schist, calc-silicate gneiss and amphibolite (Hutton, 2004). The Fat Hen Creek Complex has a transitional boundary with the Cape River Metamorphics and is interpreted to have formed *in situ*, at peak metamorphic conditions of ~730–820°C and 5–7Kb (granulite facies; Hutton, 2004). S-type granites within the complex are inferred to be melts of the Cape River Metamorphics (Hutton, 2004). Hutton (2004) divided the complex into four lithological and geochemical associations as described below.

The south-western section is non-foliated biotite granodiorite with minor muscovite, garnet and cordierite (Oak Vale association). Metasedimentary xenoliths are common and are comparable to the adjacent Cape River Metamorphics. U–Pb SHRIMP analysis of zircon yielded a crystallisation age of 483 ± 12Ma (Hutton, 2004).

In the north and north-eastern part of the complex, biotite-muscovite ± garnet orthogneiss occurs with foliated granodiorite and tonalite (Clearview association). The orthogneiss is well layered, with abundant schlieren and discontinuous leucosomes. Partly aligned megacrystic K-feldspar also commonly defines layering. In places, the orthogneiss is interlayered with a medium- to coarse-grained biotite-rich granitoid with diffuse boundaries. U–Pb SHRIMP analysis of zircon yielded a crystallisation age of 467 ± 8.2Ma (Hutton, 2004).

In the central area, this orthogneiss is interlayered with biotite-hornblende orthogneiss (Gorge Creek association). Mineralogy includes quartz, microcline and microperthite, oligoclase to andesine, albite, biotite, hornblende, subhedral epidote, opaques and minor titanite.

Migmatite is located near the boundary between the Fat Hen Creek Complex and the Cape River Metamorphics (Scrubby Creek association; Withnall & others, 1997a). Layering in the migmatite is defined by fine-scale melanosomes and leucosomes, of which the latter make up a subordinate proportion of the entire rock. U–Pb SHRIMP analysis of zircon from the Gorge Creek and Scrubby Creek association yielded crystallisation ages of ~452 – ~441Ma (Hutton, 2004).

Ravenswood Batholith

The Ravenswood Batholith consists of Early Ordovician to early Permian gabbros to alkali-feldspar granites that intrude the Seventy Mile Range Group in the south, and the Charters Towers Metamorphics and Argentine Metamorphics in the central and northern areas (Figure 12; Hutton & others, 1994; Hutton & Crouch, 1993a; Hutton, 2004). The batholith crops out over 6000–7000km^2 and is subdivided on geochemical and temporal affinities into late Cambrian to Middle Ordovician granitoids, Middle Ordovician peraluminous granites, middle Cambrian to (?)Permian mafic rocks, middle Silurian to Early Devonian granitoids, and the middle Carboniferous to early Permian intrusives (Table 4; Hutton, 2004).

The first recorded period of magmatism was between the late Cambrian and Middle Ordovician resulting in the emplacement of the Sunburst and Schreibers Granodiorites (Table 4). These are medium- to high-K calc-alkaline, I-type granitoids. Hutton & others (1993) suggested they could be comagmatic with the Mount Windsor Volcanics (Seventy Mile Range Group) based on temporal similarities, but Hutton & others (1994) later showed significant geochemical differences. Peters (1987) postulated a mantle derivation for the Sunburst Granodiorite while Hutton & others (1994) has invoked underplating and subsequent crustal melting to explain undepleted Y and depleted Sr, and an evolved εNd(i) value of –9.0.

Early to Middle Ordovician magmatism was a major phase within the Ravenswood Batholith. Intrusions of this age form part of the Macrossan Igneous Association or Province (Bain & Draper, 1997). Five lithological and geochemical supersuites of this period are defined (Hutton & others, 1994): Hogsflesh Creek, Lavery Creek, Jones Dam, Brittany and Chipley supersuites (Table 4).

The Hogsflesh Creek, Lavery Creek, Brittany and Chipley supersuites are medium- to high-K, calc-alkaline I-type granites (Hutton & others, 1994). They have all undergone recrystallisation of biotite, as well as being strained, foliated and locally mylonitised (Hutton & others, 1994). The Hogsflesh and Lavery Creek supersuites are contiguous and are commonly intermingled at boundaries. Locally the Lavery Creek Supersuite is peraluminous with one pluton (Grass Hut Granite) containing garnet. These supersuites display some volcanic arc affinities, but Hutton & others (1994) suggest this is inherited from the source.

The Jones Dam Supersuite differs significantly in having lower K_2O and MgO and higher Zr. Unlike any other plutonic rocks of the Macrossan Igneous Association, the Jones Dam Supersuite is tholeiitic. The supersuite is interpreted to have a magmatic arc origin with $TiO_2 < 1.0\%$, depleted in Nb, low Nb/U ratios, and negative TiO_2 and FeO vs. SiO_2 correlations (Hutton & others, 1994). The supersuite remains undated.

Middle Ordovician peraluminous granites collectively termed the Columbia River Supersuite intrude the Charters Towers and Argentine Metamorphics (Hutton & others, 1993; 1994). They occur as five spatially separate, but geochemically similar complexes/units; the Columbia Creek Complex, Melon Creek Tonalite, Holborn Granodiorite, Two Creek Granodiorite and the Carse Creek Complex (Table 4). They are commonly associated with high grade metamorphism (Hutton & others, 1994) although their source rocks remain unknown, with both S-type (Aluminium Saturation Index (ASI) > 1.1 and metasedimentary xenoliths), and I-type (K/Na <1 and a negative P_2O_5 vs. SiO_2 correlation) features (Hutton & others, 1994). They have a higher metamorphic grade than adjacent rocks, leading Hutton & others (1994) to suggest they were faulted into place.

Silurian to Devonian intrusions (part of the Pama Igneous Association or Province of Bain & Draper, 1997) represent up to 60% of the outcropping Ravenswood Batholith. These are typically I-type, calc-alkaline hornblende-biotite granodiorite to tonalite, except for the Britannia Supersuite which is transitional to tholeiitic. Their distribution is concentrated towards the south and south-east of the batholith, and confined to structurally bound domains striking east-north-east. They are generally unmetamorphosed and undeformed. They occur as steep-sided, elongate or sheet-like plutons and are commonly associated with significant concurrent faulting and shearing (Hutton & others, 1994). Hutton & others (1994) proposed an active north-east–south-west extensional environment of emplacement.

They were emplaced in the interval 382–426Ma, with most plutons recording an age in the range 406–418Ma (Hutton & others, 1994). Like the Ordovician granites, they display volcanic-arc affinities. Sr depletion and Y undepletion suggest a shallow crustal source (Hutton & others, 1994). Decreasing $^{87}Sr/^{86}Sr_{(i)}$ southward was used to infer differing source rocks at depth.

Mafic intrusives are common within the Ravenswood Batholith. Several are named (Rienks, 1991; Hutton & others, 1993), but many remain unnamed. They occur as dykes and dyke swarms, small plutons, and mingled with granites. Two mineral assemblages are common: plagioclase-hornblende-quartz (?) gabbro to diorite, and clinopyroxene-orthopyroxene-plagioclase-olivine gabbro. They are predominantly subalkaline, low to medium-K rocks. Their only age constraint is that they are intermingled with Ordovician to Devonian granites. Some are unmetamorphosed, suggesting they are younger than Ordovician.

Carboniferous to Permian rocks of the Kennedy Igneous Association or Province (Bain & Draper, 1997) form a volumetric minor (~6%) proportion of the Ravenswood Batholith. They occur as ring-fracture controlled stocks and complexes, elongate gabbro to granite complexes, and rhyolitic to trachytic high level plugs, vents and diatremes. Geochemically they define four supersuites: the Tuckers, Leichhardt, Barratta and Bogie supersuites (Table 4; Hutton, 2004). They are bimodal with SiO_2 in the ranges 53–64% and 66–78%. The Leichhardt and Barratta supersuites are high-K

Table 4. Components of the Ravenswood Batholith in the Charters Towers Province, modified from Hutton (2004), Rienks (1997)

Supersuite/ Unit	Lithology	Geochemical characteristics	Age
Late Cambrian to Middle Ordovician (Macrossan Igneous Association)			
Schreibers Granodiorite	Hornblende-biotite granite to granodiorite	Medium-K, calc-alkaline	490 ± 6Ma (U-Pb zircon; Hutton & others, 1994)
Sunburst Granodiorite	Biotite-hornblende, melanocratic granite to quartz diorite	Medium to high-K, calc-alkaline	482 ± 8Ma (U-Pb zircon ; Fanning, 1995, unpublished data *in* Hutton & Rienks, 1997)
Middle Ordovician (Macrossan Igneous Association)			
Hogsflesh Creek Supersuite	Grey to greyish-pink biotite and hornblende-biotite granite to granodiorite	Medium to high-K, calc-alkaline	480 ± 5Ma (Rb-Sr whole rock; Rienks, 1991)
Lavery Creek Supersuite	Pink to red and pink to grey biotite and hornblende-biotite granite	Medium to high-K, calc-alkaline to peraluminous	463 ± 3Ma (U-Pb zircon; Hutton & others, 1994)
Jones Dam Supersuite	Grey, medium-grained, subequigranular, biotite-hornblende granodiorite in places grading to monzogranites.	Medium-K, tholeiitic	Unknown
Brittany Supersuite	Pink to buff, fine to coarse grained, porphyritic hornblende-biotite granite (Brittany Granite), and grey, porphyritic biotite microgranite (Exley Microgranite)	High-K, calc-alkaline	Unknown
Chipley Supersuite	White to cream, albite rich, garnet, muscovite-biotite granite	Medium-K, calc-alkaline	Unknown
Columbia Creek Supersuite	Grey, medium-grained, locally xenolith rich, biotite-muscovite and biotite granodiorite to tonalite	Peraluminous	464 ± 5Ma (U-Pb zircon; Hutton & others, 1994)
Silurian to Devonian (Pama Igneous Association)			
Millchester Supersuite	Mainly grey, medium-grained, slightly porphrytic, biotite hornblende tonalite to granodiortite	Dominantly medium-K, calc-alkaline	411–426Ma (Rb-Sr biotite-whole rock; Hutton & others, 1994)
Brittania Supersuite	Medium-grained, grey to pink to cream, altered biotite and hornblende biotite granite, granodiorite and trondhjemite.	Low to medium-K, calc-alkaline to tholeiitic	Unknown
Barrabas Supersuite	Pink, buff and grey, medium-grained biotite hornblende granodiorite; hornblende-biotite granodiorite; biotite monzogranite; biotite-muscovite syenogranite.	High-K and Rb, calc-alkaline	405 ± 12Ma (K–Ar biotite; Wyatt & others, 1971).
Deane Supersuite	Medium-grained, biotite-hornblende granodiorite to granite	Medium to high-K, calc-alkaline	409 ± 2Ma (Rb-Sr biotite-whole rock; Hutton & others, 1994)
Broughton River Supersuite	Composite pluton with: 1) pyroxene monzogranite to diorite sheath, and 2) hornblende-biotite granodiorite to granite.	High-K calc-alkaline	406 ± 4Ma (Rb-Sr biotite-whole rock; Hutton & others, 1994)
Late Carboniferous to Early Permian (Kennedy Igneous Association – Leichhardt Supersuite)			
Tuckers Suite	Coarse-, medium- and fine-grained gabbro, diorite, mangerite, biotite-hornblende granodiorite to tonalite, biotite granite, leucogranite, monzodiorite, quartzddiorite, monzogranite.	High-K calc-alkaline	283 ± 9Ma and 284 ± 9Ma (K–Ar whole rock; Rienks, 1997).
Leichhardt Suite	Grey biotite and hornblende-biotite granodiorite, grey to pink biotite and hornblende-biotite granite, microgranite, dacite, dacitic tuff, dacitic rudite and rhyolite.	High-K calc-alkaline	Unknown
Bogie Suite	Pink to grey, biotite and hornblende-biotite granite, granodiorite, microgranodiorite, quartz diorite, porphyritic microgranite, syenogranite, biotite-arfvedonsite granite, green to pink monzogranite, minor rhyolite.	High-K calc-alkaline	311 ± 3Ma (Rb-Sr whole rock; Rienks, 1997).
Unassigned units	Pink hornblende-biotite and biotite granite and monzogranite	High-K calc-alkaline	283–296Ma (K–Ar whole rock; Rienks 1997), 283 ± 4 a (U-Pb zircon; Rienks, 1997).

calc-alkaline, whilst the Tuckers and Bogie supersuites are transitional from medium to high-K calc-alkaline. Emplacement was accommodated through the reactivation of pre-existing faults, inferred to be within a backarc region (Hutton & others, 1994).

Lolworth Batholith

The Silurian to Devonian Lolworth Batholith crops out over 1300km^2 as numerous plutons predominantly comprising biotite-muscovite granite and muscovite leucogranite (Hutton, 2004; Hutton & others, 1996). Volumetrically minor late Carboniferous to Early Permian intrusions of the Woodstock Supersuite (Kennedy Igneous Association) also occur (Rienks, 1997). Country rocks to the batholith include late Neoproterozoic to early Paleozoic Cape River Metamorphics and Fat Hen Creek Complex and the early Paleozoic Seventy Mile Range Group.

Hutton & others (1996) identified three distinct lithological and geochemical suites within the Silurian to Devonian component of the Lolworth Batholith: the Amarra, Grasstree and Hodgon suites (Table 5).

The Amarra Suite is the dominant component of the Lolworth Batholith with 11 separate plutons covering ~1000km^2. The suite is coincident with a large gravity low suggesting the granite continues at depth. The plutons are remarkably homogenous muscovite-biotite granites with rare garnet, large poikilitic megacrysts of K-feldspar with plagioclase and biotite chadacrysts and unstrained to slightly strained quartz. They are medium to high-K, subalkaline granites, with strong enrichment in Sr and depletion in Ba, and ASI < 1.1, and are interpreted as I-type granites (Hutton, 2004). Hutton (2004) inferred a volcanic arc genesis, but suggested that this geochemical characteristic could be inherited from its source region. $\varepsilon Nd_{(382)}$ of -10.2 and -10.8 suggest Proterozoic crust in the source (Hutton, 2004).

The Grasstree Suite includes a single pluton and numerous dykes, some of which are tourmaline-bearing. The Grasstree Leucogranite crops out over 105km^2 as numerous sheet-like bodies of leucocratic aplite and pegmatite that commonly conform to north-east striking fractures (Hutton, 2004). Muscovite is ubiquitous, garnet is rarer and tourmaline occurs locally. Biotite is absent from almost every unit. Geochemically, the Grasstree Suite is strongly depleted in Ba, slightly less depleted in La, Ce, Sr, Nd, Zr and Ti, weakly depleted in P and Y, and slightly enriched in U and Nb. Y is marginally undepleted, suggesting minor residual garnet in the source rocks (Hutton, 2004). Hutton (2004) suggested the magmas were boron-rich based on the presence of tourmaline. They are inferred to be S-type by the dominance of muscovite and an ASI > 1.1.

The Hodgon Suite covers 75km^2 and includes three plutons of hornblende-biotite granodiorite and biotite granite to granodiorite, locally with minor muscovite. The intrusions contain large poikilitic K-feldspar, with quartz and plagioclase chadacrysts, hornblende, biotite and titanite, with minor zircon, apatite, epidote and clinozoisite. Geochemically they are medium-K, with enrichment in Ba and slight depletion in TiO_2, P_2O_5, Nd, Ce, La, Nb, and U. A $\varepsilon Nd_{(414)}$ value of -3.04 is considerably more

Table 5. Components of the Lolworth Batholith

Suite	Lithology	Geochemical characteristics	Age
Devonian (Pama Igneous Association)			
Amarra Suite	Muscovite-biotite granite with minor garnet.	Medium to High-K, sub-alkaline	382 ± 5Ma (U-Pb zircon; Fanning, 1995; unpublished data in Hutton & Rienks, 1997)
Grasstree Suite	Garnet-muscovite leucogranite, pegmatite and aplite	High-K	Unknown
Hodgon Suite	Hornblende-biotite granodiorite and granite	Medium-K, calc-alkaline	414 ± 5Ma (U-Pb zircon; Hutton & others, 1995)
Early to Middle Permian (Kennedy Igneous Association)			
Mundic Suite	Medium-grained, pink to red, miarolitic biotite granite, hornblende-biotite granite, granodiorite, diorite, gabbro, andesite and rhyolite.	High-K, alkalic-calcic	Unknown (285–265Ma; other granites within Woodstock Supersuite; Rienks, 1997).

primitive than the Amarra Suite (Hutton, 2004). The Hodgon Suite is temporally and geochemically similar to intrusives within the Ravenswood Batholith (Hutton, 2004).

Reedy Springs Batholith

The Silurian–Devonian Reedy Springs Batholith occurs in the north-west of the Charters Towers Province (Figure 12). The batholith marks a change in the trend of the Pama Igneous Association, from north–south in Cape York, to east–west through the Charters Towers Province (Figure 5). It is comprised of 19 named plutons and numerous unnamed volcanics and intrusives. These were mapped and described by Rienks & Withnall (1996) and geochemically defined by Rienks (1997). They intrude metamorphic rocks of the Neoproterozoic–Cambrian Cape River Metamorphics, and are faulted against the Proterozoic Einasleigh Metamorphics of the Georgetown Inlier. The current morphology is as elongate, steep-sided units which are parallel to the dominant foliation. It is unknown if this represents their primary morphology.

The plutons are dominantly calcic, peraluminous two-mica granites. Rienks (1997) geochemically subdivided the batholith into four supersuites: the Craigie and Toms Hole supersuites, unassigned peraluminous granites, and unassigned trondhjemite (Table 6).

The Craigie Supersuite comprises the calcic, oxidised, transitional low to medium-K, mafic, metaluminous to weakly peraluminous, and I-type Craigie Tonalite. This unit displays differing REE patterns to petrographically similar rocks of the Ravenswood Batholith, including elevated HREEs indicative of a garnet-bearing source region.

The Toms Hole Supersuite comprises foliated, medium-grained porphyritic hornblende-biotite granodiorite of the Toms Hole Granodiorite. This unit is oxidised, peraluminous and medium-K calc-alkaline and is enriched in incompatible elements

Table 6. Components of the Reedy Springs Batholith, after Rienks (1997)

Suite	Lithology	Geochemical characteristics	Age
Devonian (Pama Igneous Association)			
Craigie Supersuite	Medium-grained, grey, subequigranular biotite-hornblende tonalite, accessory epidote, sphene and allanite.	Low- to medium-K, oxidised, calcic.	406 ± 3Ma (K–Ar hornblende; Rienks, 1997).
Toms Hole Supersuite	Foliated, grey, medium-grained porphyritic hornblende-biotite granodiorite, accessory sphene, epidote, zircon and apatite.	Medium-K, oxidised, calc-alkaline.	Unknown
Unassigned peraluminous granites	Medium-grained, grey-buff biotite granodiorite, muscovite-biotite granodiorite to monzogranite, accessory sphene, allanite, epidote and zircon.	Medium- to high-K, calcic.	403–410Ma (Rienks, 1997).
Unassigned trondhjemite	Medium and medium- to coarse-grained, white leucocratic biotite trondhjemite.	Low- to medium-K, reduced, alkalic-calcic.	Unknown

relative to the rest of the Reedy Springs Batholith. A less influential role for garnet relative to the Craigie Supersuite was inferred, suggesting a shallower source region.

The unassigned peraluminous granites group includes medium-K, silicic, oxidised, weakly peraluminous granodiorite to leucocratic, mildly peraluminous, high-K, oxidised to mildly reduced monzogranite. They are thought to have originated from a garnet-free source, with retention of plagioclase during partial melting or fractional crystallisation of plagioclase.

Unassigned trondhjemite in the north of the batholith is alkaline, felsic, low to medium-K, and weakly differentiated. It is depleted in Sr, Rb, FeO, MnO and Zr, and undepleted in Ni. It is also thought to have originated from a garnet free source, and is comparable to trondhjemite in the Ravenswood Batholith.

The Reedy Springs Batholith was emplaced synchronously with metamorphism. The presence of magmatic epidote in the Craigie Supersuite suggests pressures of 3–7Kb or midcrustal depths between 10 and 25km (Rienks, 1997). However, normative compositions of the peraluminous granites suggest emplacement later occurred at about 2Kb or 6–8km.

GREENVALE PROVINCE

The Greenvale Province is an early Paleozoic supracrustal and intracrustal wedge between the Paleozoic Mossman Orogen and the Proterozoic rocks of the Etheridge Province in the North Australian Craton (Figure 18; Fergusson & others, 2007c). White (1965) originally mapped all of the rocks as Precambrian (including some possible Archean). Withnall & others (1980) assigned the rocks east of the newly recognised Balcooma Mylonite Zone to the Greenvale Subprovince of their Georgetown Province, but they still regarded the rocks as Proterozoic although possibly much younger. Withnall & others (1988) and Withnall (1989) recognised that

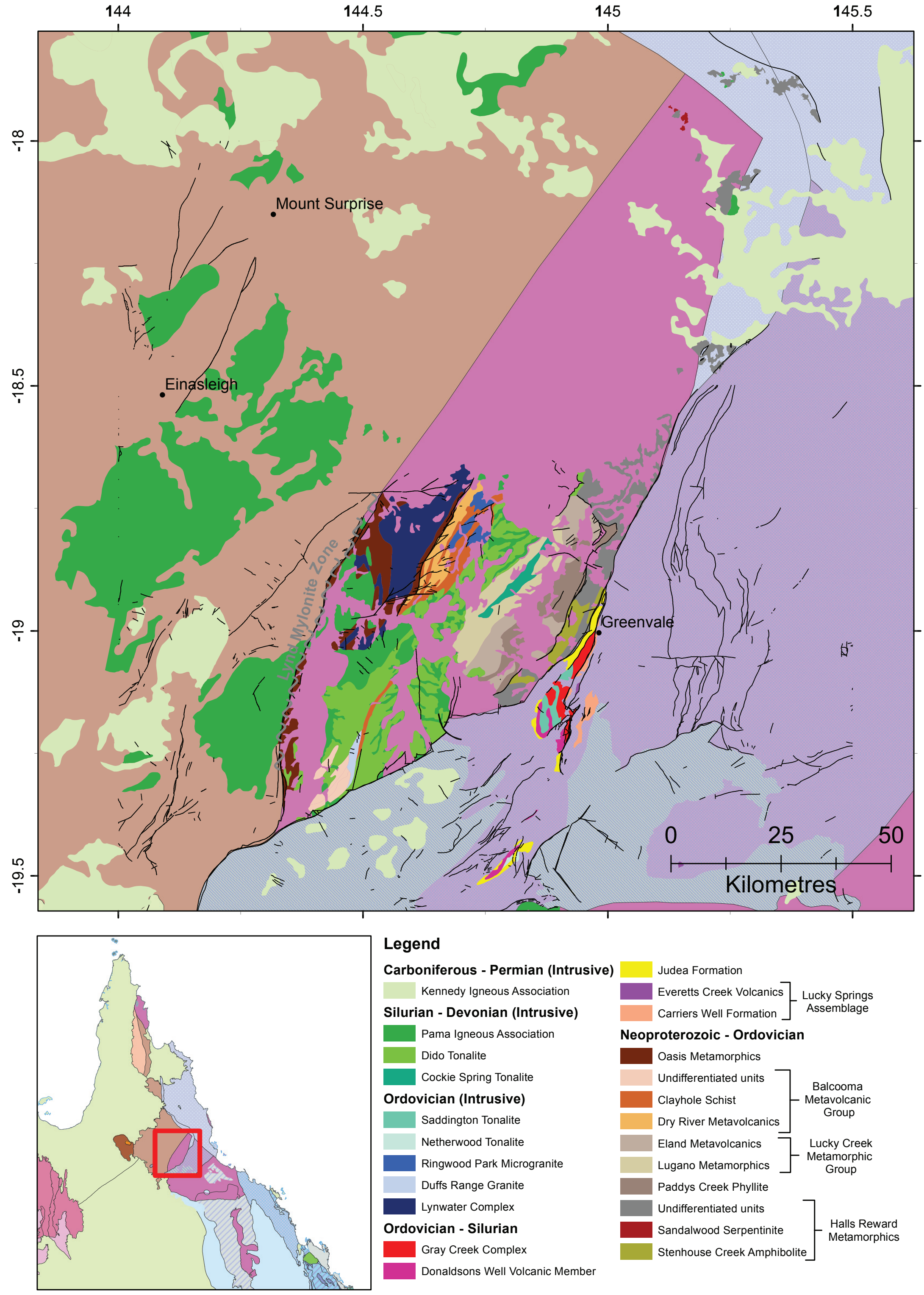


Figure 18. Outcropping geology of the Greenvale Province. Note that the Golden Creek Meta-andesite, Lochlea Metarhyolite and Highway Metavolcanics of the Balcooma Metavolcanics group are not individually distinguished. Inset shows location of the Greenvale Province relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

Table 7. Geology of the Greenvale province, after Withnall (1989) and Fergusson & others (2007c).

Note that deformation events (D_N) and their components are restricted to each unit and do not necessarily coincide with events in adjacent units.

Group/Unit	Lithology	Age constraints	Structure	Metamorphism
Oasis Metamorphics	In stratigraphic order from base: 1) calc-silicate gneiss, 2) amphibolite, minor schist, 3) biotite gneiss with minor amphibolite, 4) calc-silicate gneiss, lenses of dolomitic marble	<520Ma (U-Pb detrital zircon (Fergusson & others 2007c); >476Ma (metamorphic zircon rim Fergusson & others, 2007a)	D_1: gneissic layering (S_g), foliation (S_1) and mineral lineation (L_m) steeply dipping east. Locally boudinaged. D_2: open to near-isoclinal folding plunging moderately NE (F_2), with associated steeply inclined axial plane foliation dipping steeply east (S_2).	Upper amphibolite
Lynwater Complex	Hornblende-bearing and two-mica granitoids grading to orthogneiss.	477 – 486Ma (zircon crystallisation age; Fergusson & others, 2007a)	D_1: N trending, steeply dipping foliation (S_1).	Upper amphibolite
Balcooma Metavolcanic Group	Massive pelitic and quartzose metasandstone, overlain by massive meta-rhyolitic volcaniclastics, some meta-dolerite and meta-andesite	471 ± 4Ma (zircon crystallisation; Withnall & others, 1991).	D_1: foliation subparallel to S_0 (S_1). D_2: steeply plunging, tight to near isoclinal folding (F_2) crenulation cleavage to continuous foliation steeply dipping NE (S_2). D_3: weak crenulation cleavage dipping steeply east (S3) and folding (F_3).	Amphibolite
Ringwood Park Microgranite and Duffs Range Granite	Biotite microgranite, grading to fine-grained granite.	Unknown. Possibly comagmatic with Balcooma Metavolcanic Group (Withnall & others, 1991). Intruded by Dido Tonalite.	D_1: Weakly foliated	Amphibolite
Dido Tonalite	Biotite ± hornblende tonalite pluton	431 ± 7Ma (zircon crystallisation; Bain & others, 1997)	D_1: weak to locally strong north-east trending foliation and dipping steeply (S_1). Synchronous with intrusion.	Unknown
Lucky Creek Metamorphic Group	Lugano Metamorphics (west): amphibolite (preserving primary relict pillow lavas, hyaloclastites and amygdales), metarhyolite and volcaniclastic metasedimentary rocks. Eland Metamorphics (east): metamorphosed dacitic to basaltic volcaniclastic rocks, minor marble and metachert.	None	D_1: rare foliation and differentiated layering (S_1). D_2: Well developed foliation (S_2), tight to isoclinal folding (F_2) and stretching lineations (L_2). S_2 was gently dipping north-west pre-D_3. Locally boudinaged. D_3: Open to close, upright folds verging east to south-east and plunging gently to subhorizontal, associated north-north-east trending and steeply dipping axial plane foliation (S_3).	Amphibolite to greenschist

Table 7 (continued)

Group/Unit	Lithology	Age constraints	Structure	Metamorphism
Cockie Spring Tonalite	Hornblende-biotite tonalite, minor amphibolite and abundant mafic xenoliths	None	Intensely foliated and similar to Lynwater Complex	Unknown
Paddy's Creek Phyllite	Pelite with minor quartzite	None	D_1: rarely preserved foliation within S_2 microlithons (S_1) and folding (F_2). D_2: well developed laminar crenulation cleavage (S_2) and folding (F_2). S_2 was gently dipping north-east pre-D_3. D_3: open to close, upright folds, gently plunging north-east (F_3) with associated axial planar crenulation cleavage, dipping steeply south-east (S_3). D_4: Broad to open folds, gently plunging north-west (F_4) with associated weak axial planar crenulation (S_4).	Greenschist
Halls Reward Metamorphics	Coarse-grained muscovite-quartz schist with biotite, sillimanite and garnet. Local pegmatite and leucogranitic dykes.	>510 Ma (metamorphism; multiple methods, see Nishiya & others 2003).	D_1: rare crenulation cleavage (S_1). D_2: strong foliation and crenulation cleavage dipping steeply north to north-west (S_2), and intrafolial isoclinal folds variably plunging north (F_2). D_3: broad to open kink bands trending north and steeply dipping (S_3).	Amphibolite
(?) Boiler Gully Complex	Amphibolite, metagabbro and clinopyroxenite.	Similar to Halls Reward Metamorphics	Above	Amphibolite

many of the rocks were probably early Paleozoic, although some were still thought to be correlatives of rocks in the Etheridge Province. Withnall & others (2002) recognised that most of the rocks east of the Lynd Mylonite Zone were likely to be Neoproterozoic to early Paleozoic and assigned them to the Cape River Province of Bain & Draper (1997), which is now referred to as the Charters Towers Province (see above). However, Fergusson & others (2007c) resurrected the name Greenvale Province for the rocks east of the Lynd Mylonite Zone, which they suggested was coincident with the Tasman Line. A distinction was based on the absence of Mesoproterozoic rocks to the east of the Lynd Mylonite Zone, as well as a noticeable difference in the metamorphic and deformational history of adjacent rocks.

The units of the Greenvale Province were described by Withnall (1989) and Fergusson & others (2007c), and summarised in Table 7.

Metamorphism and deformation in the Greenvale Province were described by Fergusson & others (2007c) in four domains separated by mylonite and fault zones of steeply dipping intense foliation, except the eastern margin of the Halls Reward domain where it is at a low angle. From east to west these include the Lynd Mylonite Zone, Balcooma Mylonite Zone, Nickel Mine Fault and Halls Reward Fault. The Lynd Mylonite zone displays east-over-west shear sense (Withnall, 1989), the Balcooma Mylonite Zone shows sinistral shear sense and the Nickel Mine Fault shows west-over-east shearing (Fergusson & others, 2007c). The Halls Reward Fault is steeply dipping with a ~200m wide mylonitic zone (Withnall, 1989). Elsewhere this mylonite displays an S_3 foliation with S-C planes and shear bands indicating south-west transport. Fergusson & others (2007c) considered these as north-trending extensional structures.

Oasis Metamorphics

The Oasis Metamorphics are separated from the Mesoproterozoic Einasleigh Metamorphics to the west and to which they were previously equated (Withnall, 1989) by the Lynd Mylonite Zone (Figure 18). The eastern boundary with the Balcooma Metavolcanic Group occurs at the Balcooma Mylonite Zone. The Oasis Metamorphics include calc-silicate gneiss (Figure 19), amphibolite with minor biotite schist, and biotite gneiss with less abundant amphibolite, calc-silicate gneiss, dolomitic marble and serpentinite (Withnall & others, 2002). Fergusson & others (2007c) interpreted the group to represent a sequence of metamorphosed shallow-marine clastic sediments and mafic volcanics and/or intrusions.

Within the Oasis Metamorphics, the dominant D_1 event caused amphibolite facies metamorphism shown by the coexistence of hornblende and diopside in calc-silicate gneiss and the formation of granitic and pegmatite veins (Withnall, 1989; Fergusson & others, 2007c). This coincided with the emplacement of the 486–477Ma Lynwater Complex whose foliation is parallel to S_1 in the Oasis Metamorphics (Fergusson & others, 2007c). D_2 is poorly preserved and poorly constrained.

Figure 19. Calc-silicate gneiss of the Oasis Metamorphics (GR E237350 N7911048)

U–Pb analyses of detrital zircon yielded inheritance peaks between 1300–1250Ma, 1200–1150Ma and 540–520Ma, with metamorphic rims at 476 ± 5Ma (Fergusson & others, 2007c). Metamorphism coincided with the intrusion of the 486–477Ma Lynwater Complex (Fergusson & others, 2007c) which is temporally associated with the older part of the Lolworth Batholith (Hutton & others, 1997b). The Silurian McKinnons Creek Granite also intrudes the Oasis Metamorphics, but it is significantly less foliated than the Lynwater Complex.

Preliminary zircon and titanate dating of the calc-silicate unit suggests high-grade metamorphism at ~1.6Ga and would suggest that it is actually part of the Precambrian Einasleigh Metamorphics (D Dunkley, unpublished data, 2012).

Balcooma Metavolcanic Group

The Balcooma Metavolcanic Group is bounded by the Balcooma Mylonite Zone to the west and the Dido Tonalite to the east (Figure 18). Huston (1990) subdivided the group (in stratigraphic order from the base) into the Clayhole Schist, Golden Creek Meta-andesite, Dry River Metavolcanics, Lochlea Metarhyolite, Highway Metavolcanics and unnamed sills.

The **Clayhole Schist** includes interbedded mica schist locally containing andalusite (Figure 20a), thin- to thick-bedded quartzite and rare volcaniclastic metasandstone, carbonaceous phyllite and impure marble. Within the upper part of the Clayhole Schist there is a small lens (~2km long) of mafic volcaniclastic rocks, minor breccia, lithic sandstone and poorly sorted conglomerate containing granules to pebbles of metarhyolite (Fergusson & others, 2013a) known as the **Golden Creek Meta-andesite**. The **Dry River Metavolcanics** include metarhyolite and amygdaloidal meta-andesite (Figure 20b) with minor metasedimentary rocks. Relict phenocrysts of quartz, plagioclase and K-feldspar are commonly broken and indicate that most of the protolith was probably a volcaniclastic rather than lava (Fergusson & others, 2013a). The overlying **Lochlea Metarhyolite** is differentiated from the Dry River Metavolcanics by significant decrease in phenocrysts. The **Highway Metavolcanics**

Figure 20. Outcrop of the Balcooma Metavolcanic Group: a) fine-grained schist of the Clayhole Schist with probable andalusite porphyroblasts; b) amygdoidal meta-andesite of the Dry River Metavolcanics

includes well-bedded to laminated pyritic siliceous siltstone or metatuff and minor metarhyolite (Fergusson & others, 2012).

Within the Balcooma Metavolcanic Group the dominant structural fabric is associated with D_2. Metamorphic grade reached amphibolite facies shown by the presence of staurolite, andalusite and cordierite porphyroblasts in a schist, and was inferred to have occurred at mid-crustal levels (~4.6–6.2kb and ~530–630°C), along a clockwise P-T-t-D (pressure-temperature-time-depth) path (Ali, 2010). Ali (2010) suggested this occurred during crustal thickening, followed by decompression and mineral growth at ~2kb and ~450°C. Dating of metamorphic monazite constrains this event to ~443–425Ma (Ali, 2010) which is contemporaneous with the widespread Benambran Orogeny (e.g. Glen, 2005). This contractional event likely caused the reactivation of the Lynd, Balcooma and Nickel Mine Faults (Fergusson & others, 2007c). The ~430Ma Dido Tonalite (Bain & others, 1997; Withnall & others, 2002) which truncates these faults, displays a weak to strong north-east trending and steeply dipping foliation interpreted to have formed synchronous with fault reactivation and within a contractional environment (Fergusson & others, 2007c).

Harvey (1984) first noted distinct lithological similarities between the Balcooma Metavolcanic Group and the volcanics of the Seventy Mile Range Group in the Charters Towers Province. This is confirmed by U–Pb SHRIMP dating by Withnall & others (1991). Geochemically driven tectonic models suggest a backarc basin setting for the Seventy Mile Range Group (Henderson, 1986; Stolz, 1995), but the limited geochemical data for the Balcooma Metavolcanic Group are mostly of the felsic rocks and do not allow similar conclusions to be made.

Lucky Creek Metamorphic Group

The Lucky Creek Metamorphic Group lies between Dido Tonalite (west) and the Halls Reward Metamorphics (east) (Figure 18). In the east it interfingers with metasediments of the Paddys Creek Phyllite, but they have a different deformational history (Fergusson & others, 2007c). The Lucky Creek Metamorphic Group includes amphibolite, metarhyolite and volcaniclastic metasedimentary rocks of the Lugarno Metamorphics (which predominate in the west; Figure 21) and metamorphosed dacitic to basaltic volcaniclastic rocks, with minor marble and metachert of the Eland Metamorphics (which predominate in the east). Geochemical analyses of igneous rocks in the Lucky Creek Metamorphic Group are interpreted to indicate a backarc tectonic setting (Withnall, 1989; Fergusson & others, 2007c).

D_1 is rarely preserved as an S_1 foliation due to a pervasive S_2 foliation. S_2 is generally moderately dipping to the north-west but has been subsequently folded by upright F_3 folds that plunge at 40° or less. This indicates that S_2 was likely originally shallowly dipping (Fergusson & others, 2007c). Pre-D_3 shearing occurs locally, is oblique to S_2 and has a dextral shear sense.

Figure 21. Thick bedded, schistose, well-cleaved volcaniclastic metasiltstone and metasandstone of the Eland Metavolcanics.

Paddys Creek Phyllite

The Paddys Creek Phyllite abuts the Nickel Mine Fault to the east, and interfingers with the Eland Metavolcanics to the west (Figure 18). It includes phyllite with lesser quartzite.

The Paddys Creek Phyllite is of lower metamorphic grade than the Lucky Creek Metamorphic group (lower greenschist facies) but displays a subsequent deformational event (Fergusson & others, 2007c). D_4 has resulted in northwest plunging F_4 folds and an associated S_4 foliation which dips gently to moderately northeast (Fergusson & others, 2007c).

In the Lucky Creek Metamorphics and Paddy's Creek Phyllite, metamorphic grade increases from east to west from greenschist to amphibolite facies. Furthermore the overall dip of S_2 decreases eastwards, and an eastward sense of shear is apparent along S_2.

Halls Reward Metamorphics

The Halls Reward Metamorphics are bounded to the west by the Nickel Mine Fault, and to the east by the Halls Reward Fault (Figure 18). The group includes medium- to coarse-grained mica schist, quartzite and biotite-muscovite gneiss. Sillimanite and garnet occur locally within schists.

Metamorphosed mafic and ultramafic rocks within the Halls Reward Metamorphics are assigned to the **Boiler Gully Complex**, which includes amphibolite, metagabbro and clinopyroxenite of the **Stenhouse Creek Amphibolite**, and lizardite, chrysotile and antigorite-bearing serpentinite of the **Sandalwood Serpentinite**.

Within the Halls Reward Metamorphics D_1 is rarely preserved, but is described as a crenulation cleavage (Fergusson & others, 2007c). The most pervasive deformation accompanied D_2 with the development of an S_2 foliation that trends east–west and dips steeply north. During D_3, weak S_3 kink bands developed and are steeply dipping and north striking.

The Halls Reward Metamorphics and Boiler Gully Complex were previously thought to represent Proterozoic crust juxtaposed against Cambrian to Ordovician rocks of the Greenvale Province (Arnold & Rubenach, 1976; Withnall, 1989; Withnall & others, 1991). Furthermore Black & others (1979) reported Ar–Ar isotopic ages of 1316 and 1111Ma in hornblende of the Gray Creek Complex, thought to be an equivalent of the Boiler Gully Complex. However, Nishiya & others (2003) showed that they underwent amphibolite facies metamorphism at *ca* 510Ma during the Delamerian Orogeny, and contain Mesoproterozoic to Neoproterozoic detrital zircon. Fergusson & others (2007c) interpreted the Halls Reward Metamorphics and Boiler Gully Complex to represent a Delamerian basement block that was upstanding as a horst during an Early Ordovician extensional episode.

BARNARD PROVINCE

The Barnard Province is a distinct element of the Thomson Orogen, separated from the Greenvale and Charters Towers Provinces by the younger Hodgkinson Province (Figure 5). Korsch & others (2012) believe the rocks of Greenvale and Barnard provinces are continuous beneath the Hodgkinson Province.

The Barnard Province forms a 70km-long north-north-west trending belt of multiply deformed metasedimentary and meta-igneous rocks. These occur along the coastline and nearby islands near Innisfail (Figure 22), and are separated from the Silurian–Devonian Hodgkinson Province to the west by the Russel Mulgrave Shear Zone.

A small area (5km by 1km) of fault-bounded oceanic crust, named the **Cowley Ophiolite Complex**, occurs adjacent to the Russel Mulgrave Shear Zone in the Silkwood area (Figure 22). There are no age constraints on this unit, however Bultitude & others (1998) considered the unit to be Neoproterozoic–Cambrian? oceanic crust. The unit forms deeply weathered ridges overlain by thick vegetation. The best outcrop is confined to road cuttings. The unit includes metamorphosed serpentinite, talc schist, (talc-) tremolite schist, (tremolite-) chloritic schist, and talc-magnesite rocks (containing relict peridotite kernels), as well as some gabbro, and basaltic or andesitic dykes (Rubenach, 1978; Bultitude & others, 1999). Tectonic emplacement into the Hodgkinson Formation likely occurred during the Permian–Triassic Hunter–Bowen Orogeny (Bultitude & others, 1999).

Rocks of the Barnard Province were described by Bultitude & others (1999). Two main units are defined: the Barnard Metamorphics and the Babalangee Amphibolite (Table 8).

The **Barnard Metamorphics** include poorly exposed meta-arenite/quartzite, phyllite, greenstone, chlorite schist, muscovite-chlorite and biotite-muscovite schist, biotite gneiss, migmatitic gneiss, and metagranite. The greenstones are interpreted to represent a series of sheared and altered mafic volcanics including volcaniclastics. Other, less dominant rock types include hornblende granulite (Bultitude & others, 1996), massive amphibolite, garnet-bearing para?-amphibolite, metagabbro, metamorphosed ultramafic rocks, and talc-rich rocks (Bultitude & others, 1999). Biotite granite and granodiorite intrude the Barnard Metamorphics, predominantly in the southern area.

The **Babalangee Amphibolite** is represented by a small ~20km^2 area of outcrop east of Babinda township (Figure 22). It is massive to schistose amphibolite containing ~75% hornblende, ~23% plagioclase (calcic andesine), and 1–2% titanite, apatite, epidote/clinozoisite and sulphides. The rocks have been metasomatised by the adjacent early Permian Bellenden Ker Granite (Garrad & Bultitude, 1999) forming an aureole defined by tourmaline formation.

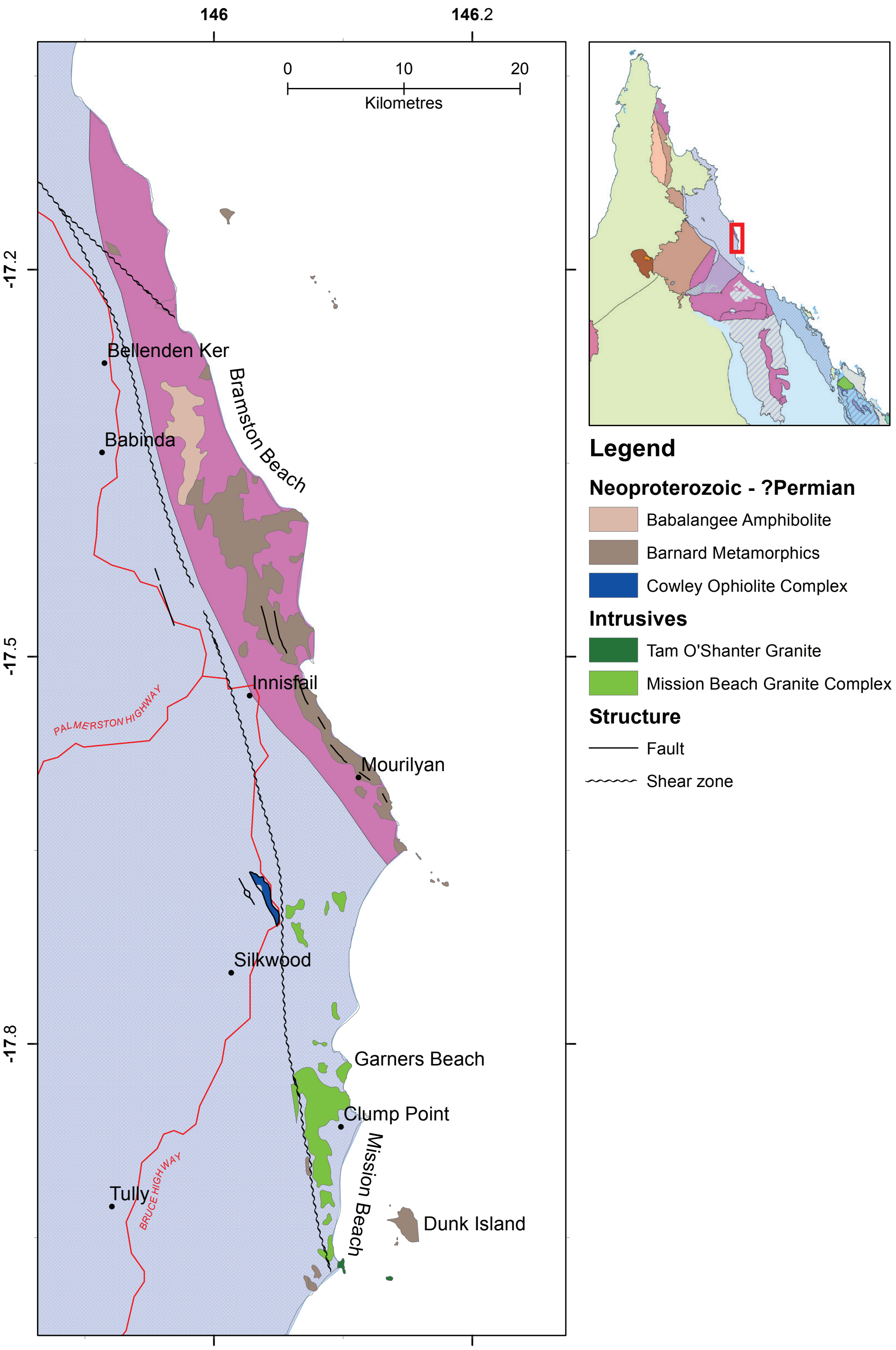


Figure 22. Outcropping geology of the Barnard Province. Inset shows location of the Barnard Province relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

Metamorphism and deformation

The Barnard Metamorphics display greenschist to upper amphibolite and locally granulite facies metamorphism. The low-grade, greenschist facies rocks (meta-arenite/quartzite, muscovite-chlorite and biotite-muscovite schist, and phyllite) predominantly occur along the coast between Bramston Beach and Mourilyan Harbour, at the northern end of Garners Beach, and on Dunk Island (Figure 22). Within these rocks Rubenach (1978) identified a distinct chlorite zone at Mourilyan, and a biotite zone in the Bramston Beach area. Locally high grade granulite facies rocks (mainly migmatitic to massive biotite gneiss) containing sillimanite are in part associated with the emplacement of the Permian Bellenden Ker Batholith (Bultitude & others, 1999). Elsewhere (e.g. on Frankland Islands, and Cooper Point) pelitic and psammopelitic rocks containing K-feldspar porphroblasts variably altered to cordierite, andalusite and sillimanite occur and are both typical of prograde metamorphism (Bultitude & others, 1999).

At least three major deformational events have affected the Barnard Metamorphics, but up to 6 have been suggested locally (Richards, 1977). The Babalangee Amphibolite, however, appears to have been only affected by D_3. D_1 predates the emplacement of the Tam O'Shanter Granite, and is defined by the development of a mylonitic fabric and gneissic layering in the high grade rocks, and a bedding parallel slaty cleavage (S_1) in low grade rocks. The second and most pervasive event, D_2, reorientated S_1 to create intense crenulation cleavage and schistosity (S_2). Langbein (2010) suggested that this event coincided with peak metamorphism (upper amphibolite), resulting in the formation of high temperature – low pressure mineral assemblages and migmatite. S_2 is a well developed foliation within the Tam O'Shanter Granite, and other unnamed S-type granites. Felsic I-type granites within the province have a more poorly developed S_2 foliation. An ~460Ma SHRIMP age of these I-type granites provides a maximum age constraint on D_2. D_3 produced a generally north to north-west trending crenulation cleavage (S_3) and mesoscopic folds. This foliation is most prevalent in low strain rocks. This event has affected the adjacent Hodgkinson Formation, as well as early Permian (~280–285Ma) granites of the Bellenden Ker Batholith, providing a maximum age constraint. In the Barnard Province a metamorphic monazite crystallisation age of 268 ± 4Ma was identified by Bultitude & others (1999), further constraining this event, which is contemporaneous with the Hunter-Bowen Orogeny that affected much of eastern Australia during the Permian–Triassic (Fergusson, 1991).

Age

There has been no direct dating of the supracrustal and intracrustal rocks of the Barnard Province, but the age of the Barnard Metamorphics and the Babalangee Amphibolite can be constrained by subsequent deformation and intrusive events (see below). Therefore a minimum age of *ca* 485Ma is provided by the intrusion of the Tam O'Shanter Granite. The Babalangee Amphibolite is even more poorly constrained, with a minimum early Permian age provided by the Bellenden Ker Batholith.

Table 8. Components of the Barnard Province

Unit	Lithology	Structure	Metamorphism	Age
Barnard Metamorphics	Meta-arenite/quartzite, phyllite, ‘greenstone’, chlorite schist, muscovite-chlorite and biotite-muscovite schist, biotite gneiss, mimgatitic gneiss, and meta-granite.	D_1: mylonitic fabric with associated gneissic layering to slaty cleavage (S_1). D_2: crenulation cleavage (S_2), D_3: N to NW trending crenulation cleavage (S_3) and mesocopic folds.	Middle to upper amphibolite, locally granulite.	> 485Ma (Tam O’Shanter Granite)
Babalangee Amphibolite	Massive to schistose amphibolite with hornblende, plagioclase and minor sphene, apatite, epidote/clinozoisite and sulphides	D_3: N to NW trending crenulation cleavage (S_3) and mesocopic folds.	Amphibolite	> 280Ma (Bellenden Ker Granite)
Tam O’Shatner Granite	Medium-grained, equigranular to slightly porphyritic muscovite-biotite S-type granite with altered cordierite and metamorphic enclaves	Extensively deformed and recrystallised, gneissic foliation		486 ± 10Ma (Bultitude & Garrad, 1997)
Mission Beach Granite Complex	Mainly medium-grained, equigranular biotite granite with common metamorphic enclaves (country rock), rare garnet xenocrysts, minor granodiorite-diorite	Weak to intense foliation, recrystallised		463 ± 7Ma (Bultitude & Garrad, 1997)

Intrusive units

Granitoids are a major component of the Barnard Province. They intrude the metasedimentary rocks and are grouped as the **Mission Beach Granite Complex** (Figure 22; Bultitude & others, 1999). Three mineralogical and geochemical groups are defined: mafic I-types, felsic I-types, and felsic S-type plutons (Bultitude & Garrad, 1997). The I-type granites occur as irregular dykes and pods, containing abundant sodic plagioclase (An_2–An_{37}; Bultitude & Garrad, 1997), interstitial biotite and rare muscovite and apatite. Geochemically they are comparable with the Ravenswood Batholith in the Charters Towers Province. A U–Pb zircon crystallisation age of 463 ± 7Ma was obtained from these rocks (Bultitude & Garrad, 1997). The S-type granite forms dykes and pods, as well as the Tam O’Shanter Granite pluton. These units contain large biotite flakes, lesser muscovite, rare aggregates of fine mica (possibly representing former cordierite grains), numerous lensoidal biotite-rich clots, and inclusions of quartz and biotite gneiss. Plagioclase within these rocks is predominantly sodic (An_{13}–An_{29}; Bultitude & Garrad, 1997). The S-type granites are highly saturated with aluminium (ASI = 1.58–1.72; Bultitude & Garrad, 1997), but this may be due to removal of alkalis during metamorphism. These granites yielded a U–Pb zircon age of 486 ± 10Ma (Bultitude & Garrad, 1997) indicating that they are components of the Ordovician Macrossan Igneous Association. Bultitude & Garrad (1997) suggested that the S-type granites were not derived from the enclosing gneisses but that they are geochemically more similar to younger (Permian) granites that intrude the Hodgkinson Province.

COMPONENTS WITHIN THE MOSSMAN OROGEN

The Mossman Orogen of north Queensland is largely composed of Silurian–Devonian sedimentary and igneous rocks of the Broken River and Hodgkinson provinces. It differs from the Thomson Orogen in post-dating the Benambran Orogeny, a Late Ordovician to Early Silurian compressional event. In the south, the Mossman Orogen is bounded to the west by the Greenvale Province and in the north by the Precambrian terranes of the North Australian Craton. These boundaries are faulted, and adjacent to them are thrust slices of rocks considered to be components of the Thomson Orogen (e.g. Henderson & others, 2011; Vos & others, 2007).

Western margin of the Broken River Province

Thrust slices of Cambrian to Ordovician rocks occur between the Broken River (including the Graveyard Creek and Camel Creek Subprovinces) and Greenvale Provinces, adjacent to the north-east trending Gray Creek Fault (Figure 18). From north-west to south-east they include the Judea Formation, the Gray Creek Complex, and the Lucky Springs assemblage (Carriers Well Formation and the Everetts Creek Volcanics). The Gray Creek Complex is in fault contact with the Judea Formation and the Carriers Well Formation. These rocks form the basement to the Silurian Graveyard Creek and Camel Creek Subprovinces of the Broken River Province.

Gray Creek Complex

The Gray Creek Complex forms a 20km long and 6km wide (at widest point) body of serpentinised ultramafic to mafic rocks which are folded with surrounding Ordovician to Silurian rocks (Figure 18; Arnold & Rubenach, 1976; Withnall, 1993). Peak metamorphism is interpreted to be at amphibolite grade (Rubenach, 1982) and a strong foliation developed, particularly in the north of the unit. Locally near the Gray Creek Fault, the unit is mylonitic. The age of the complex was originally thought to be Mesoproterozoic (Black & others, 1979), but this was questioned by Rubenach (1982). An age of ~470Ma is suggested (Kositcin & others, 2009) based on preliminary Nd-Sm data and geological relationships. An initial εNd value of +8 indicates a juvenile source (Kositcin & others, 2009) and the protolith is postulated to be either a layered ultramafic complex with basal dunite and wehrlite grading up into clinopyroxenite, then layered gabbro (Green, 1958, White, 1965) or an ophiolite complex (Rubenach, 1982, Henderson & others, 2011).

Judea Formation

The Judea Formation as mapped by Withnall (1993) crops out in a belt up to 2km wide to the west of the Gray Creek Complex and within the cores of anticlines in the Broken River area (Figure 18). The western boundary, with the Halls Reward

Figure 23. Typical folded phyllitic metasedimentary rocks of the Judea Formation

Metamorphics, is defined by a mylonitic zone. The formation includes an upper unit of quartzose arenite and cleaved mudstone turbidites (Figure 23) and a lower section of basaltic to Na-rich rhyolitic lavas (Donaldsons Well Volcanic Member). The upper unit is up to 500m thick. Clasts in the arenite are predominantly quartz, with minor feldspar and lithic grains including phyllite and felsic volcanic rocks. The Donaldsons Well Volcanic Member is dominantly aphyric with minor porphyritic textures. The volcanics are generally massive, but pillow lavas are present. Multi-element plots (not shown) indicate enrichment in LILE, but lack Nb anomalies, and have thus been inferred to have formed in a back-arc basin environment (Withnall & Lang, 1993).

Deformation and metamorphism

The Judea Formation is thought to have undergone three deformational events (Withnall, 1993). Metamorphic grade is greenschist, forming chlorite-epidote-sericite alteration within volcanic rocks and the development of a slaty cleavage in pelitic rocks.

The first event (D_s) resulted in abundant boudinage, local mesoscopic isoclinal folding, bedding-parallel faulting and cleavage, and mélange. D_1 caused mesoscopic folding with a pervasive axial planar cleavage. This event also affected overlying Silurian–Devonian rocks in the east. D_2 imparted a crenulation cleavage axial planar to moderately tight, mesoscopic folds. These predominantly trend north-north-east.

Age

The age of the Judea Formation is constrained by an Early Ordovician tetragraptoid graptolite in the turbidites (Jell, 1993), and the intrusion of the Middle Ordovician Saddington Tonalite.

Lucky Springs assemblage

The Lucky Springs assemblage (Henderson & others, 2011) includes the basal **Everetts Creek Volcanics** which grades into the **Carriers Well Formation**. Rock descriptions and geochemistry were provided by Withnall & Lang (1993)and Henderson & others (2011). The assemblage is in fault contact to the west with the Gray Creek Complex along the Gray Creek Fault (Figure 18).

The Everetts Creek Volcanics include mafic to intermediate, massive to locally amygdaloidal and pillowed lava flows or subvolcanic intrusives. The volcanics are moderately to strongly calc-alkaline, have positive LILE to HFSE ratios and strong negative Nb anomalies, indicative of a subduction-related volcanism (Withnall & Lang, 1993; Henderson & others, 2011). Volcaniclastic and minor chert and siltstone units are interbedded with the lavas.

The Carriers Well Formation predominantly contains sediments including chert, shale, volcaniclastic and quartzose sandstones, micritic and oolitic limestone (Figure 24a), and volcanic breccias. Limestone occurs commonly as discontinuous bodies. A minor volcanic component includes mafic to intermediate, rarely pillowed flows and/or sills (Figure 24b) and peperite. The setting is interpreted to be deep marine with strong input from mass flows with a volcanic source (Henderson & others, 2011).

Deformation and metamorphism

Deformation has resulted in the formation of steeply inclined and widespread mélange and stratal disruption (D_1). Later folding events are complex, but a rare open steeply plunging fold set is interpreted as D_2 (Henderson & others, 2011). The metamorphism was sub-greenschist facies.

Age

Coralline, conodont and trilobite assemblages within limestone of the Carriers Well Formation indicate Late Ordovician (Jell, 1993, Feist & Talent ,2000). Age spectra of detrital zircon from the Carriers Well Formation provide a maximum depositional age of 454 ± 13Ma (Henderson & others, 2011), in agreement with the fossils.

Intrusive units

The **Netherwood Tonalite**, as described by Withnall (1993), is composed of two small plutons (~5km^2) of greenish grey, fine- to medium-grained, and equigranular biotite-hornblende tonalite to quartz diorite. It is restricted to, and intrudes, the Donaldsons Well Volcanics of the Judea Formation (Figure 18). The plutons are relatively undeformed.

The **Saddington Tonalite**, as described by Withnall (1993), forms a single pluton, but occupies a much larger area than the Netherwood Tonalite (~20km^2). It intrudes

Figure 24. Outcrops of the Carriers Well Formation:
a) thin oolitic limestone beds and metasiltstone;
b) pillow lavas and volcaniclastic breccias

rocks of the Cambrian Gray Creek Complex (Figure 18). It is grey, medium-grained, equigranular hornblende tonalite, quartz diorite and diorite (Withnall, 1993). The unit is moderately foliated locally.

Geochemical analyses identify multiple phases of intrusives within the Saddington Tonalite, whilst the Netherwood Tonalite is generally more homogenous. Both units are metaluminous to marginally peraluminous. U–Pb dating of zircon within the Saddington Tonalite using LA-ICP-MS methods yielded a crystallisation age of 487.8 ± 5.8Ma (R Wormald, unpublished in Henderson & Withnall, 2013).

Western margin of the Hodgkinson Province

Ordovician rocks adjacent to the Palmerville Fault and the western margin of the Hodgkinson Province are considered correlatives of the Thomson Orogen (Figure 25; Fawckner, 1981; Bultitude & Donchak, 1992; Bultitude & others, 1993). They occur as three distinct elongate units dominated by sediments, with minor mafic volcanics, and are mapped as the Mulgrave Formation, Mountain Creek Conglomerate and Van

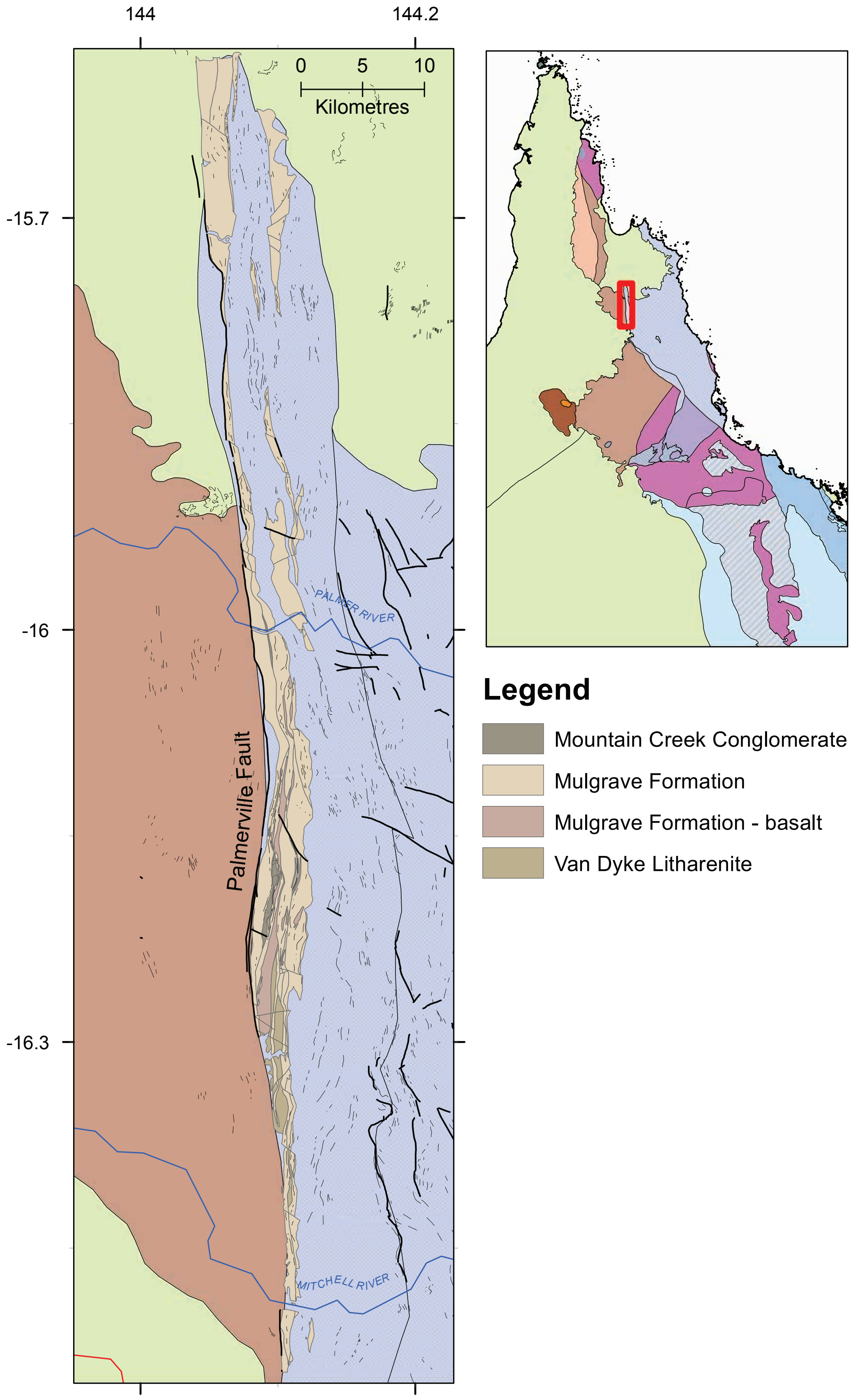


Figure 25. Outcropping components of the Thomson Orogen within the Hodgkinson Formation. Inset shows location relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

Dyke Litharenite. Deep-crustal seismic data indicate that these rocks may be extensive below the Hodgkinson Province (Henderson & Withnall, 2009; Korsch & others, 2012). The most comprehensive description of these units is by Bultitude & Donchak (1992) and much of the summary below is derived from that work.

Mulgrave Formation

The Mulgrave Formation crops out discontinuously as an elongate belt approximately 130km long (Figure 25). Its width ranges from about 100m to 4km, although the wider sections are the result of thrust fault repetition so its thickness is not known. In places (e.g. Palmer River area), the formation is structurally interlayered with the adjacent Chillagoe Formation of the Mossman Orogen.

The dominant rocks are fine-grained, quartz rich greywacke with subordinate chert, hematitic mudstone and metabasalt (Bultitude & others, 1997). Sedimentary beds range from centimetres to tens of meters thick, are predominantly rhythmically layered, and commonly contain partial Bouma sequences. The metabasalt is 20m to 2000m thick, fine-grained, massive, locally porphyritic, commonly pillowed and extensively altered. Marginal breccias and possible hyaloclastites are common.

The volcanics are basaltic with trace element contents transitional between MORB and arc-related environments (Vos & others, 2006). Bultitude & others (1997) suggested a deep marine depositional setting, with density currents forming the greywacke, and quieter periods forming the chert and mudstone units.

The Mulgrave Formation is considered Ordovician due to its lithological similarities with the Judea Formation (Bultitude & others, 1997). It is unconformably overlain by the Mountain Creek Conglomerate which contains clasts of the Mulgrave Formation.

Mountain Creek Conglomerate

The Mountain Creek Conglomerate crops out as generally small elongate lenses within the Mulgrave Formation (Figure 25). The largest lens is 7km long and 300m wide. The unit is dominated and characterised by massive, polymictic conglomerate, with minor arenite and limestone. The limestone forms the basal section, which has a maximum thickness of about 30m. It contains bioclasts, peloids, oncolites and ooids with minor siliciclastic components. Fossils suggest Late Ordovician (Richmondian; ~447 Ma) (Bultitude & others, 1997). The conglomerate is clast-supported with very well-rounded, and commonly imbricated and graded clasts. The matrix consists of coarse-grained feldspathic and lithofeldspathic arenite. Clasts include quartzite, quartz veined arenite, intermediate to felsic volcanics, minor granodiorite and limestone. A dacitic clast yielded a crystallisation age of 455 ± 5Ma, providing a maximum depositional age (Bultitude & others, 1997).

The environment of deposition for the Mountain Creek Conglomerate is shallow marine and during a period of eustatic trangressive change (Bultitude & others, 1997).

Van Dyke Litharenite

The Van Dyke Litharenite is a minor component occurring as two narrow (<1km) lenses up to 20km long within the Mulgrave Formation (Figure 25). The unit contains thin- to medium- rhythmically bedded arenite and mudstone with minor thick-bedded hematitic mudstone and chert, and rare conglomeratic feldspathic sandstone. Quartz-rich arenite is identical to equivalent rocks in the Mulgrave Formation. Dewatering structures and partial Bouma sequences suggest a deep marine environment fed by turbidity currents. Bultitude & others (1997) speculated two provenances for the arenite due to distinct differences in the clast types. One type probably had the same source as the Mulgrave Formation, and the other probably had the same source as the Mountain Creek Conglomerate. They are thus inferred to be of comparable age to the Mulgrave Formation and Mountain Creek Conglomerate.

THE IRON RANGE PROVINCE

The Iron Range Province is a ~150km by ~50km region along the eastern margin of Cape York Peninsula bounded to the west by the Proterozoic Savannah and Etheridge provinces (Figure 26). The northern boundary is unknown, but may extend into northern Cape York Peninsula and Torres Strait (Withnall & others, 2013). The eastern boundary is also unknown, and lies offshore. The province is considered a possible northerly extension of the Thomson Orogen due to comparable rocks and age constraints. Withnall & others (2013) considered the province to represent a shallow marine environment with minor magmatism, likely within a rifting regime.

Outcrop is poor in the Iron Range Province, occurring discontinuously over ~450km^2. The **Sefton Metamorphics** is the only unit identified (Willmott & others, 1973) although fourteen internal units, inferred to be up to 2000m thick were informally described by Teluk (1984). Rocks types include quartzite, quartz–hematite schist, magnetite quartzite, metagreywacke, argillite, phyllite, slate, phyllitic schist, quartz-muscovite schist, greenstone, recrystallised schistose limestone and other calc-silicate rocks (Trail & others, 1969; Teluk, 1984; Blewett & Knutson, 1997). Small interbeds of quartzofeldspathic pebble conglomerate exist in the metagreywacke. The greenstone in the north-western portion of the province includes metadolerite composed of sericitised plagioclase, augite, chlorite and minor quartz whereas elsewhere greenstones are composed of quartz, actinolite, epidote and cloudy plagioclase.

Deformation and metamorphism

The Sefton Metamorphics are generally of sub-greenschist to greenschist grade, but locally reach lower amphibolite grade (Blewett & others, 1997). Contact metamorphism is also apparent with andalusite-bearing rocks abutting Permian intrusives (Trail & others, 1969). Four deformation events are recorded with the first two (D_1 and D_2) being the strongest (Blewett & others, 1997; Withnall & others, 2013). D_1 developed isoclinal folds with associated axial planar foliation with an original east–west orientation and steep dip suggested. D_2 developed north-north-west orientated, upright, tight to isoclinal, mesoscopic to macroscopic folding and associated axial planar cleavage which often formed crenulations and a schistosity. This event is thought to have occurred at sub-greenschist facies conditions during the emplacement of the Silurian–Devonian Pama Igneous Association. D_3 and D_4 were weak events which produced minor folds and kinks.

Age

A sponge spicule and organic matter within recrystallised limestone in the Bolt Head area suggests a Paleozoic age (Trail & others, 1969). However, this broad age may not be regionally representative because the Bolt Head area comprises different rock types (e.g. limestone) and is considerably north of, and separated from, the main bodies of Sefton Metamorphics. U–Pb analysis of detrital zircon from a metaconglomerate within the Sefton Metamorphics further south yielded an imprecise maximum deposition age of ~1200Ma from 5 grains (Blewett & others, 1998). The youngest population ranged between 1062 ± 29Ma and 1232 ± 18Ma, leading the authors to the assumption that these zircons grew during a series of Grenvillian events (Blewett & others, 1998). This differs significantly from the adjacent rocks in the Savannah Province, which have crystallisation ages of > 1500Ma (Blewett & others, 1998). Additionally, prominent ages from the adjacent Yambo and Dargalong Inliers (~1580–1590Ma) do not appear in the Sefton Metamorphics detrital spectrum. Blewett & others (1998) suggested that the Cape River Metamorphics of the Thomson Orogen were the likely source of zircons for the Sefton Metamorphics of the Iron Range Province due to strong ~1200Ma peaks in both groups. T_{DM} ages for the Sefton Metamorphics range between 2226–2054Ma, whilst a single sample from the Cape River Metamorphics yielded a T_{DM} of 1927Ma (Blewett & others, 1998).

Intrusive units

Intrusive rocks of the Iron Range Province are associated with both the Silurian–Devonian Pama Igneous Association (dominantly in the south) and the late Carboniferous – early Permian Kennedy Igneous Association (dominantly in the north) (Figure 26) and are listed in Table 9. They form extensive outcrop known as the Cape York Peninsula Batholith that intrudes the Iron Range Province and adjacent Savannah and Etheridge Provinces.

Intrusive rocks of the Pama Igneous Association form part of the ~395Ma to ~410Ma Cape York Peninsula Batholith (Black & others, 1992) which extends for ~450km^2 south-south-east to the Yambo Inlier of the Etheridge Province (Champion & others, 2009). Their western extent is known to continue in the subsurface with a granite in a drillhole ~155km north-north-west of Coen yielding a U–Pb zircon (SHRIMP) age of 397 ± 2Ma (OZCHRON).

The Kintore Supersuite is the volumetrically dominant component of the Cape York Peninsula Batholith incorporating ~80% of the total outcrop (Knutson, 1997). The supersuite is S-type and mineralogical, textural and geochemical variations have allowed for the identification of 47 separate named units and some unnamed units

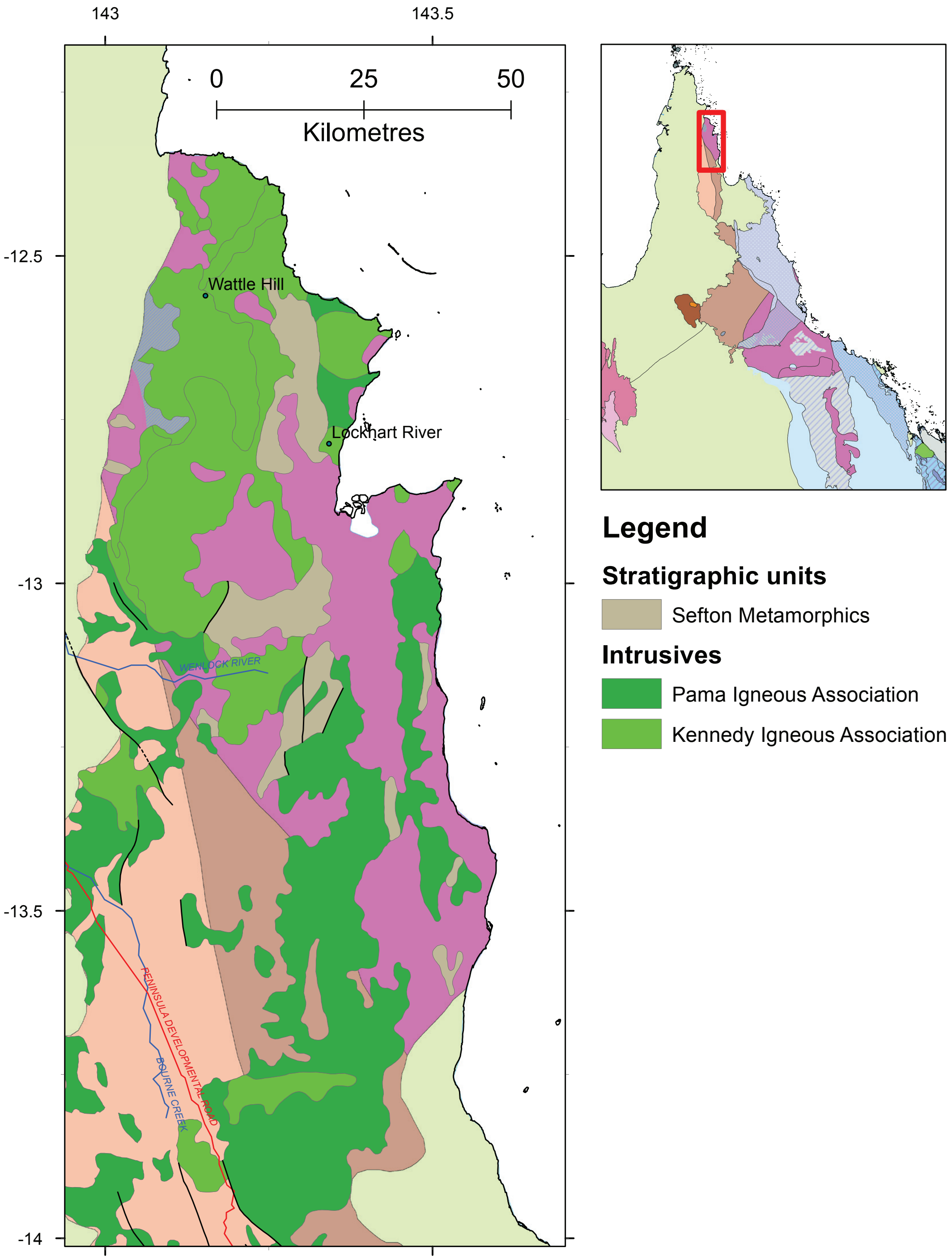


Figure 26. Outcropping components of the Iron Range Province. Inset shows location relative to other tectonic provinces of the Tasmanides and North Australian Craton (see Figure 5 for annotation of inset).

(Bultitude & Champion, 2013). Champion & Bultitude (2003) stated that these granites were geochemically similar to rocks in the Lachlan Fold Belt but Bultitude & Champion (2013) noted distinct differences in their Sr/Y ratios. The Kintore Supersuite has initial $\varepsilon Nd_{(407Ma)}$ values from –12.1 to –14.7 and depleted mantle model ages of 2009 to 2200Ma suggesting long crustal residence time (Knutson, 1997). Depleted mantle model ages from the Mesoproterozoic Coen Metamorphic Group are similar (2081–2288Ma), suggesting common source rocks (Knutson, 1997). The Flyspeck Supersuite includes 16 named units and some unnamed units. It is compositionally an I-type supersuite and ranges from diorite to monzogranite, with initial $\varepsilon Nd_{(407Ma)}$ values range from –11.6 to –12.6 and depleted mantle model ages from 1958 to 2088Ma (Knutson, 1997). An inherited zircon age of 1560Ma could possibly represent the age of the igneous source material (Knutson, 1997). The Blue Mountains Supersuite is also I-type and consists of two named units of granite to granodiorite. Initial $\varepsilon Nd_{(406Ma)}$ values range from –9.9 to –11.6 and depleted mantle model ages range from 1837 to 1965Ma (Knutson, 1997).

Intrusive and comagmatic extrusive rocks of the Kennedy Igneous Association occur in the northern part of the Cape York Peninsula Batholith. Similar rocks (Badu Granite and Torres Strait Volcanic Group) occur further north into the Torres Strait and this has lead to the assumption that the province continues subsurface to the north (Withnall & others, 2013). The Weymouth Supersuite occurs within the Iron Range Province and includes 5 named units with minor unnamed units (Champion & Bultitude, 2013). The Janet Ranges Volcanic Group, which consists of rhyolite welded tuff, breccia, rhyolite and dacitic ignimbrite, and rhyolite and dacite lava, is thought to be a comagmatic extrusive equivalent of the Weymouth Supersuite (Willmott & others, 1973; Knutson, 1997). Initial $\varepsilon Nd_{(285Ma)}$ values range from –5.0 to –7.8 and depleted mantle model ages range from 1372Ma in the north to 1637Ma in the south (Knutson, 1997).

Table 9. Intrusive supersuites of the Iron Range Province, modified from Blewett & others (1997)

Suite	Lithology	Geochemical characteristics	Age
Early Devonian (Pama Igneous Association)			
Flyspeck Supersuite	Biotite monzogranite to granodiorite, biotite/pyroxene-hornblende diorite, biotite and hornblende-biotite leucogranite.	I-type, reduced, metaluminous to peraluminous, medium- to ultra high-K	406 ± 10Ma and 398 ± 10Ma (U-Pb zircon SHRIMP; Black & others, 1992)
Blue Mountains Supersuite	Equigranular to moderately porphyritic hornblende-biotite to biotite-hornblende granite, biotite microgranite, biotite-muscovite granite, hornblende-biotite granodiorite; coarsely porphyritic biotite granite	I-type, weakly oxidised to reduced, mainly peraluminous, medium- to ultra high-K	405 ± 13Ma and 409 ± 7Ma (U-Pb zircon SHRIMP; Black & others, 1992)
Kintore Supersuite	Variably porphyritic muscovite-biotite granite, biotite-muscovite granite and granodiorite, (biotite-) muscovite leucogranite, pegmatite, aplite.	S-type, reduced, peraluminous, medium- to high K.	408 ± 10Ma and 405 ± 9Ma (U-Pb zircon SHRIMP; Black & others, 1992)
Early Permian (Kennedy Igneous Association)			
Weymouth Supersuite	Hornblende-biotite and biotite granodiorite, biotite/pyroxene-hornblende diorite, biotite and hornblende-biotite leucogranite.	I-type, weakly oxidised to reduced.	287 ± 8Ma and 284 ± 4Ma (U-Pb zircon SHRIMP; Black & others, 1992)
Unassigned rocks	Pyroxene/biotite-hornblende diorite, porphyritic biotite microgranite, sparsely porphyritic rhyolite.	I-type	Unknown

UNDERCOVER GEOLOGY

The overwhelming majority of the interpreted extent of the Thomson Orogen is covered by Devonian to Cretaceous basins (Figure 2). These include the Devonian Adavale Basin, Warrabin Trough and Barrolka Trough, the Late Devonian to early Carboniferous Burdekin Basin and Drummond Basin, the mid-Carboniferous to Middle Triassic Galilee Basin, the early Permian to Middle Triassic Cooper Basin and the Jurassic to Cretaceous Eromanga Basin and Surat Basin. The only information regarding the Thomson Orogen in this area comes from commercial petroleum exploration wells and State and Federal stratigraphic drilling. Fortunately, the Bureau of Mineral Resources (now Geoscience Australia) subsidised stratigraphic drilling to basement in the 1950s and 1960s (Condon, 1965). However, drill holes are unevenly distributed, with the petroliferous parts of the Cooper Basin, Surat Basin, and parts of the Eromanga Basin being the most densely penetrated.

The first major synthesis of the undercover Thomson Orogen was completed by Murray (1994) who investigated basal lithologies from drill core in 233 commercial petroleum exploration wells and 20 stratigraphic wells. This has recently been augmented by a database compilation (Brown & others, 2012) which includes lithological and depth to basement information for 1398 drill holes that penetrate both the Thomson Orogen and Roma Shelf. Of these only 221 contain core, the remaining being rock chips (Figure 27a,b).

Depth to the undercover Thomson Orogen surface (i.e. our definition of basement) differs significantly, with a maximum depth of ~4000m beneath the Cooper Basin in far south-west Queensland (Figure 27a; Brown & others, 2012). Rock types encountered (Figure 27b) were divided into two groups by Murray (1994): the Nebine Ridge rocks and the south-western and northern Thomson Orogen rocks.

THE NEBINE RIDGE

The Nebine Ridge is defined by a broad gravity and basement high extending south-south-west from the exposed Anakie Inlier (Figure 27a). Although predominantly subsurface, a small body of ultramafic to mafic rocks 130km north of Mitchell (the Eddystone Inlier; Figure 27a) may represent a rare area of outcrop.

The subsurface rocks, as described by Murray (1994), are intersected in seven drill holes and comprise muscovite phyllite, chlorite-biotite-muscovite phyllite, and garnet-muscovite-biotite schist. Primary sedimentary layering is rarely preserved. Three deformational events are recorded within the phyllite. In the southernmost hole (NAI Whyenbirra 1) a steeply dipping, bedding-parallel, foliation defined by muscovite (S_1) is cut by a biotite-defined crenulation cleavage at a moderate angle (possibly S_2). D_2 is identified elsewhere as a steeply dipping crenulation cleavage, which has been gently folded by small scale open folds (F_3). Metamorphic grade ranges from lower greenschist to amphibolite. In NA1 Whyenbirra 1, peak metamorphism is associated with D_2. Murray (1986) obtained a K–Ar biotite age of 416 ± 2Ma from AOP Alba 1.

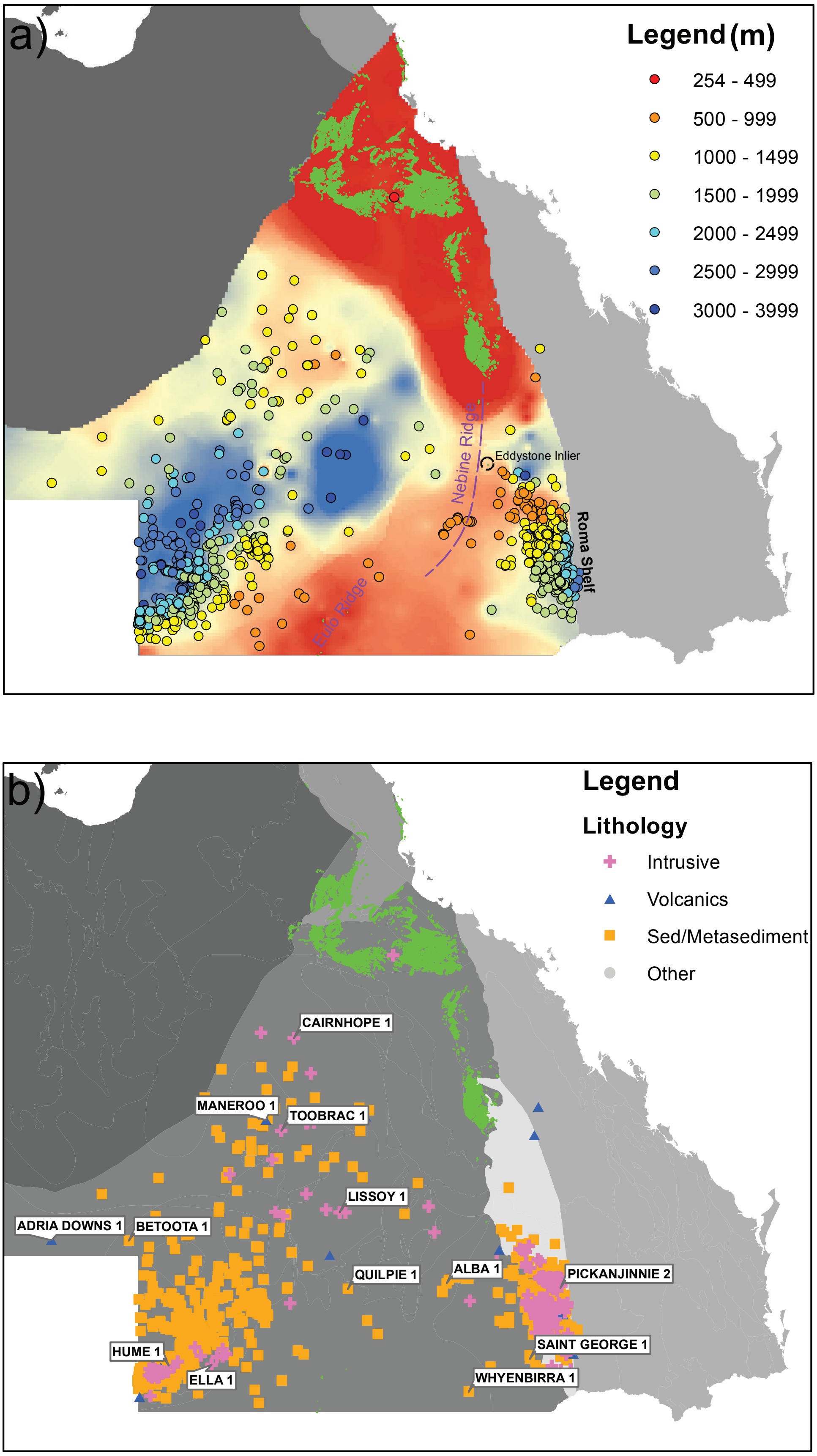


Figure 27. Subsurface geology of the Thomson Orogen (modified from Brown & others, 2012). Green represents outcropping geology: a) depth to top of basement (i.e. top of Thomson Orogen) in Queensland. Circles represent drill holes and depth of basement, and b) lithology of undercover basement intersections.

Targeting a different structural fabric, Wood (2006) obtained a similar muscovite Ar-Ar plateau age of 412.9 ± 1.3Ma from the same core. These are interpreted as a regional metamorphic cooling age which is significantly younger than metamorphism in the Anakie Inlier (Cambrian to Ordovician; Withnall & others 1995; 1996).

A possible outcropping component of the Nebine Ridge, referred to as the **Eddystone Inlier**, crops out for over 1000m with an east–west trend in the core of the north–south trending Maranoa Anticline. The outcrop is coincident with a distinct circular magnetic high. Exon (1968) described the rocks as diallage-rich gabbro and pyroxenite, which is locally sheared and altered to tremolite and chlorite. Derrick (1988) described the unit as containing a southern zone of tremolite schist and chlorite-tremolite serpentinite, and a northern zone of diallage gabbro and anorthosite characterised by phenocrystic clinopyroxene. Petrographic analysis suggests the serpentinites are tectonised pyroxenites, dunite(?) and peridotite occurring with coarse-grained gabbro and anorthosite (Derrick, 1988). Very limited geochemical assaying shows that the rocks are enriched in Ni (up to 3400ppm) and Cr (up to 840ppm) (Martin, 1990).

The schistosity is poorly developed, strikes east–west and dips shallowly to the south (Derrick, 1988). It is commonly refolded and contains a late north-north-east trending fracture system suggesting multiple deformational events (Derrick, 1988). These fractures contain fine-grained magnetite, which along with the growth of magnetite porphyroblasts within the serpentinite are probably the main reason for the strong magnetic response of the unit. The gabbroic rocks are generally less deformed and were suggested to be younger intrusives by Derrick (1988).

The only age constraint on the Eddystone Inlier is an unpublished K–Ar date which suggests an early Paleozoic age (Webb, *in* Exon, 1968).

SOUTH-WESTERN AND NORTHERN THOMSON OROGEN

West of the Nebine Ridge, Thomson Orogen rocks observed in drill cores are grouped on the basis of the remarkably uniform character of metasediments (Murray, 1994). Rocks include low metamorphic grade siliciclastic sediments, calcareous sediments, conglomeratic red-beds and volcanics.

Sediments

The dominant rocks intersected in drill cores throughout the Thomson Orogen are steeply dipping siliciclastic metasediments. In general they are interbedded, fine-grained, pale grey, quartzofeldspathic sandstone, grey siltstone and laminated dark grey to black argillite. In thin section they are quartz-rich of inferred plutonic/metamorphic provenance, and include both plagioclase and K feldspar. Lithic clasts include micaceous and siliceous metasediments, and minor, possible volcanic fragments. Minor and accessory components include muscovite, biotite, tourmaline, apatite, zircon and garnet. The calcareous sediments include interbedded limestone and siliciclastics, and quartzose sandstone and siltstone with abundant calcite (predominantly as recrystallised calcareous matrix). Red-bed sequences also occur in the Thomson Orogen drill cores. DIO Betoota 1 for example contains unique conglomeratic red-beds which are steeply dipping (50–70°), and rich in fine-grained, tabular and slightly imbricated sedimentary clasts. Minor quartz clasts are also present and many clasts have been sheared and compacted. Minor recrystallisation has occurred, particularly within the calcareous matrix.

These metasediments display a cleavage parallel to subparallel to bedding, but this could be depositional bedding-plane fissility rather than of deformational origin (Murray, 1994). Metamorphic grade is generally within the sub-greenschist facies, but hornfelsing occurs locally (e.g. DIO Hume 1). Graded bedding in GSQ Quilpie 1 suggests that at least some of the metasediments are overturned (Murray, 1994).

Depositional age constraints for the metasediments are limited (Table 7), and do not include direct modern geochronological techniques (e.g. U–Pb SHRIMP of detrital zircon). The most reliable minimum age constraint is from Draper (2006) who suggested that deposition and deformation occurred prior to emplacement of rhyolite at 472 ± 2.7Ma in GSQ Maneroo 1. Previous K–Ar and Rb-Sr ages range between 416–545Ma (Table 10).

Volcanics

Dominantly felsic volcanics are intersected in a few scattered Thomson Orogen drill holes (Figure 27). In south-western Queensland, altered felsic ignimbrite in DIO Adria Downs 1 contains elongate clasts interpreted as compacted pumice fragments dipping at ~60°. In thin section the ignimbrite is microphenocrystic (probably feldspar), and strongly altered to quartz, sericite, chlorite and clay minerals. U–Pb SHRIMP dating of zircon yielded a crystallisation age of 510 ± 2.8Ma (Draper, 2006). This age overlaps with predominantly felsic volcanism recorded in the Mooracoochie Volcanics of the Warburton Basin (Gatehouse, 1986; PIRSA, 2007).

Draper (2006) inferred an Ordovician volcanic province in the north-eastern undercover Thomson Orogen. This included a brecciated crystal tuff in PPC Carlow 1 dated at 483.6 ± 5.9Ma (U–Pb zircon; Draper, 2006), basalt in PPC Gumbardo 1 dated at 489 ± 50Ma (K–Ar pyroxene; Galloway, 1970), porphyritic rhyolite in GSQ Maneroo 1 (472 ± 2.7Ma; Draper, 2006) and rhyolite in BEA Coreena 1 (477.8 ± 2.6Ma; Draper, 2006). In GSQ Maneroo 1, the porphyritic rhyolite unconformably overlies low grade sedimentary rocks of the Thomson Orogen previously described by Murray (1994) providing a key constraint on sedimentation age.

Other felsic volcanic intersections throughout the Thomson Orogen area are younger, being either basal to the Adavale Basin (Gumbardo Formation) (e.g. PPC Gumbardo 1 – 401.8 ± 2.1Ma; PPC Carlow 1: 408.3 ± 2.4Ma) or of poorly understood relationships (e.g. rhyolitic ignimbrite in AAE Towerhill 1 – 385.0 ± 4.6Ma) (Draper, 2006).

Table 10. Age constraints for metasediments, volcanics and granites of the undercover Thomson Orogen

Drillhole	Lithology	Method	Age	Reference
Metasediments				
AOP Alba 1	Garnet-biotite schist	K–Ar biotite	416 ± 2Ma	Murray (1986)
PPC Buckabie 1	Mica-rich phyllite	K–Ar whole rock	425 ± 25Ma	Bennett & others (1975)
AAP Fermoy 1	Muscovite phyllite	K–Ar whole rock	482Ma and 540Ma	Australian Aquitaine Petroleum PTY. LTD, (1964)
		Rb-Sr whole rock	527Ma and 545Ma	Australian Aquitaine Petroleum PTY. LTD, (1964)
	Phyllite	K–Ar whole rock	541 ± 14Ma	Harding (1969)
		Rb-Sr whole rock	536 ± 22	Harding (1969)
FPC Galway 1	Muscovite phyllite	K–Ar whole rock	488 ± 15Ma	Bennett & others (1975)
Volcanics				
GSQManeroo 1	Porphyritic rhyolite	U-Pb zircon SHRIMP	472.9 ± 2.7Ma	Draper (2006)
BEA Coreena 1	Rhyolite	U-Pb zircon SHRIMP	477.8 ± 2.6Ma	Draper (2006)
PPC Carlow 1	Brecciated crystal tuff	U-Pb zircon SHRIMP	483.6 ± 5.9Ma	Draper (2006)
PPC Gumbardo 1	Mafic volcanics	K–Ar pyroxene	489 ± 50Ma	Phillips-Sunray (1963)
DIO Adria Downs 1	Rhyolitic ignimbrite	U-Pb zircon SHRIMP	510.0 ± 2.8Ma	Draper (2006)
Intrusives				
DIO Ella 1	Granite	K–Ar muscovite	408 ± 2Ma	Moore (1987)
		U-Pb zircon SHRIMP	428.3 ± 5.2Ma	Draper (2006)
PPC Etonvale 1	Granite	Rb-Sr on total rock and feldspar concentrate	420Ma	Galloway (1970)
LOL LOL 1 (Cleeve)	Granite	K–Ar biotite	434 ± 9Ma	Webb & McDougall (1968)
TEA Roseneath 1	Granite	K–Ar muscovite	405 ± 2Ma	Murray (1986)
AMX Toobrac 1	Granite	K–Ar muscovite	446 ± 2Ma	Schmedje & Forder (1986)
		U-Pb zircon SHRIMP	469.4 ± 7.7Ma	Draper (2006)

Intrusive units

Intersections of intrusive rocks within the undercover Thomson Orogen occur throughout the entire region, but are concentrated in the south-west (Figure 27b; Murray, 1994; Brown & others, 2012). Drilling density is high in this area and intrusive intersections occur in clusters (e.g. in the area around DIO Ella 1). Elsewhere, intrusive intersections appear more scattered, but this may simply relate to drilling density. Intrusive rocks are intersected below the Adavale Basin (e.g. PPC Lissoy 1), near Longreach (e.g. LOL (Cleeve 1)), and further north (e.g. BRP Cairnhope 1). The intrusive rocks are mostly biotite-muscovite granites. Only two U–Pb SHRIMP zircon dates are published (DIO Ella 1 — 428.3 ± 5.2Ma; AMX

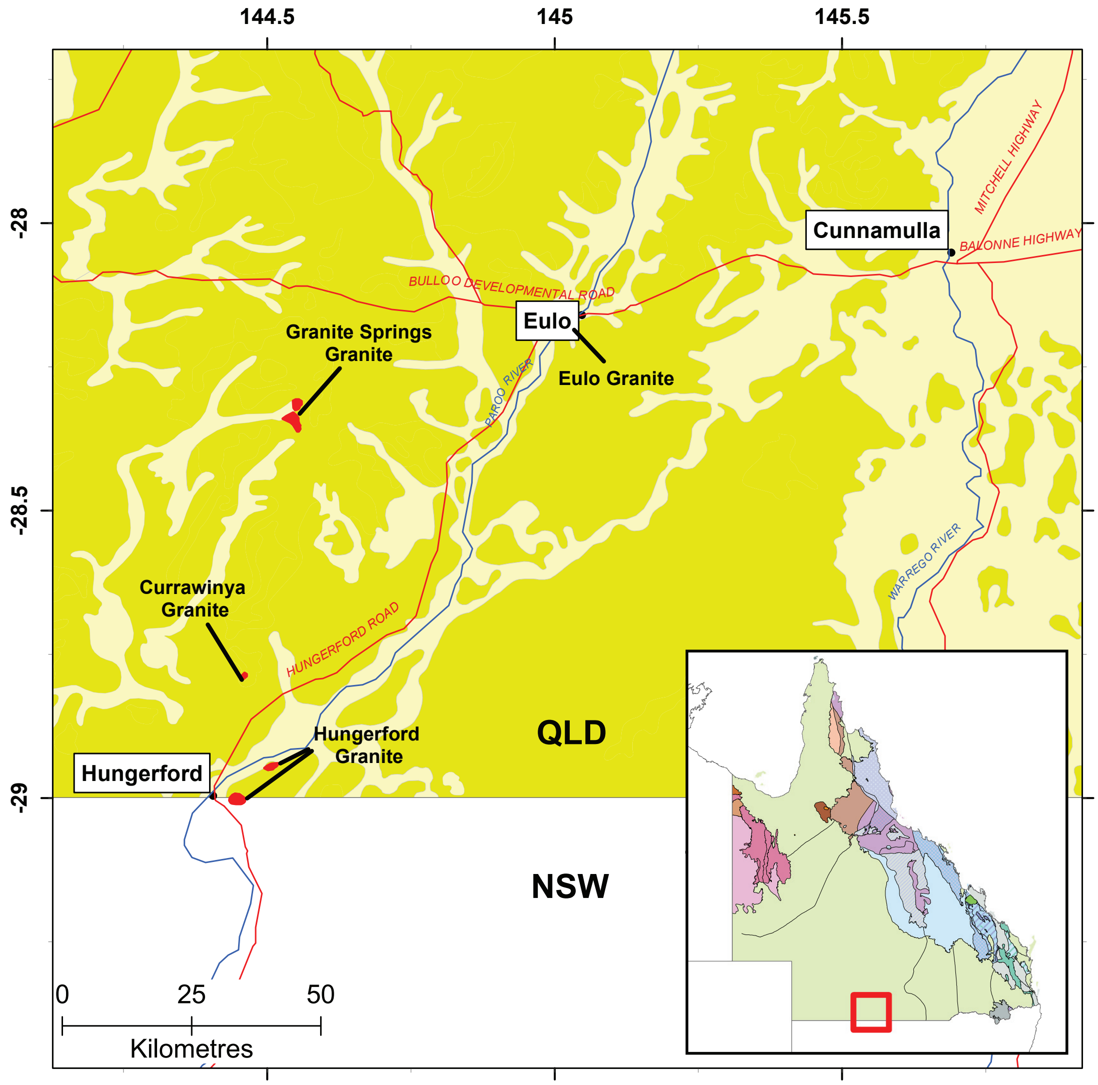


Figure 28. Outcropping granites of the Eulo Ridge. Yellow represents Mesozoic–Cenozoic cover sequence (modified from Senior & others 1968)

Toobrac 1 — 469.4 ± 7.7Ma — Draper, 2006) and these are older than previously reported K–Ar dates (Table 7).

Rare outcrop of intrusive rocks near Eulo on the Queensland – New South Wales border (Figure 28), lies on the broad north-north-east positive gravity anomaly known as the Eulo Ridge (Figure 27a). They have been described in outcrop by Bultitude & Cross (2013), in the subsurface by Senior (1971), and in New South Wales by Scheibner & Basden (1996). In Queensland they outcrop as the Currawinya (Figure 29a), Eulo, Hungerford and Granite Springs granites (Figure 29b). They are porphyritic, muscovite ± biotite monzogranite commonly containing schistose and gneissic xenoliths. They are deformed and recrystallised. Recent U–Pb zircon SHRIMP dating yielded the following crystallisation ages (Bultitude & Cross, 2013):

Currawinya Granite:	381.5 ± 2.4Ma
Eulo Granite:	385.0 ±2.5Ma
Hungerford Granite:	419.1 ± 2.5Ma
Granite Springs Granite:	456.3 ± 3.9Ma

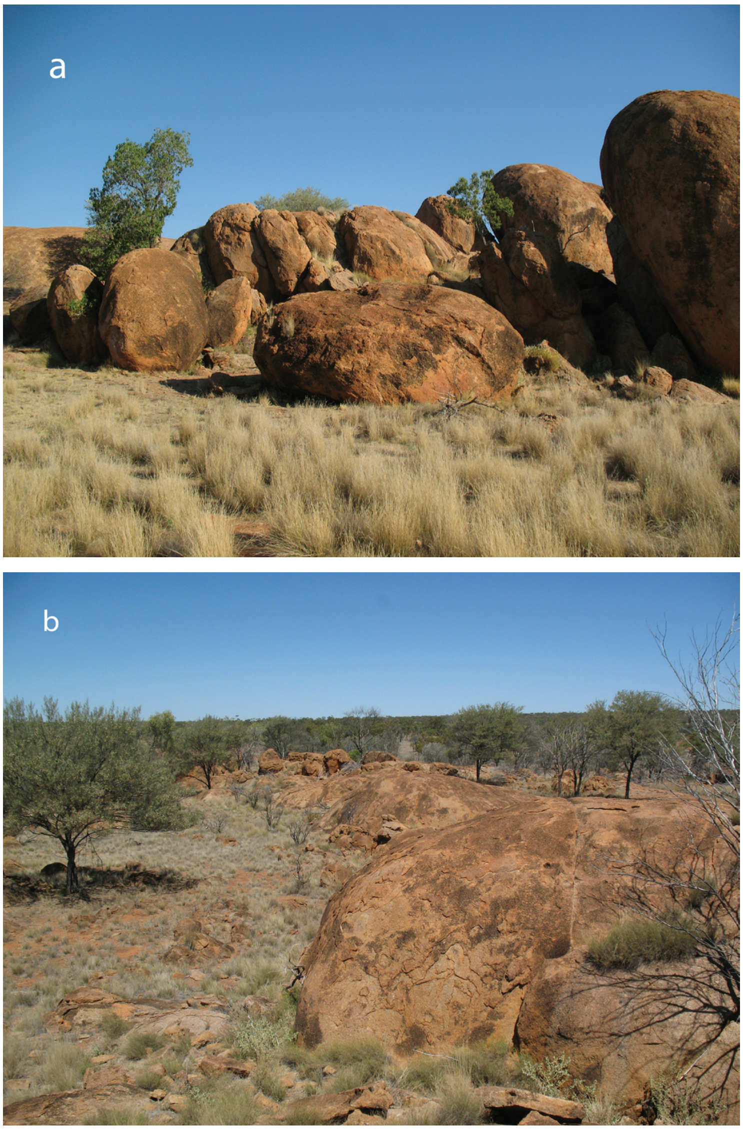


Figure 29. Outcrops of the Currawinya Granite (a) in the Currawinya National Park and the Granite Springs Granite (b) on Werewilka Station.

THE WARBURTON BASIN

The Warburton Basin is an entirely concealed early Paleozoic basin predominantly occurring in north-eastern South Australia, but extending into the Northern Territory, Queensland and New South Wales (Gatehouse, 1986). The basin is within the sixth episode of deposition of the Centralian Superbasin that received sediments throughout central Australia between the Neoproterozoic to Devonian (Walter & others, 1995; Maidment & others, 2007). Gatehouse (1986) suggested that the basal volcanics of the Warburton Basin (the Mooracoochie Volcanics) were part of the Gidgealpa Volcanic Arc, a northerly extension of the Mount Wright Arc in New South Wales. Correlatives of the Warburton Basin are located in the Amadeus Basin (Northern Territory), Canning Basin (Western Australia), Arrowie Basin (South Australia) and Stansbury Basin (South Australia, New South Wales, Victoria) (Jago & others, 2002; Maidment & others, 2007). Murray (1994) suggested that rocks of the Thomson Orogen in south-west Queensland may correlate with the Dullingari Group of the Warburton Basin.

The lithology and structure of the basin are determined from numerous oil and gas well intercepts, targeting the overlying Cooper and Eromanga basins (Gatehouse, 1986), and seismic data (Sun, 1997a). The south-west, west and north-east boundaries are defined by the Muloorinna Ridge, Musgrave Block and Arunta Block respectively (Figure 30). However the eastern margin, with the largely non-calcareous Thomson Orogen, remains unknown. Most recently it has been loosely based on the distribution of calcareous rocks in basement drill holes (DIO Innamincka 3, DIO Jackson 1, FPN Arrabury 1, DIO Arrabury 2, DIO Alkina 1 and DIO Orientos North 1) in south-west Queensland (Figure 2). The Warburton Basin is divided into eastern and western subgroups due to the north-north-east trending Birdsville Track Ridge basement high (Figure 30). Drill hole intercepts are predominantly in the eastern Warburton Basin, where it is overlain by the Cooper Basin and have provided invaluable information sources for the subsurface rocks (Figure 31).

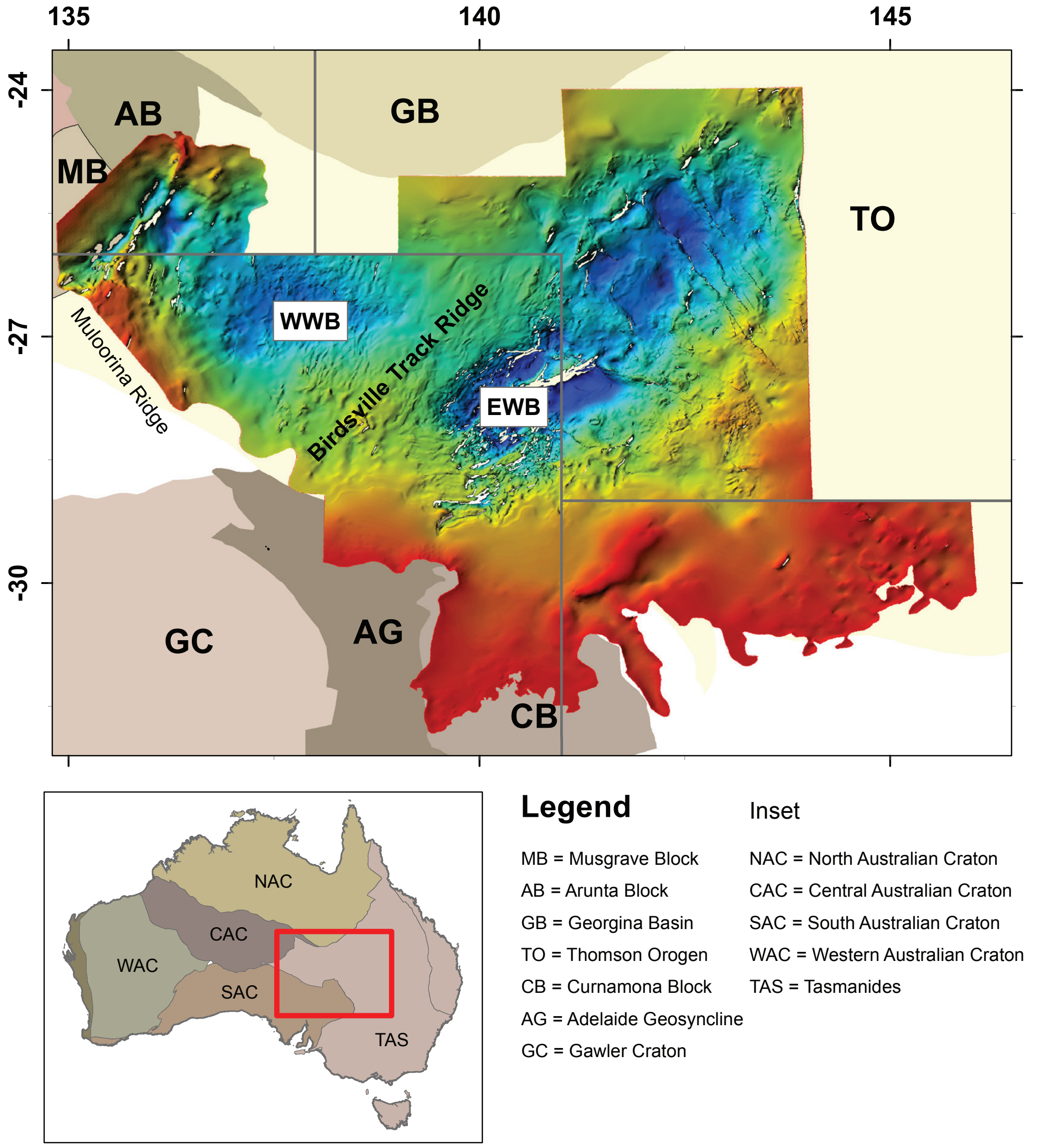


Figure 30. Depth to the Warburton Basin and surrounding tectonic blocks. Depth image is from NGMA, 1998. WWB = Western Warburton Basin, EWB = Eastern Warburton Basin. Tectonic provinces in figure and inset are from Borrisova & Kilgour (1998).

Basement to the Warburton Basin is still speculative. Gatehouse (1986) suggested quartz muscovite phyllite within the Fortville 3 (South Australia) and Naryilco 1 (Queensland) drillholes is part of the Precambrian Willyama Supergroup. Gravestock & Gatehouse (1995) suggested metasediments within the Daralingie 1, Mulga 1, Gurra 1, Fortville 3 and Paxton 1 drillholes of South Australia were Paleoproterozoic to Neoproterozoic basement. The Warburton Basin sediments are intruded by the Big Lake Suite of late Carboniferous to Early Permian granitoids (Gatehouse & others, 1995).

Four depositional sequences are identified within the Warburton Basin spanning from the early Cambrian to the Middle Ordovician (Figure 32). However, numerous units at the top of the succession are not assigned to a depositional sequence. Sequences Є1–

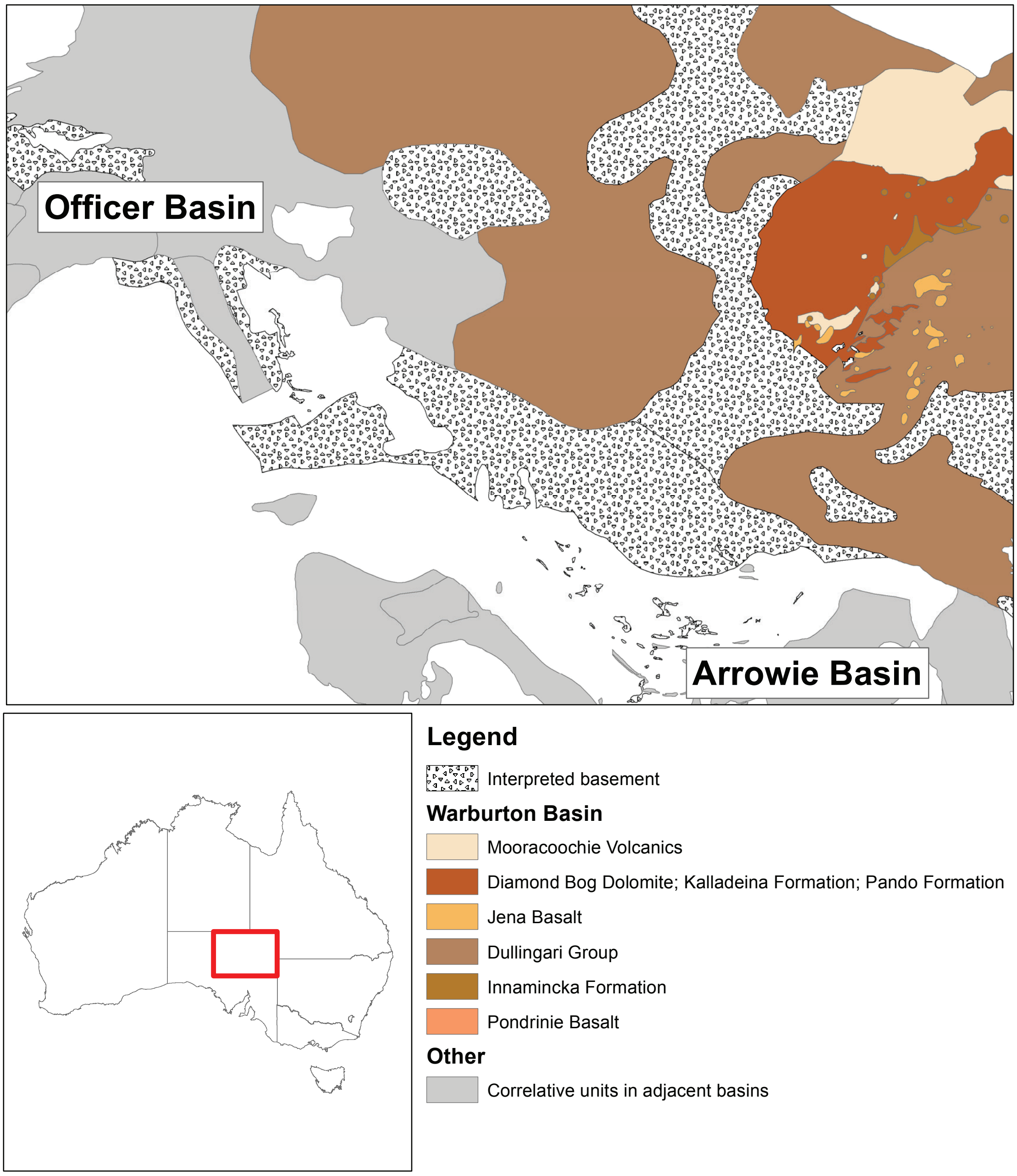


Figure 31. Geology of the top of basement (Warburton Basin and similar basins) in South Australia. Modified from PIRSA (2006).

Є3 are correlated with similar depositional units in the nearby Arrowie and Stansburg basins, whereas Є4 and the unassigned units are unique to the Warburton Basin. Table 11 summarises the available information on the basin from numerous sources (Gatehouse, 1986; Gravestock & Gatehouse, 1995; Gatehouse & others, 1995; Sun, 1996; Sun & Gravestock, 2001; PIRSA, 2007; Radke, 2009). Units are predominantly flat lying with minor perturbations due to folding and faulting preceding and during the deposition of the overlying Cooper Basin (Sun, 1997a).

The first depositional sequence (**Є1**) includes subaerial to subaqueous dacite to rhyodacite lava flows, ignimbrite, and tuffs of the **Mooracoochie Volcanics**. Lava flows are typically flow-foliated, felsic (Figure 33) and porphyritic with phenocrystic feldspar ± quartz + pyroxene in a glassy to trachytic groundmass (Sun, 1996). Syn-volcanic sediments are also common near the top of the sequence with hyaloclastic tuffs, carbonates, epiclastic conglomerates and sandstones (Sun & Gravestock, 2001). A continental rift setting is suggested (Sun, 1996) based on volcanic and sedimentary facies and within-plate geochemical affinities.

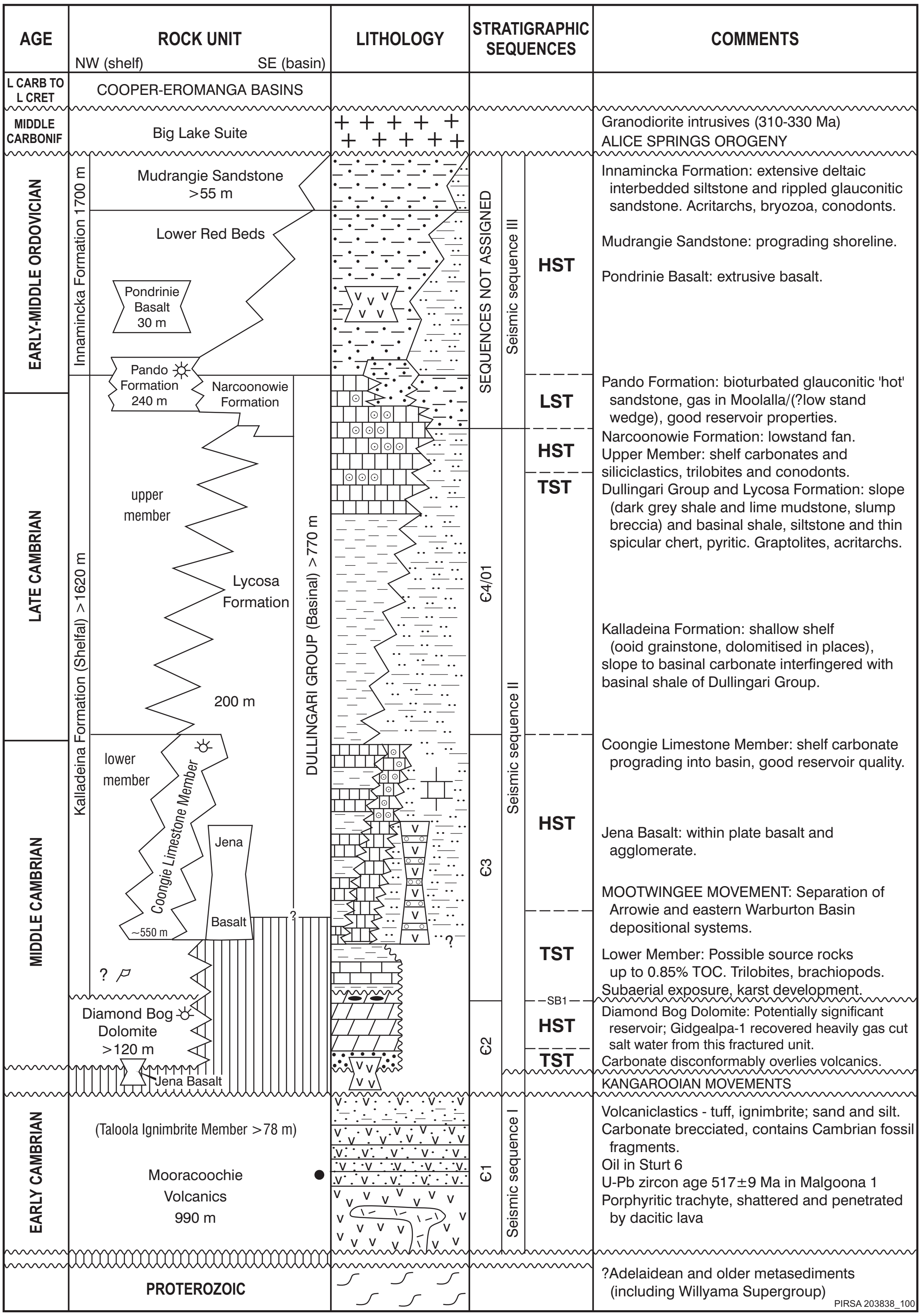
The age of the Mooracoochie Volcanics is constrained by a U–Pb SHRIMP zircon date of 517 ± 9Ma (PIRSA, 2007), but the base of the unit has not been penetrated. This age is comparable with the Mount Wright Arc (~510Ma; Greenfield & others, 2011) in New South Wales and felsic volcanics in DIO Adria Downs 1 (510.0 ± 2.8Ma; Draper, 2006) in Queensland.

At the top of this sequence, the **Taloola Ignimbrite Member** reaches a maximum thickness of 78m (Radke, 2009), and is characterised by coarse-grained, crystal- and shard-rich ignimbrite with euhedral phenocrysts of quartz, alkali feldspar, pyroxene and biotite (Sun & Gravestock, 2001). No age constraints are available.

The second depositional sequence (**Є2**) reaches a maximum thickness of 120m and only includes one unit; the **Diamond Bog Dolomite (Figure 32)**. It is a vuggy, fractured dolomite, with rare granules and pebbles of felsic tuff. Sun & Gravestock (2001) suggested that secondary dolomitisation and karstification have created the vuggy texture and suggested a limestone protolith that may include wackestone (Carroll, 1990) and ooid grainstone (Gravestock & Gatehouse, 1995). Former oncoids, intraclasts, fragments of trilobites, echinoderms and calcified cyanobacteria are also present (Sun, 1996; 1997b).

The age of this unit is constrained by the underlying middle Cambrian Mooracoochie Volcanics and overlying middle Cambrian to Early Ordovician Kalladeina Formation.

The third depositional sequence (**Є3**) includes the lower part of the **Kalladeina Formation** (Figure 32; Sun & Gravestock, 2001) which includes the **Coongie Limestone Member** and the **Jena Basalt**. Rocks are carbonate-dominated and include bioclastic wackestone, packstone, grainstone, dolomitic limestone, siltstone and shale, and shale/lime interbeds which are indicative of a broad shelf to basin depositional system (Sun, 1996). The Coongie Limestone Member includes a thick



Granodiorite intrusives (310-330 Ma)
ALICE SPRINGS OROGENY

Innamincka Formation: extensive deltaic interbedded siltstone and rippled glauconitic sandstone. Acritarchs, bryozoa, conodonts.

Mudrangie Sandstone: prograding shoreline.

Pondrinie Basalt: extrusive basalt.

Pando Formation: bioturbated glauconitic 'hot' sandstone, gas in Moolalla/(?low stand wedge), good reservoir properties.
Narcoonowie Formation: lowstand fan.
Upper Member: shelf carbonates and siliciclastics, trilobites and conodonts.
Dullingari Group and Lycosa Formation: slope (dark grey shale and lime mudstone, slump breccia) and basinal shale, siltstone and thin spicular chert, pyritic. Graptolites, acritarchs.

Kalladeina Formation: shallow shelf (ooid grainstone, dolomitised in places), slope to basinal carbonate interfingered with basinal shale of Dullingari Group.

Coongie Limestone Member: shelf carbonate prograding into basin, good reservoir quality.

Jena Basalt: within plate basalt and agglomerate.

MOOTWINGEE MOVEMENT: Separation of Arrowie and eastern Warburton Basin depositional systems.

Lower Member: Possible source rocks up to 0.85% TOC. Trilobites, brachiopods.
Subaerial exposure, karst development.

Diamond Bog Dolomite: Potentially significant reservoir; Gidgealpa-1 recovered heavily gas cut salt water from this fractured unit.
Carbonate disconformably overlies volcanics.

KANGAROOIAN MOVEMENTS

Volcaniclastics - tuff, ignimbrite; sand and silt.
Carbonate brecciated, contains Cambrian fossil fragments.
Oil in Sturt 6
U-Pb zircon age 517±9 Ma in Malgoona 1
Porphyritic trachyte, shattered and penetrated by dacitic lava

?Adelaidean and older metasediments (including Willyama Supergroup)

Figure 32. Stratigraphy of the Warburton Basin from PIRSA (2007)

limestone and dolomite succession interpreted as a peritidal carbonate deposit (Sun, 1997b). Trilobites with the unit suggest Middle to Late Cambrian (Sun, 1996).

The subaerial to subaqueous Jena Basalt (Boucher, 1991) has three interbedded facies (Sun, 1996; Sun & Gravestock, 2001): 1) a massive, fine-grained amygdaloidal basalt with densely packed plagioclase laths, 2) a basaltic hyaloclastite or brecciated lava which is extensively chloritised and intercalated with deep-water limestone and, 3) a porphyritic basalt which has plagioclase phenocrysts in a groundmass of strongly flow-aligned plagioclase microlites. Geochemical analysis of five samples indicates the lavas are alkaline basalts, distinct from the Mooracoochie Volcanics (Figure 33). The Jena Basalt is predominantly within the Kalladeina Formation, but a minor basalt with similar geochemistry was intersected overlying the Mooracoochie Volcanics and underlying the Diamond Bog Dolomite. This means that the basalt was erupted episodically from the early Middle Cambrian until the Late Cambrian (Sun, 1996).

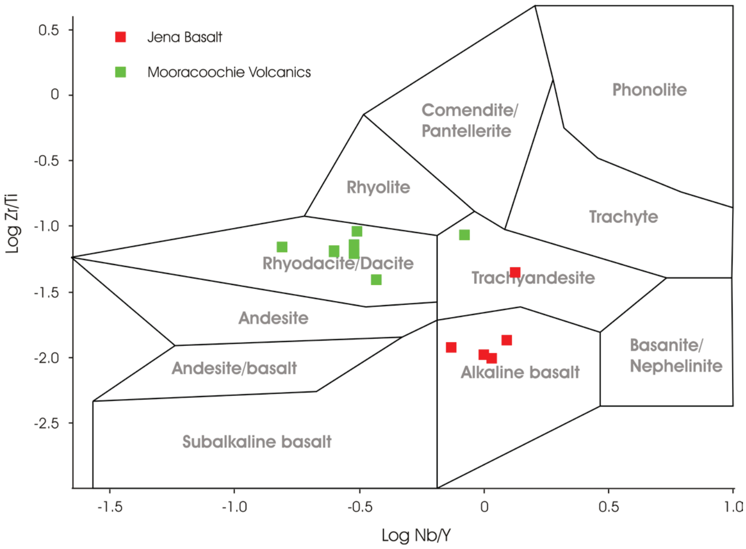


Figure 33. Geochemical classification diagram (Winchester & Floyd, 1977) of the igneous rocks in the Warburton Basin, South Australia. Note the alkaline nature of the Jena Basalt in comparison to the Mooracoochie Volcanics. Data from Gatehouse (1986) and Sun (1996).

The fourth depositional sequence (**Є4**) includes the upper Kalladeina Formation and the Lycosa Formation of the lower Dullingari Group (Sun & Gravestock, 2001). The Dullingari Group predominates in the south-east of the basin, but Sun (1996) suggested that it could be a lateral equivalent of the Kalladeina Formation.

The upper Kalladeina Formation (Sun & Gravestock, 2001) marks the begging of the **Є4**. It differs from the lower part by being siliciclastic-dominated including siltstone, shale and mudstone, with interbedded shoal-water carbonates and sandy carbonates (Sun & Gravestock, 2001). They are interpreted to be mainly storm-dominated shelf deposits (Sun, 1996). The fossil record within the unit is rich, with interpreted ages of middle to late Cambrian (Sun, 1996).

The Lycosa Formation includes pyritic mudstone and shale interlaminated with starved-ripple siltstone and fine-grained sandstone inferred to represent a distal starved basinal turbidite (Sun & Gravestock, 2001).

Subsequent tectonism has resulted in steep dips, folding dissolution seams, quartz veining and sulphide mineralisation.

At the top of the Dullingari Group, overlying the Lycosa Formation is thinly bedded sandstone, siltstone and shale with minor pebbly sandstone or sandy breccia of the **Narcoonowie Formation** (Sun & Gravestock, 2001). The sandstone is feldspathic to lithic, contains between 10–20% matrix, and commonly has slump and dewatering structures. Lithic clasts include felsic volcanics and shale, and the quartz is primarily volcanic. A 14.5m thick sandstone or breccia within a Dullingari 1 is inferred to represent a slump deposit (Sun & Gravestock, 2001). Clasts of the Jena Basalt, Mooracoochie Volcanics, Kalladeina Formation and possible Willyama Supergroup (basement) occur. Fossils are common, including trilobites, brachiopods, hyoliths, calcispheres, and graptolite assemblages. An Early Ordovician age was interpreted for rocks intercepted in Dullingari 1 (unpublished well completion report), but Sun & Gravestock (2001) contested this. This unit is used as a marker horizon for a new depositional sequence within a higher energy environment.

The **Pando Formation** overlies the Lycosa Formation predominantly in the Pando to Daralingie areas. Sun & Gravestock (2001) revised the definition of Gravestock & Gatehouse (1995) to include only quartzose sandstone, orthoquartzite and glauconitic sandstone. Gravestock & Gatehouse (1995) had originally included shale of the Lycosa Formation and an ignimbrite of the Mooracoochie Volcanics within the formation. The Pando Formation is bioturbated and cross-bedded, with sporadic concentrations of rounded heavy minerals; interpreted as forming within a high energy, upper shoreface to middle shoreface, shallow marine zone (Sun, 1996). An Early Ordovician age is inferred by the presence of possible bryozoa in cuttings (Sun & Gravestock, 2001).

The **Innamincka Formation** is widely distributed throughout the north-eastern region of the eastern Warburton Basin and is inferred to be 1700m thick (Sun, 1996). Two subunits are identified (Sun & Gravestock, 2001); an informal lower red bed subunit and the **Mudrangie Sandstone Member**.

The lower red bed subunit is a thick succession of strongly bioturbated, red-brownish mudstone and shale, cross-laminated siltstone and minor intraclastic, pebbly sandstone (Sun & Gravestock, 2001). The Mudrangie Sandstone Member includes horizontal- to cross-laminated, moderately well sorted quartzose sandstone with heavy-mineral laminae and interbeds containing rounded green mudstone and shale pebbles (Sun & Gravestock, 2001). These facies are commonly interfingered in a cyclic fashion. The formation was interpreted as a deltaic deposit (Zang, 1993). A fragment of a worn spicule within the Mudrangie Sandstone Member suggests an age younger than Early Ordovician (Sun & Gravestock, 2001).

Within the lower red bed sequence, thin basaltic and rhyolitic sills, flows or dykes of the **Pondrinie Basalt** occur with a maximum thickness of 30m (Sun & Gravestock, 2001). The presence of amygdales suggests a subaerial or shallow level emplacement.

Table 11. Key Components of the Warburton Basin

Formation	Distribution	Lithology	Age constraints	Depositional Environment
Innamincka Formation	Central eastern Warburton Basin	Lower unit dominantly homogenous red mudstone, shale, siltstone and intraclastic sandstone. Commonly cross laminated and bioturbated. Upper section is green, laminated, glauconitic, more sandy, and cemented with calcite. Common interbeds of amygdaloidal basalt.	Early Ordovician (Fossils; Sun, 1996)	Interpreted as a shallow marine deposits (Ludbrook, 1961), a shallow subtidal deposit (Gravestock & Gatehouse, 1995), and as a deltaic deposit (Zang, 1993).
Pando Formation	Restricted to 6 drill holes in the Daralingie-Pando-Boxwood area; ~240m thick.	Irregularly laminated, bioturbated and silty sandstone with common glauconite and detrital zircon.	Early Ordovician (Fossils; Sun, 1996)	Marginal marine (Sun, 1996).
Dullingari Group	Widespread	Basal laminated pyritic siltstone and shale. A thin (15m) breccia unit overlies these sediments in a single drill hole, containing slightly rounded clasts of sandstone, siltstone and shale, basalt, and a few rounded carbonate pebbles. Upper unit includes a light grey to dark grey shale interbedded with feldspathic sandstone.	Early to Middle Ordovician (Fossils; Sun, 1996)	Deep marine turbidite flows with brief period of uplift (forming breccia) (Sun, 1996).
Kalladeina Formation	Central eastern Warburton Basin; 1600m thick at Kalladeina	Fossilferous limestone, dolomite, shale, siltstone and sandstone, minor tuff.	Middle Cambrian to Early Ordovician (Fossils; Sun, 1996; Sun & Jago, 1998)	Early broad shelf to basin environment followed by a shallow marine shelf (Sun, 1996).
Diamond Bog Dolomite	Restricted to Gidgealpa area; 30–120m thick.	Vuggy and fractured dolomite, occasional granules and pebbles of felsic tuff.	Unknown	Peritidal (Sun, 1996)
Mooracoochie Volcanics	Widespread; ~990m thick.	Rhylotic and dacitic flows, tuffs, ignimbrite, minor basalts, as well as tuffaceous, calcareous and fossilferous sediments (Taloola Ignimbrite Member).	517 ± 9Ma (U-Pb zircon; PIRSA, 2007).	Subaerial to subaqueous (hyaloclastite present at Kalladeina) (Sun, 1996)

ROMA SHELF

The Roma Shelf is a broadly north–south trending basement platform adjacent to the Taroom Trough, the major depocenter of the Bowen Basin (Figure 27a). Significant oil and gas shows within the overlying Bowen and Surat basins have promoted extensive drilling with many holes intersecting basement. The density of drilling allowed Murray (1994) to interpret a basic geological map of the basement surface (Figure 34). Rocks include deep marine metasedimentary rocks of the Timbury Hills Formation intruded by the muscovite ± biotite granite referred to informally as "Roma granites". Rock types, metamorphic grade and degree of deformation observed in the Roma Shelf are similar to rocks further west in the main Thomson Orogen region.

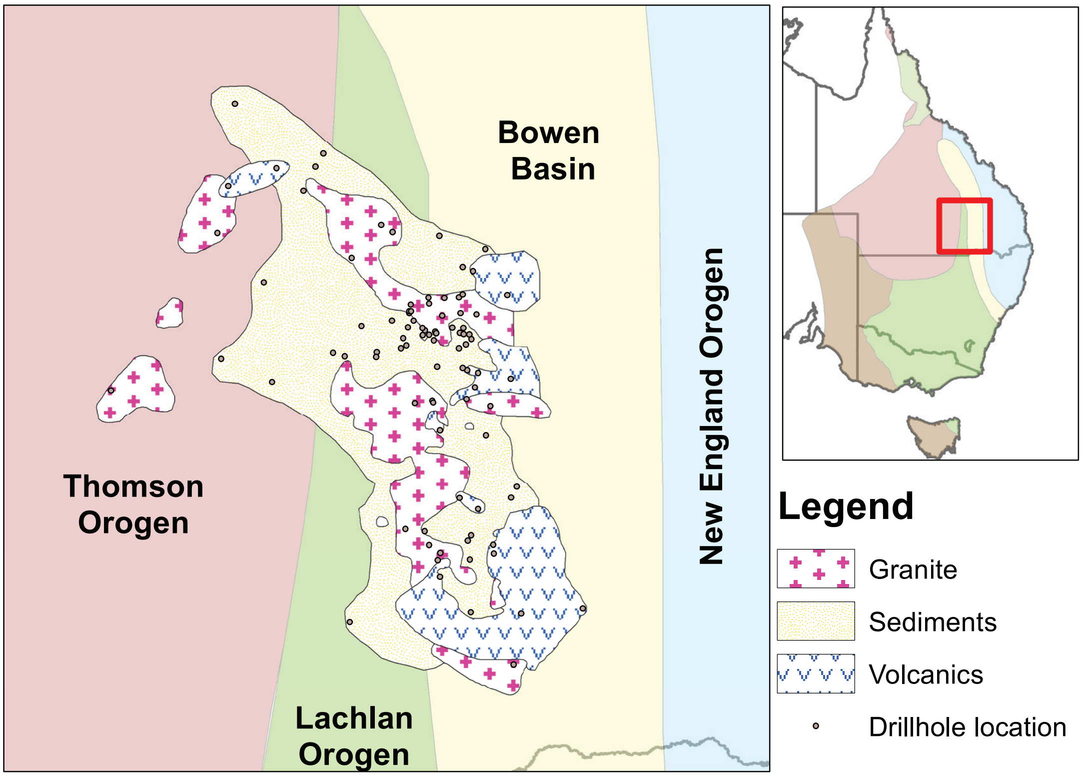


Figure 34. Geology of the Roma Shelf beneath cover, modified from Murray (1994)

The Timbury Hills Formation

The **Timbury Hills Formation** is described as predominantly interbedded sandstone, siltstone and argillite metamorphosed to at least lower greenschist facies. Sandstone units are pale grey, thick (up to 1m), poorly sorted, subangular and quartzose. Lithic clasts are subordinate to quartz, and include metasedimentary and felsic volcanic rocks. Laminated siltstone is compositionally similar to these sandstones whilst the cleaved argillite is pelitic. Murray (1994) noted possible cross-bedding and graded bedding in a few cores, as well as single-crystal, carbonate clasts inferred to represent fossil fragments.

Figure 35. Plant fossils within AAO Pickanjinnie 2 providing a general Devonian depositional age

Metamorphism and deformation

The Timbury Hills Formation displays a general bedding-parallel cleavage, dipping at 60° or greater. In the sandstones this cleavage is defined by sericitic muscovite, chlorite and calcite interpreted to represent a single stage of regional folding during lower greenschist facies metamorphism. On the western margin of the Roma Shelf, a crenulation cleavage was noted in two holes (AAO Arbroath 1 and UOD Saint George 1). Murray (1994) postulated increasing metamorphic grade southwards by the presence of garnet-muscovite-biotite schist or gneiss (HPP Bendiboi 1), andalusite (?) -biotite-muscovite-plagioclase quartz phyllite (BON Silver Springs 4), and calcite-chlorite-biotite-muscovite-quartz semi-schist (UOD Moombah 1).

Age

Age constraints on the age of the Timbury Hills Formation are poor. The sediments are intruded by the Devonian-Carboniferous Roma granites (see below) providing a minimum age constraint. Plant fossils within AAO Pickanjinnie 2 (Figure 35) indicate a Devonian age; but it is unknown whether this age represents the entire unit (Murray 1994).

Roma granites

Intersections of granite are abundant amongst Roma Shelf drill holes (Figure 34). These are collectively referred to informally as the Roma granites. They intrude the Timbury Hills Formation as multiple plutons and are unconformably overlain by sediments of the Bowen Basin and Surat Basin. Significant weathering profiles suggest a prolonged surface residence. Murray (1994) tentatively classified the granites as mainly S-type, with only two occurrences of I-types (in AAO Boondara 1 and AAO Sunnybank 1). The “S-type” granites are massive and medium- to coarse-grained. They contain quartz, alkali feldspar (typically microperthite), plagioclase, 5–15% biotite and subordinate muscovite. Tourmaline and possible cordierite are common accessory minerals. The “I-type” granites are massive, medium-grained

Table 12. K–Ar dates for granites of the Roma Shelf

Drillhole	Method	Age	Reference
AAO Sawpit Creek 1	K–Ar biotite	343Ma	Harding (1969)
AAO Mount Hope 1	K–Ar biotite	355Ma	Harding (1969)
AAO Brucedale 1	K–Ar biotite	304Ma	Harding (1969)
AAO Pleasant Hills 1	K–Ar biotite	337 ± 7Ma	Webb & others (1963)
AAO Rosewood 1	K–Ar biotite	356 ± 7Ma	Webb & others (1963)
AOP Scalby 1	K–Ar biotite	331 ± 12Ma	Hamilton (1966)

and predominantly contain quartz, alkali feldspar (microperthite), plagioclase and biotite (5–10% of rock). Hornblende, opaques and titanite are accessory minerals. No geochemical analyses of the Roma Granites are yet published.

Age

Numerous samples have been retrieved for K–Ar dating of biotite (Table 12). Despite all samples being altered to some degree, Murray (1994) considers that the S-type granites are *ca* 355 to 360Ma. The I-type granites remain undated, but are at most as old as the Devonian rocks they intrude.

THE THOMSON OROGEN IN NEW SOUTH WALES

Although dominantly occurring within Queensland, the Thomson Orogen does extend into northern New South Wales where it is truncated by the Olepoloko Fault (Gray & Foster, 2004; Glen, 2005; Glen & others, 2007, Hegarty, 2010). On the western edge, the Thomson Orogen abuts rocks within the Koonenberry Belt that have been deformed by the Cambrian Delamerian Orogen. Some of those units are summarised here (below and Table 13) because they overlap in age with the Thomson Orogen as it is defined in Queensland. In the central area, the Thomson Orogen is believed to be juxtaposed against the Lachlan Orogen by the north dipping Olepoloko Fault (Glen, 2005; Glen & others, 2007), but here it is concealed beneath Devonian sediments.

The majority of the Thomson Orogen in New South Wales is concealed beneath up to 1400m of cover sediments (predominantly Eromanga Basin) (Hill & others, 2008). Small inliers of outcrop have been mapped at 1:25 000 scale between Tibooburra and Milparinka in north-western New South Wales as part of the Koonenberry Belt Project (Figure 36; Greenfield & others, 2010a). These rocks continue further south (Figure 37) but are poorly exposed (Sharp & Buckley, 2008; Mills & Hicks, 2009). New geophysics and drilling has resulted in interpretation of a basement lithology map for the Thomson Orogen in New South Wales (Figure 38; Hegarty, 2010) and a depth-to-basement surface. In addition, recent detrital and magmatic zircon dating (Glen & others, 2010) has provided significant temporal constraints for the evolution of the southern Thomson Orogen.

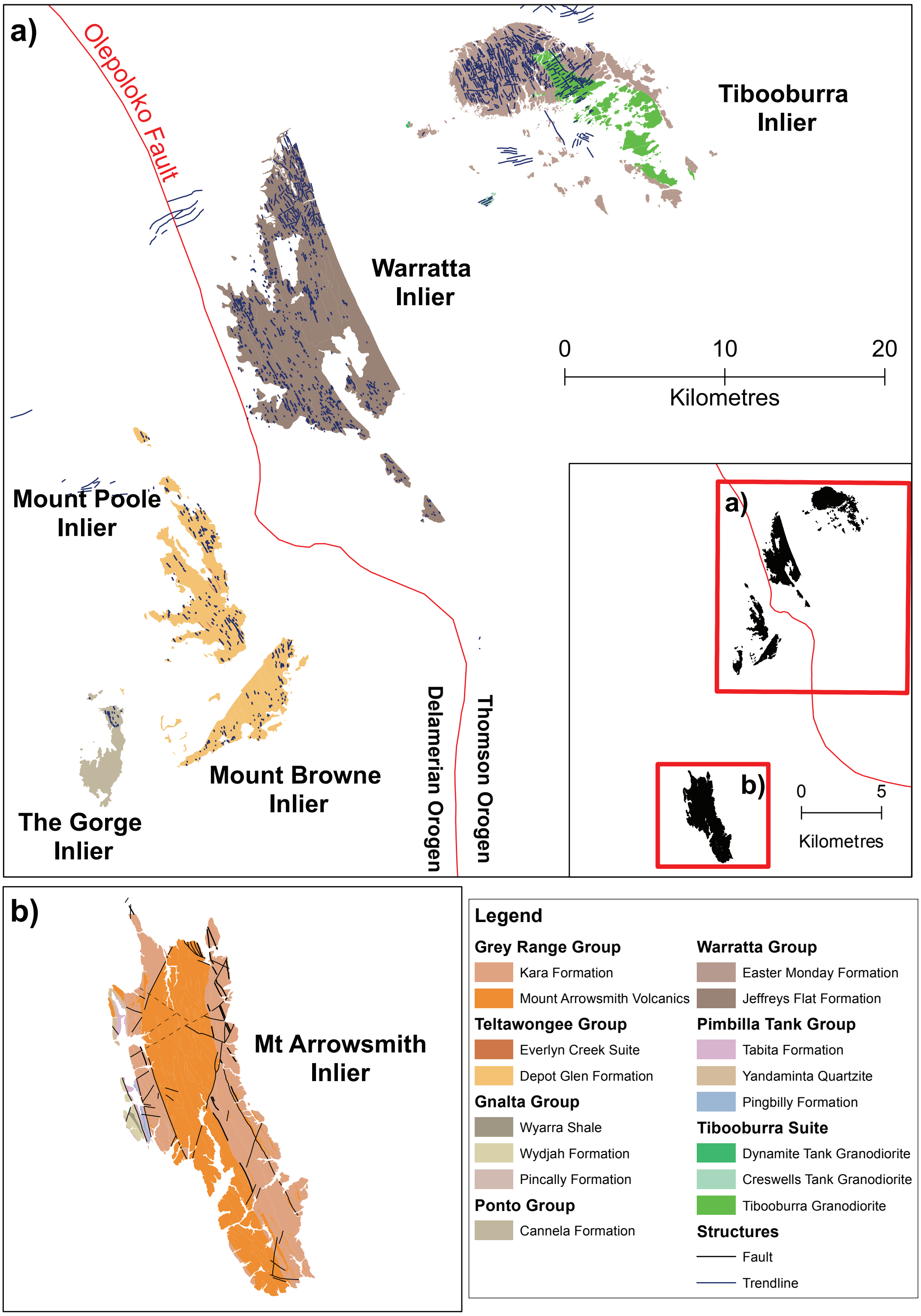


Figure 36. Outcropping geology of the Thomson and Delamerian orogenies in New South Wales; modified from Greenfield & others (2010a)

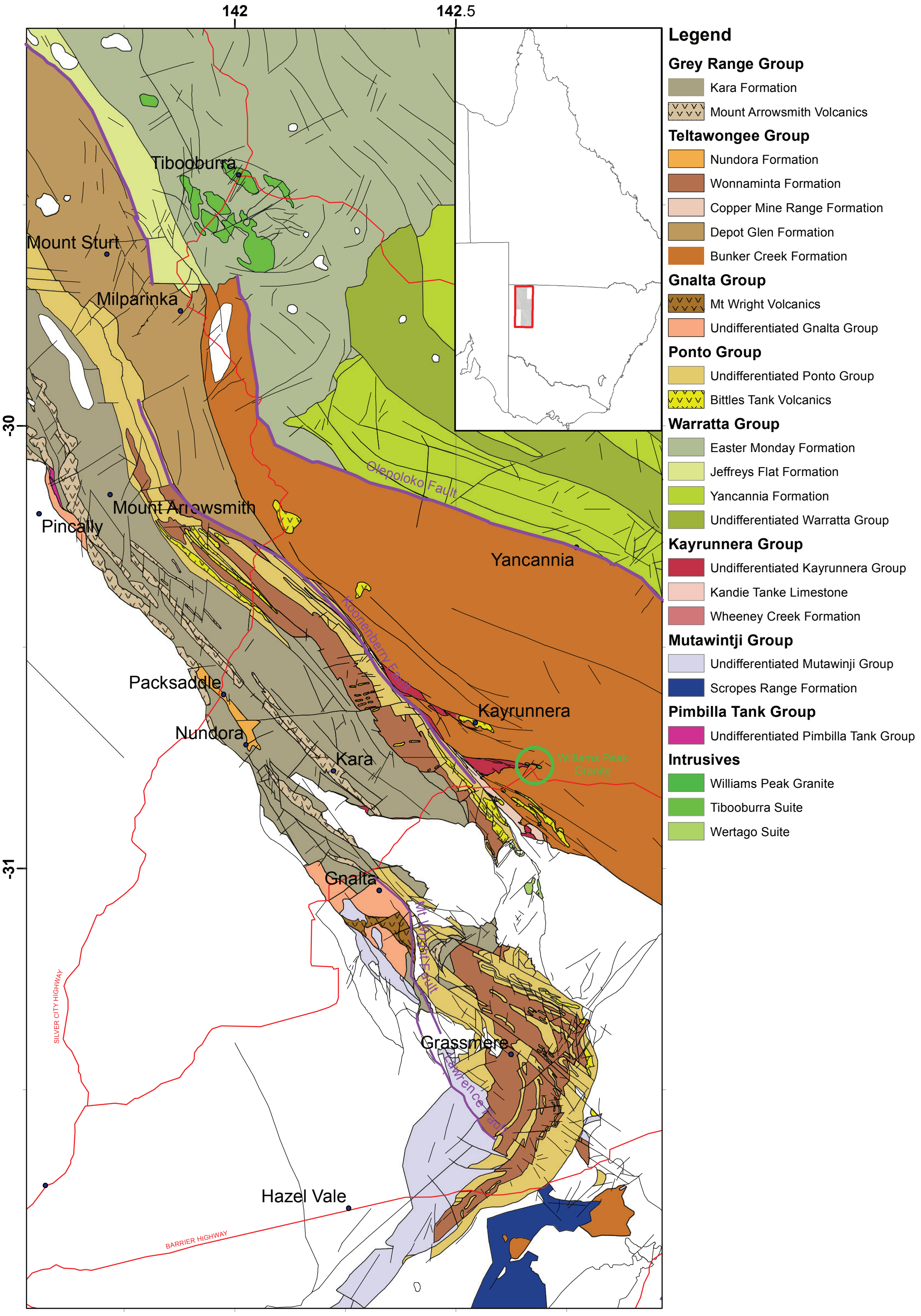


Figure 37. Solid geology of the Thomson and Delamerian orogenies in New South Wales; data from GSNSW

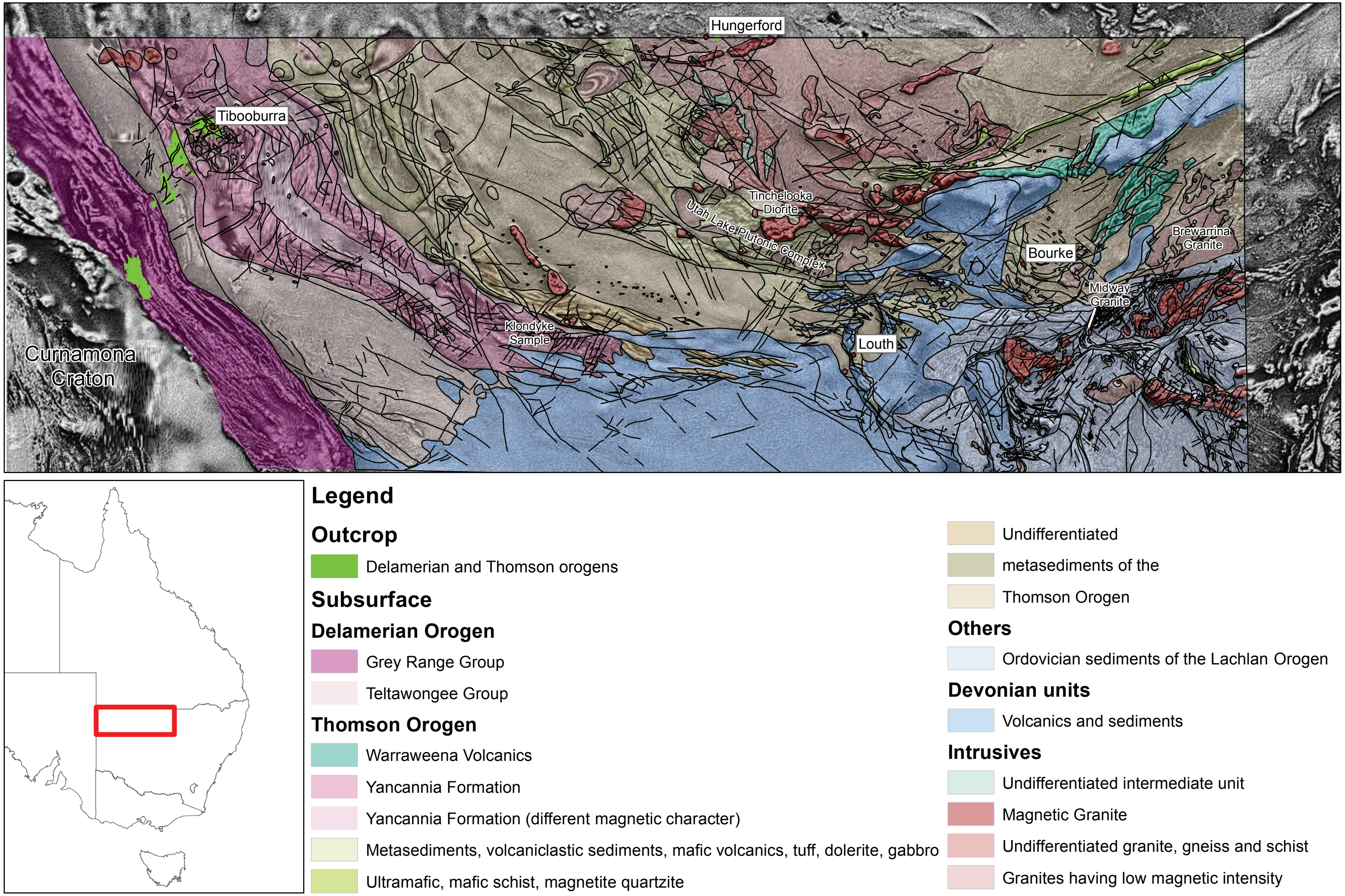


Figure 38. Subsurface geology of the Thomson and Delamerian orogens in New South Wales. Geology polygons are from Hegarty (2010) and overlain on a 1VD TMI image.

NEOPROTEROZOIC

Grey Range Group

In the Koonenberry Belt, exposed Neoproterozoic rocks of the Grey Range Group are separated from the Curnamona Block to the west by downfaulted post-Delamerian Paleozoic sediments of the Bancannia Trough (Figure 38). Mills (2010b) suggested that the shallow marine continental shelf sequence of the Grey Range Group could be correlatives of the Farnell Group of the Adelaide Geosyncline (Preiss, 2000). The group consists of the Kara Formation and Gravel Creek Member, and the Mount Arrowsmith Volcanics (Greenfield & Mills, 2010).

The **Kara Formation** is a 5km-thick succession of sandstone, mudstone, limestone and chert that is regionally metamorphosed to lower greenschist facies (Figure 39; Greenfield & Mills, 2010). The sediments are commonly calcareous, feldspathic and quartzose. Primary sedimentary features are commonly preserved and include ripples, bioturbation, ooids, cross-bedding and load structures. Fossils include oncolites, possible lenticular stromatolites and shell-like fragments. The **Gravel Creek Member**, which occurs west of Mount Arrowsmith, is a continuous ridge up to 4500m long and 350m wide of thick-bedded slate, calcareous sandstone to impure limestone, lithic-feldspathic sandstone and pebbly sandstone with siltstone interbeds (Greenfield & Mills, 2010). The unit is interpreted to have formed in a fluvio-deltaic to shallow marine setting (Greenfield & Mills, 2010).

The **Mount Arrowsmith Volcanics** include numerous alkaline basaltic to trachytic, subaqueous and subaerial flows, dykes, sills and plugs with minor rhyolite (Greenfield & Mills, 2010). A small outcrop of albite-aegirine-nepheline-natrolite rock, termed nundorite (Figure 40a), is endemic to the area (Greenfield & Mills, 2010). Associated

Figure 39. Steeply dipping sequence of interbedded metasandstone and metasiltstone of the Kara Formation

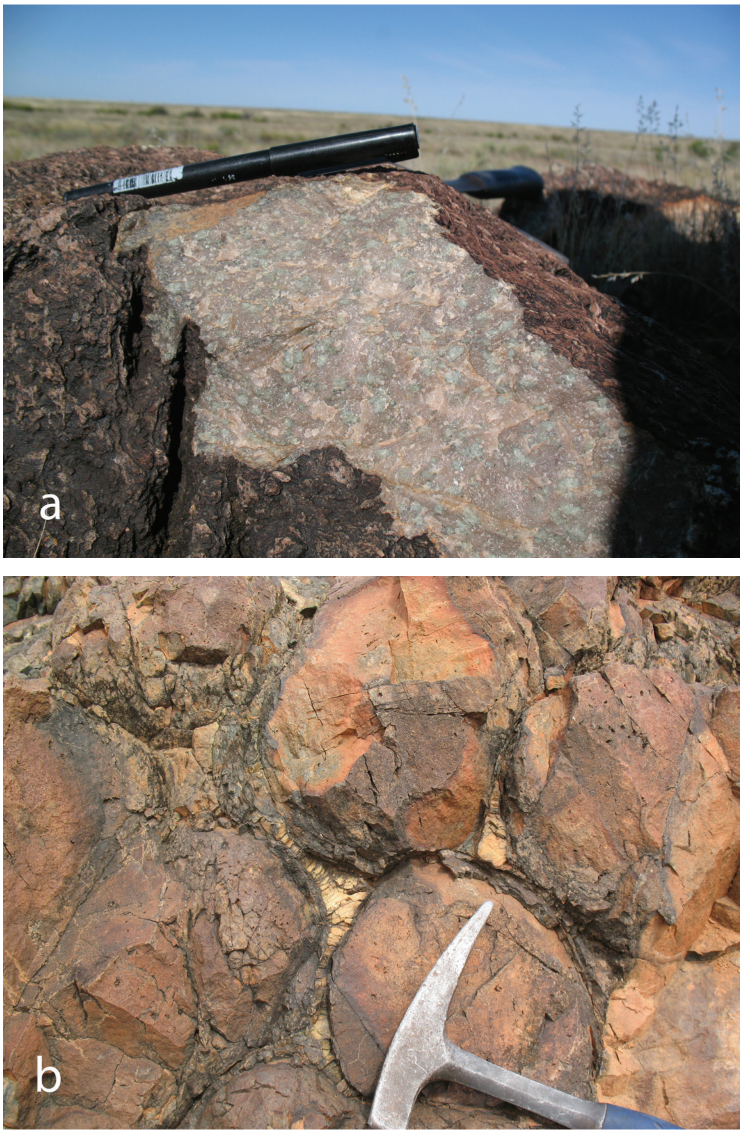


Figure 40. a) Outcrop of the endemic nundorite (albite-aergirine-nepheline-natrolite rock) near Nundora;
b) Pillow lavas of the Mount Arrowsmith Volcanics near Mount Arrowsmith

volcaniclastic deposits and calcareous sediments include pyroclastic flows, tuffs, hyaloclastite and pillow basalts (Figure 40b) and limestone. Within the lava flows, pillow, quench and amygdaloidal textures are common and indicative of shallow marine eruption (Greenfield & Mills, 2010). At Mount Arrowsmith calcareous sediments underlie largely basaltic pillow lavas (Figure 41).

The Mount Arrowsmith Volcanics are alkaline with strong 'within-plate' geochemical affinities demonstrated by Zr–Nb–Y ratios (Meschede, 1986), REE concentrations and Sm–Nd and Sr isotopic ratios (Crawford & others, 1997; Bruce & Vickery, 2010). Assimilation and fractional crystallisation processes are inferred to have had a minor influence. The age of the Mount Arrowsmith Volcanics is constrained by a U–Pb zircon (SHRIMP) dates of 585.5 ± 3.2Ma (Black, 2007), and 586 ± 7Ma (Crawford & others, 1997) on an alkali rhyolite. This is further evidenced by a T_{DM} age of ~577Ma (Bruce & Vickery, 2010).

Rocks of the Grey Range Group display a well developed, subvertical slaty cleavage associated with the late Cambrian Delamerian Orogen (Greenfield & Mills, 2010). A second deformational event can be seen locally with the development of a crenulation

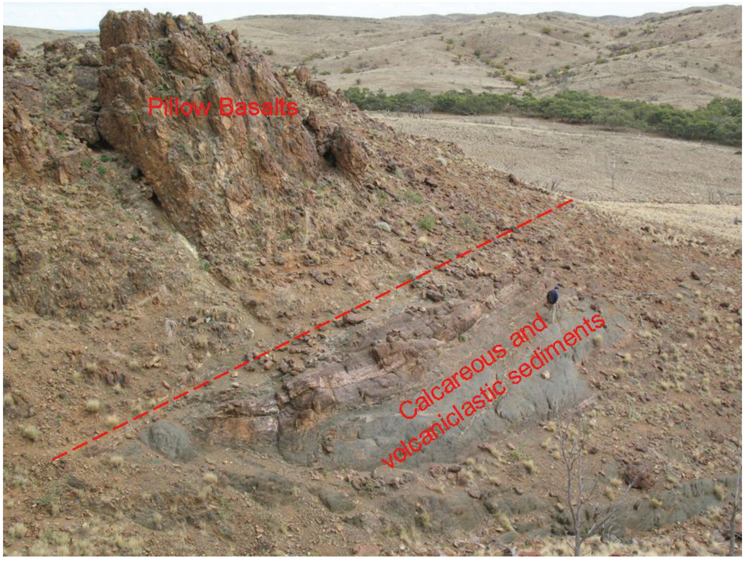


Figure 41. Package of predominantly calcareous and volcaniclastic sediments underlying pillow lavas

cleavage or pencil cleavage structures. This event has been correlated with the Ordovician-Silurian Benambran Orogeny (Greenfield & Mills, 2010).

Warraweena Volcanics (Thomson Orogen)

The oldest known rocks within the undercover southern Thomson Orogen, the **Warraweena Volcanics**, occur east of Bourke (Figure 38). They are entirely covered by sediments of the Eromanga Basin, but their distribution is likely to be represented by north-east trending, relative-high magnetic lineaments (Burton & others, 2008). They have been tentatively dated as Neoproterozoic (580Ma) based on magmatic zircon within a single sample (Glen & others, 2010). An Ordovician age had previously been suggested (Burton & others, 2008) based on the geochemical similarities with the Macquarie Arc.

The Warraweena Volcanics include massive ultramafic to basaltic andesite flows, dolerite, volcaniclastic breccias and tuffs (Burton & others, 2008). Burton & others (2008) identified three geochemical suites within a restricted sample group. Two suites contain calc-alkaline to shoshonitic rocks, with volcanic-arc like immobile element patterns. These are inferred to represent an arc, now orientated north-east, as defined by magnetic trends. The third suite has intraplate characteristics and is inferred to represent rifting.

Early to Middle Cambrian

Teltawongee Group

The Teltawongee Group crops out in the Mount Poole and Mount Browne inliers (Figure 36) as the Depot Glen Formation, and continues further south as the Bunker Creek Formation, Copper Mine Range Formation, Wonnaminta Formation and Nundora Formation (Figure 37; Mills, 2010a). Its subsurface extent is considered much more expansive (Figures 37, 38). The Depot Glen Formation and Bunker Creek Formation are probably lateral equivalents (Mills, 2010a). The group includes predominantly greenschist facies metamorphosed interbedded sandstone and siltstone. The Nundora, Wonnaminta, Depot Glen and Bunker Creek formations were probably deposited on an east-facing continental slope, whereas the Copper Mine Range Formation probably represents a shallow water environment, above wave base (Mills, 2010a).

The **Nundora Formation** crops out as a small elongate body of interbedded siltstone and sandstone containing Bouma sequences. It is generally massive, but is also known to have graded bedding, climbing ripples and laminations. Beds within the formation are maroon-red in colour, which is unique to the Teltawongee Group, and suggest they formed in a more oxidised environment (Mills, 2010a). Detrital U–Pb zircon analysis yielded a maximum depositional age of 652Ma with major inheritance peaks at 780–800Ma, 1178 ± 17Ma, 1589 ± 11Ma and 1862 ± 11Ma (Greenfield, 2010b).

The **Wonnaminta Formation** crops out in a north-west trending belt of interbedded siltstone and sandstone Bouma sequences similar to the Nundora Formation. Phyllitic or slaty metamudstone and well-indurated, massive quartz-rich metasandstone also occur, commonly as marker beds throughout. The slate hosts fragments of hexactinellid sponges which suggest at least a Cambrian age (Mills, 2010a).

The **Copper Mine Range Formation** is a shallow water equivalent of the Teltawongee Group with dolomite, quartzite, and possible conglomeratic beds within a general metamudstone and metasiltstone sequence (Mills, 2010a). The unit hosts a variety of trace fossils (*Chondrites* sp. and *Planolites* sp.), sponge spicules and evidence of paterinide brachiopods indicative of lower to middle Cambrian (Webby, 1984; Percival & Pickett, 1996).

The **Depot Glen Formation** crops out extensively within the Mount Poole and Mount Browne Inliers. Rocks include interbedded and strongly cleaved slate, phyllite, metasandstone and quartz arenite up to greenschist facies metamorphic grade (Mills, 2010a). The rocks dip sub-vertically (Figure 42) with a pervasive cleavage defined by muscovite and rare biotite. A tuffaceous bed within the formation yielded a SHRIMP zircon crystallisation age of 504.5 ± 2.6Ma (Black, 2006). Ar-Ar muscovite dating of a phyllite from the Mount Poole Inlier yielded a 475.3 ± 1.3Ma (Greenfield, 2010b) cooling age from peak metamorphism.

The **Bunker Creek Formation** occurs in the southern areas of outcrop as poorly exposed and weathered turbidite sequences. Rocks are dominated by massive, upward-fining sandstone beds. The top of these beds commonly have climbing ripples, laminations and a muddy cap. Rare trace fossils of vertical burrows suggest at least a Cambrian age (Mills, 2010a).

The majority of the Teltawongee Group is steeply dipping with tight, upright folds associated with the Cambrian Delamerian Orogeny (Greenfield, 2010b). Metamorphism reached the chlorite zone of the greenschist facies.

Figure 42. Steeply dipping, interbedded slate and metasandstone of the Depot Glen Formation in the Mount Poole Inlier

Evelyn Creek Volcanics

The Evelyn Creek Volcanics crop out as elongate areas (1km by 200m) of strongly altered metabasalt and associated intrusives in the Tibooburra and Mount Poole Inliers (Figure 36). The metabasalt flow unit is aphanitic, and commonly interlayered with the Easter Monday Formation of the Warratta Group (see below). Intrusive units include mafic to intermediate dykes, sills, and monzodiorite. A dark-brown to green, foliated amygdaloidal unit within the Depot Glen Formation could be a flow unit or shallow intrusive (Mills, 2010a). The unit has been regionally folded and foliated during the Benambran Orogeny (Mills, 2010a).

Geochemically this unit is alkaline with “within-plate” affinities (Bruce & Vickery, 2010). Low Sm–Nd and high Sr isotopic ratios suggest that minor crustal contamination has occurred, suggesting a intracontinental rift environment (Bruce & Vickery, 2010).

The age of the Evelyn Creek Volcanics is unknown. If the dark-brown to green amygdaloidal unit is extrusive then magmatism started at least in the Middle Cambrian. A possible second phase of magmatism resulted in the emplacement of intrusives into the Depot Glen Formation between the middle and late Cambrian. A possible final stage of magmatism occurred when extrusive flows were emplaced within units of the late Cambrian Easter Monday Formation.

The Gnalta Group

The Gnalta Group forms small outcrops within the Gnalta Syncline (Roberts & Jell 1990) on the western boundary of the Mount Arrowsmith Inlier (Figure 36) and further south in the Bynguano Range and the Mount Wright areas. Units of the Gnalta Group include the calc-alkaline igneous rocks of the Mount Wright Volcanics and Cymbric Vale Formation, and fine-grained sediments and limestone of the Coonigan, Pically, Wydjah formations and Wyarra Shale (Percival, 2010a). They are likely to be lateral equivalents to the Ponto Group (see below; Mills, 2010b).

The Mount **Wright Volcanics** predominate in the southern outcrop area. They are calc-alkaline to tholeiitic and include rhyolite to basalt flows intruded by minor dolerite to microdiorite dykes (Crawford & others, 1997; Bruce & Vickery, 2010; Percival, 2010a). Associated sediments include shale, chert and rare dolomitic limestone.

The geochemistry of the volcanic rocks is ambiguous in delineating a tectonic setting (Crawford & others, 1997; Bruce & Vickery, 2010). Samples generally show enrichment in LREE, Th, Pb, Rb, Ba and K, with a relative depletion in Nb. εNd_{525Ma} values range between 0 and -7.5. Bruce & Vickery (2010) suggested that this has resulted from multiple sources (including MORB, enriched OIB and subduction zone components) as well as crustal contamination. The authors suggest a transition between arc and backarc environments.

The overlying **Cymbric Vale Formation** is made up of rhyolitic tuffs, ignimbrite with common flow and fiamme textures, siltstone, chert, lithic and feldspathic sandstone, and limestone. Quartz-plagioclase porphyry with quartz-rich ground mass occurs locally (Percival, 2010a). Fossils within the limestone contain abundant trilobites, hyoliths, monoplacophoran molluscs and archaeocyathids (Percival, 2010b). Geochemically the volcanics show few affinities with the underlying Mount Wright Volcanics. However Crawford & others (1997) suggested that the Cymbric Vale Formation could represent highly fractioned components of the Mount Wright Volcanics that formed during a waning phase of extension.

The age of the formation is given by two U–Pb zircon (SHRIMP) dates at 510.3 ± 3.2Ma (Black, 2006) and 510.5 ± 2.9Ma (Black, 2007), as well as an early Cambrian age determined from fossils (Jago & others, 1997).

The remaining units of the Gnalta Group are the shallow marine sediments of the **Coonigan Formation** and the **First Discovery Limestone Member** and their lateral equivalents to the north, the **Pincally and Wydjah** formations.

The Coonigan Formation is a thick (up to 130m) sequence of bleached to very light brown interbedded shale and siltstone (Percival, 2010a). The top of the unit hosts numerous species of trilobites (Jell, 1975). Within this unit is the First Discovery Limestone Member, which has a minimum thickness of 117m (Roberts & Jell, 1990), and is highly fossiliferous limestone with minor siltstone and sandstone near the top of the unit (Percival, 2010a). Fossils include molluscs, corals, echinoderms, sphinctozoan sponges, brachiopods, hyoliths, tommotiids, and chanelloriid sponge spicules indicative of latest early Cambrian (Percival, 2010b). The rocks are relatively undeformed.

The Pincally Formation is restricted to the western edge of the Mount Arrowsmith Inlier (Figure 36). It hosts thin interbeds of shale, siltstone and limestone and is comparable to the First Discovery Limestone (Percival, 2010a). The overlying Wydjah Formation includes cross-bedded, quartzose sandstone grading into conglomerate. Clasts within the conglomerate are foliated schist and altered volcanics. Towards the top of the formation is the Pimpira Member, a ~76m thick (Brock & Percival, 2006) unit of dolostone which displays microscopic, syn-depositional brecciation (Percival, 2010a). Rocks of the Wydjah Formation and the Pincally Formation are folded within a north-plunging syncline resulting in the development of an axial planar slaty cleavage (Percival, 2010a).

The Ponto Group

The Ponto Group is a fault-bounded, Cambrian, deep water assemblage of fine-grained sediments (the Baroorangee Creek, Weinteriga Creek, Grassmere, Cannela and Noonthorangee, Koonenberry and Yandenberry formations) and tholeiitic igneous rocks (Bittles Tank Volcanics; Mills, 2010c). Outcrop is predominantly adjacent to the Koonenberry Fault with minor components in the Gorge Inlier (Figure 36), and adjacent to the Mount Wright Fault. Sediments of the Ponto Group are interpreted to be laterally equivalent to the Kars Zone in the Loch Lilly-Kars Belt (Sharp & others, 2006), whilst the igneous rocks are comparable to Cambrian tholeiitic suites in the Warburton Basin, Adelaide Fold Belt, and Victorian Glenelg Complex of the Stavely Belt (Foden & others, 2002).

The **Baroorangee Creek**, **Weinteriga Creek**, **Grassmere, Cannela** and **Noonthorangee, Koonenberry** and **Yandenberry** formations of the Ponto Group are a conformable succession dominated by interbedded metasandstone and metasiltstone turbidite deposits with minor basalt flows, chert and quartz-magnetite rocks (Mills, 2010c). Felsic tuffs begin to appear within the Grassmere Formation and become more prevalent in the Cannela Formation. Possible amygdales and flow banding textures are seen within the extrusive rocks and graded bedding is seen in sediments.

These formations exhibit tight to isoclinal, upright folding and development of widespread schistosity, transposition, shearing and thrust faulting associated with the Delamerian Orogen (Mills, 2010c). The Baroorangee Creek Formation displays amphibolite facies metamorphism (Mills, 1992), whereas the remaining units only reach greenschist facies (Mills, 2010c).

Age constraints for these units are from U–Pb zircon (SHRIMP) dating of felsic tuff samples yielding ages of 508.3 ± 2.2Ma from the Cannela Formation (Black, 2006) and 508.6 ± 3.2Ma, 512.0 ± 3.1Ma and 511.7 ± 3.5Ma from the Noonthorangee Formation (Black, 2005).

The **Bittles Tank Volcanics** are predominantly tholeiitic, intrusive and extrusive basalts (Mills, 2010c). Extrusive units are restricted to the Ponto Group, but intrusive equivalents are present within the Grey Range and Teltawongee groups. Rocks include basaltic, amygdaloidal pillow lavas which are locally porphyritic, and gabbro to dolerite containing plagioclase + amphibole ± pyroxene (Mills, 2010c). Three geochemical suites have been identified (Bruce & Vickery, 2010): Kayrunnera gabbros, Nuntherungie dolerites, and Bittles Tank basalts. The variation is thought to have originated from a variety of sources (including depleted MORB, enriched OIB, subduction zone components and crustal contamination by oceanic sediments and/or selective fluid enrichment) and subsequent magma mixing (Bruce & Vickery, 2010). The tectonic environment is suggested to be in an oceanic intra-plate rifting setting in a back-arc system (Bruce & Vickery, 2010).

Early units of the Bittles Tank Volcanics display Delamerian Orogen deformational effects including upright folding and the development of a pervasive foliation. Late-stage units post-dating the Delamerian Orogen were emplaced in late-stage dilatational structures, and thus display a weak tectonic fabric (Mills, 2010c). Alteration assemblages of epidote-carbonate-sericite and epidote-albite-chlorite-quartz assemblages in the intrusive rocks are suggestive of greenschist facies metamorphism.

Intrusive units

The **Williams Peak Granite** crops out at six locations where it intrudes the Bunker Creek Formation (Figure 37; Mills, 2010a). The unit is well-cleaved, porphyritic with phenocrysts of feldspar and quartz (up to 3mm) in a fine-grained pink groundmass, and described as rhyodacitic in composition (Mills, 2010a). A U–Pb zircon (SHRIMP) age of 515.1 ± 2.7Ma is the only temporal constraint (Black, 2007).

Cambrian–Ordovician sedimentary rocks

Warratta Group (Thomson Orogen)

Cambrian–Ordovician sediments are inferred to represent a large proportion of the southern Thompson Orogen (Glen & others, 2010; Hegarty, 2010). In the west, in the Tibooburra and Warratta Inliers, they are mapped as Warratta Group (Easter Monday and Jeffreys Flat formations; Figure 36) and near Yancannia (Yancannia Formation; Greenfield & others, 2010a). The group includes variably deformed and metamorphosed siltstone, sandstone and mudstones with minor volcanics. Its subsurface extent is geophysically defined to the east, where it is penetrated by a drill hole (Klondyke; Figure 37, Figure 38). Greenfield (2010a) interpreted the Warratta Group to represent a paleo-marine shelf to deep marine environment and suggested correlation with the Dullingari Group of the Warburton Basin that formed from subsidence and marine transgression at the end of the Delamerian Orogen.

The **Easter Monday Formation** is interpreted as turbidite deposits comprising interbedded, variably cleaved and metamorphosed metamudstone and metasandstone with minor tuffaceous beds, diamictite and calcareous sandstone (Greenfield, 2010a). The **Jeffreys Flat Formation** also hosts variably cleaved and metamorphosed metamudstone and metasandstone, but also contains quartzite, conglomerate and limestone (Greenfield, 2010a). The environment of deposition has been suggested to be deep water (Webby, 1984; Leitch & others, 1987), deltaic (Stevens & Etheridge, 1989), and transitional from shallow to deep marine (Greenfield, 2010a). The **Yancannia Formation** is a completely subsurface unit of monotonous, weakly cleaved metamudstone with minor metasiltstone and metasandstone (Greenfield, 2010a).

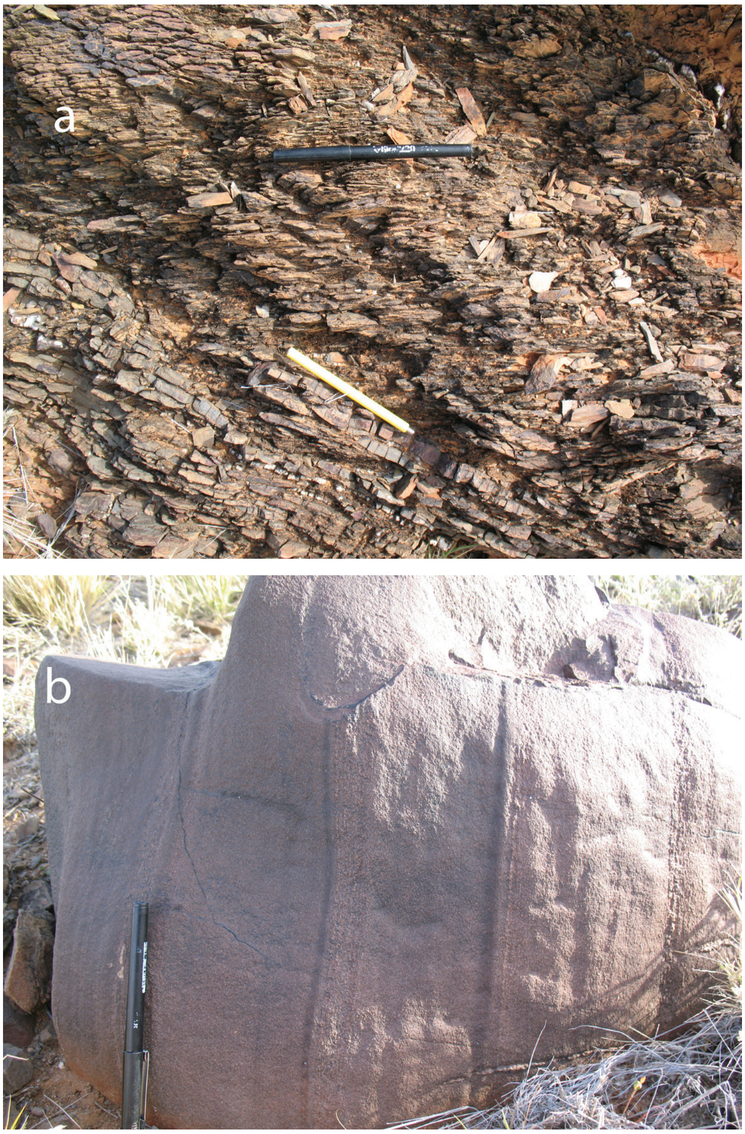


Figure 43. a) Structural fabrics in the Warratta Group — yellow pen defines S_0 and black pen defines S_1;
b) hornfelsed Easter Monday Formation showing fining-up sequence. This photo was taken approximately 15m from the contact with the Tibooburra Granodiorite.

The Waratta Group were affected by a major deformational event, imparting a pervasive foliation (Figure 43a), inclined folding and reverse faulting. Deformation is interpreted to have occurred at lower greenschist facies pressures and temperatures (Greenfield, 2010b). The Easter Monday Formation is locally hornfelsed adjacent to the Tibooburra Granodiorite (Figure 43b). The depositional age is constrained by a laminated, felsic tuffaceous bed within the Easter Monday Formation dated at 497.2 ± 2.6Ma (U–Pb SHRIMP zircon; Black, 2006).

These rocks can be traced geophysically eastwards (Hegarty, 2010). A sample of cleaved, very fine- to medium-grained sandstone from a drill hole on Klondyke Station (Klondyke F16), beneath ~375m of cover, yielded a maximum depositional age of 504Ma (Glen & others, 2010). Further east, 5km north-east of Louth, and under ~65m of cover, greenish-grey, fine- to medium-grained sandstone gave a maximum depositional age of 495Ma (Glen & others, 2010).

Kayrunnera Group

The Kayrunnera Group is an entirely sedimentary assemblage of Cambrian–Ordovician mudstone, siltstone, sandstone, limestone and polymictic conglomerate regionally metamorphosed to the lower greenschist facies (Webby & others, 1988; Greenfield & others, 2010b). Greenfield & others (2010b) interpreted these rocks to represent deposition in a fluvial to shallow marine shoreline to deeper slope or shelf setting, adjacent to the deep water deposits of the Warratta Group.

The units are thought to have formed in at least three basins, the Kayrunnera, Nuntherungie and Cupala Creek basins (Powell & others ,1982; Qizheng & others, 1989), which generally show overall fining-upwards sequences (Greenfield & others, 2010b). Outcrop abuts the Koonenberry Fault and associated splay faults near Kayrunnera, with minor outcrop of the Boshy Formation near Kara (Figure 37).

The basal unit of the Kayrunnera Basin, the **Morden Formation**, is composed of calcareous pebbly quartzite. This is overlain by quartzite, limestone, siltstone and conglomerate of the **Boshy Formation.** Late Cambrian trilobites are common in this unit (Opik, 1976). The next overlying unit is the **Watties Bore Formation** which includes slate with marine mudstone, siltstone and minor calcareous to dolomitic breccia protoliths. It contains a variety of late Cambrian to Early Ordovician trilobites (Webby & others, 1988).

In the Nuntherungie and Cupala Creek basins, polymictic conglomerates and quartzose pebbly sandstone of the **Williams Creek Conglomerate** form the basal unit. Clasts within the conglomerate are both allochthonous and autochthonous. The **Hummock Formation** overlies the Williams Creek Conglomerate and consists of well-laminated to cross-bedded quartzite with minor siltstone and conglomerate. Orthide brachiopods occur in the upper section (Powell & others, 1982). In the overlying **Cupala Creek Formation** sediments include shale and siltstone with calcareous and dolomitic lenses, containing orthide and oboloid brachiopods, trilobites and molluscs (Powell & others, 1982; Percival, 2010b).

The Funeral Creek Limestone occurs within the Wheeney Creek Formation abutting the Koonenberry Fault. The **Funeral Creek Limestone** is interpreted to be a large allochthonous block of brecciated limestone based on overturned bedding and highly brecciated contacts (Zhen & Percival, 2006). The unit is highly fossiliferous, containing late Cambrian to Early Ordovician conodonts (Zhen & Percival, 2006; Percival, 2010b). The **Wheeney Creek Formation** consists of low metamorphic grade polymictic conglomerate, quartzite, sandstone, siltstone, limestone and dolomite. Early Ordovician conodonts, hyoliths, trilobites and brachiopods occur within limestone lenses (Zhen & others, 2001; Zhen & Percival, 2006).

The **Kandie Tank Limestone** is an isolated outcrop of massive to brecciated, recrystallised limestone including interbeds of crinoidal biosparite and algal biomicrite (Pogson & Scheibner, 1971; Greenfield & others, 2010b). Conodonts and brachiopods indicate late Cambrian to Early Ordovician (Pickett, 1971).

Metamorphic grade within the Kayrunnera Group increases from prehnite-pumpellyite in the southern Cupala Creek Basin to lower greenschist facies in the northern Nuntherungie Basin (Greenfield & others, 2010b). Sediments within the Kayrunnera Basin dip and face steeply west and are variably cleaved and folded. This has been attributed to the Benambran Orogeny (Greenfield & others, 2010b).

Mutawintji Group

The Mutawintji Group is a Cambrian–Ordovician sedimentary succession consisting predominantly of quartzite with lesser conglomerate, pebbly sandstone and siltstone (Greenfield & others, 2010c). It overlies the Gnalta, Teltawongee, Ponto and Grey Range groups in the Gnalta – Hazel Vale – Grassmere area (Figure 37). It is interpreted as fluvial to deltaic deposits that formed contemporaneously with other units of the Kayrunnera Group (Greenfield & others, 2010c).

The group includes, in stratigraphic order, the Bilpa Conglomerate, Nuchea Conglomerate, Nootumbulla Sandstone, Bynguano Quartzite, Rowena Formation and Scropes Range Formation (Greenfield & others, 2010c).

The basal Bilpa Conglomerate occurs in the southern area, east of Hazel Vale where it underlies the Nuchea Conglomerate (Packham & Benedek, 1968). However, south of Gnalta, the Nuchea Conglomerate is the basal layer. The **Bilpa Conglomerate** is a poorly sorted, polymictic conglomerate cemented by carbonate-rich and ferruginous mud (Pahl & Sikorska, 2004; Greenfield & others, 2010c). Clasts include mafic volcanics, phyllite, metasandstone, vein quartz, gabbro, and felsic tuff in the lower section and rhyolite, andesite, garnet-bearing granite, gabbro, metasandstone, limestone and metapelite in the upper section. Clasts are imbricated throughout, suggesting a north to north-west flow direction. The **Nuchea Conglomerate** is a monomictic conglomerate with large (up to 60cm) boulders of quartzite of unknown provenance.

The **Nootumbulla Formation** conformably overlies the Nuchea Conglomerate with a sharp contact, and is composed of interbedded, feldspathic to quartzose and fossiliferous sandstone and shale with lenses of conglomerate and a single limestone horizon. Trilobites, brachiopods and conodonts are preserved and indicate latest Cambrian deposition (Zhen & Percival, 2006; Percival, 2010b). The overlying **Bynguano Quartzite** contains quartzite and sandstone beds with minor conglomerate and comparable fossils to the Nootumbulla Formation (Greenfield & others, 2010c; Percival, 2010b). The **Rowena Formation** overlies the Bynguano Quartzite in the Gnalta–Grassmere area, but not elsewhere (Greenfield & others, 2010c). It consists of interbedded sandstone, siltstone, shale and conglomerate, which are commonly quartzose and occasionally calcareous. The Gundara Quartzite Member is a marker bed within the Rowena Formation. Fossils are again similar to those found in underlying Noothumbulla Formation and Bynguano Quartzite (Webby, 1983; Zhen & Percival, 2006; Percival, 2010b), but possible Middle Ordovician trilobites are recognised (Paterson, 2006). The **Scropes Range Formation** forms the upper unit south-east of Hazel Vale (Figure 37), and unconformably underlies Devonian sediments. The unit hosts quartz sandstones, quartzite and limestone (Shergold & others, 1982; Webby, 1983; Greenfield & others, 2010c). Fossils include trilobites, an indeterminate gastropod, and brachiopods (Webby, 1983; Percival & Engelbretsen, 2007; Percival, 2010b).

The Mutawintji Group is relatively undeformed and metamorphosed only to prehnite-pumpellyite facies during the Benambran Orogeny (Greenfield, 2010b). The Bilpa Conglomerate is shallowly dipping north-west, whereas the remaining units are generally openly folded and weakly cleaved, particularly those adjacent to the Lawrence Fault (Figure 37).

Age constraints of the Mutawintji Group are only provided through fossils, which suggest late Cambrian to Middle Ordovician (Webby, 1983; Zhen & Percival, 2006; Paterson, 2006; Percival, 2010b).

Pimbilla Tank Group

The Pimbilla Tank Group forms restricted outcrop of conformable quartzite, mudstone, siltstone, limestone and dolostone within the core of a syncline on the western edge of the Mount Arrowsmith Inlier (Figures 36, 37; Percival, 2010c). The group is interpreted to represent a shallow shelf environment with fluctuating sea level (Percival, 2010c).

The constituent units, in stratigraphic order, are the Yandaminta Quartzite, Tabita Formation and Pingbilly Formation (Paterson & Brock, 2003; Percival, 2010c). The **Yandaminta Quartzite** includes medium-grained, massive quartzite above and below a carbonaceous mudstone. The unit contains late Early Ordovician conodonts and molluscs (Zhen & others, 2003). The Yandaminta Quartzite is conformably overlain by mudstone and limestone which grades into dolostone of the **Tabita Formation.** The limestone and dolostone contains numerous nautiloids, gastropods, bivalves, brachiopods and trilobites indicative of a late Early Ordovician age (Percival, 2010b). The overlying **Pingbilly Formation** includes micaceous mudstone and siltstone. A single brachiopod from this unit has been described as late Early Ordovician (Paterson & Brock, 2003).

The Pimbilla Tank Group is relatively undeformed and unmetamorphosed (Percival 2010c). Structures are best preserved in the fine-grained units which show weak to moderate cleavage associated with a syncline.

Ordovician turbidites

Thin-bedded, quartz-rich turbidites are identified within drill core (Louth DH 5) from near Louth (Figure 38; Glen & others, 2010), where they are in fault contact with the Louth Volcanics (see below). Graptolites within shaly beds are late Ordovician (Brunker, 1968) and U–Pb analysis of detrital zircon provided a maximum depositional age of 484Ma (Glen & others, 2010). Rocks of this lithology and age are rare in the Thomson Orogen, but are present in the Sunbury Group of the Melbourne Zone (Glen & others, 2009).

Early Devonian

Louth Volcanics (Thomson Orogen)

The Louth Volcanics, which occur on the southern boundary of the Thomson Orogen, are completely concealed, and include mafic volcanics and volcaniclastics and fine-grained sedimentary rocks (Glen & others, 2010). The mafic volcanic rocks include pillow lavas and pillow breccias, and hyaloclastites occur. They are geophysically represented by positive magnetic and gravity trends (Hegarty, 2010). Early Devonian conodonts were identified within limestone fragments, but it is unclear whether this age is representative for the entire geophysically defined unit (Glen & others, 2010). Dadd (2006) suggested that these volcanics formed either within an OIB or intracratonic rifting setting. The later model was favoured by Glen & others (2010).

Relative magnetic lows surrounding the Louth Volcanics are inferred to represent either fault contacted Ordovician turbidites or Early Devonian sediments that interfinger with the volcanics (Glen & others, 2010). Glen & others (2010) tentatively infer the latter because of the presence of Early Devonian sediments in the adjacent Cobar Basin.

Late Silurian – Devonian intrusive units

Intrusive activity within the southern Thomson Orogen spans the middle Silurian to the Middle to Late Triassic. Outcrop is restricted to the west in the Tibooburra Inlier (Figure 36), but it is inferred geophysically that intrusives are more common beneath cover in the east (Figure 38; Hegarty, 2010).

The **Tibooburra Suite** intrudes the Easter Monday Formation of the Warratta Group. The suite includes three mapped units; the Creswell Tank, Dynamite and Tibooburra granodiorites, as well as unnamed quartz-feldspar porphyry dykes, pegmatite, aplite, monzogabbro dykes and stocks, and diorite (Vickery, 2010). The Creswell Tank Granodiorite is medium-grained, leucocratic equigranular, massive quartz-feldspar-biotite granodiorite. The Dynamite Tank Granodiorite is massive, medium-grained quartz-feldspar-biotite-hornblende granodiorite with associated aplitic dykes and a single diorite phase. The Tibooburra Granodiorite is the main outcropping pluton of the suite and comprises mesocratic, medium-grained quartz-plagioclase-biotite-hornblende granodiorite (containing minor orthoclase, zircon and apatite), associated quartz-feldspar porphyry dykes, and pegmatitic bodies (Figures 44a,b). All three of the Tibooburra Suite intrusions are considered to form part of the same, more extensive body at depth. They were emplaced after the Benambran Orogeny and pre- or syn-D_3. The suite ranges from 427.7 ± 2.3Ma to 420.2 ± 3.3Ma (middle to late Silurian; Black, 2006; 2007).

Figure 44. a) outcrop of the Tibooburra Granodiorite near Tibooburra;
b) medium-grained quartz-plagioclase-biotite-hornblende unit of the Tibooburra Granodiorite

The Tibooburra Suite is generally I-type and granodiorite in composition (Thalhammer & others, 1998; Vickery, 2010). It has geochemical characteristics interpreted as representing melting of a heterogeneous mantle source with crustal contamination and a continental rift-related basin setting (Bruce & Vickery, 2010).

Intrusions in the New South Wales part of the Thomson Orogen are interpreted to be abundant in the subsurface. They are defined from regional geophysical images and are broadly divided into: granites and intermediate intrusives with high magnetic intensity, granites having low magnetic intensity, and undifferentiated granite, gneiss and schist (Hegarty, 2010). They range from individual zoned plutons to larger plutonic complexes and very large batholiths (Figure 38), but very little is known about their geology and petrogenesis, and only a few have age constraints.

On the far eastern boundary of the southern Thomson Orogen, the S-type **Brewarrina Granite** (Figure 38) has a preliminary U–Pb SHRIMP zircon age of ~421Ma, contemporaneous with the Tibooburra suite. The youngest population of inherited zircons are dated at ~ 467Ma (Glen & others, 2010).

Table 13. General characteristics of stratigraphic groups in the Delamerian and Thomson Orogens in north-west New South Wales (summarised from Greenfield & others, 2010a)

Group	Constituent Units	Lithology	Structure/Metamorphism	Age	Depositional/emplacement environment
Grey Range Group	Kara Formation	Interbedded sandstone, siltstone; locally dolomitic and calcareous.	Macroboudinage, large, tight macroscopic folds and well-developed near-vertical slaty cleavage associated with Delamerian Orogeny. Well-developed mesoscopic folding and crenulation cleavage associated with Benabmran orogeny largely confined to zone through Nundora, Packsaddle and Milpa. Metamorphosed to prehnite-pumpellyite or lower greenschist facies (locally to upper greenschist facies)	Late Neoproterozoic, may extend to earliest Cambrian based on shell-like fragments. Mount Arrowsmith Volcanics U-Pb SHRIMP (zircon) ages of 586 ± 7Ma (Crawford & others, 1997); 585.5 ± 3.2Ma (Black, 2007).	Shallow marine shelfal to basinal environment – deposition on a continental platform/ plateau adjacent to craton. Mount Arrowsmith Volcanics include some subaerial lavas and associated intrusions. Depositional enviroments and alkaline geochemistry suggests continental rifting.
	Mount Arrowsmith Volcanics	Basaltic to rhyolitic submarine flows, sills and intrusions.			
Teltawongee Group	Nundora, Wonnaminta, Copper Mine Range, Depot Glen, Bunker Creek formations	Predominantly interbedded sandstone and siltstone. Monotonous graded-bedded sandstones.	Steeply dipping bedding, tight upright folds (mesoscopic and macroscopic), strong slaty cleavage due to recrystallisation of mud and silt fraction within sandstones. Metamorphosed to chlorite zone (greenschist facies).	Early Cambrian based on non-diagnostic fossils and a U-Pb SHRIMP (zircon) date of 515.1 ± 2.7Ma for a quasi-conformable sill (Williams Peak Granite) (Black, 2007)	Turbidites deposited on east-facing continental slope or basin margin
	Evelyn Creek Volcanics	Mafic to intermediate sills, dykes and lava flows. Alkaline compositions.	Variably folded and strongly foliated parallel to regional fabric developed during Benambran Orogeny. Greenschist (locally upper) facies metamorphism	Middle to Late Cambrian (Stratigraphic evidence) (Mills, 2010a)	Intra-continental rift setting (Bruce & Vickery, 2010)
Gnalta Group	Mount Wright Volcanics and Cymbric Vale Formation	Calc-alkaline andesite, dacite, minor basaltic andesite, less abundant shale, chert, dolomitic limestone lenses.	Relatively undeformed, locally strong axial planar slaty cleavage. Pervasive low grade (phehnite-pumpellyite facies) metamorphism.	Early Cambrian-Late Cambrian. Abundant fossils; U-Pb SHRIMP (zircon) dates from pyroclastic deposits in the Cymbric Vale Fm (510.3 ± 3.2Ma and 510.5 ± 2.9Ma (Black, 2005; 2007).	Continental rift (Crawford & others, 1997); or transitional back-arc fore-arc (Bruce & Vickery, 2010); or Continental margin arc (Greenfield & others, 2011); subaqueous.
	Coonigan, Pincally and Wydjah Formations	Shale, siltstone, fossiliferous limestone, cross-bedded quartzose sandstone, dolostone.			Shallow marine to moderately deep open shelf (Percival, 2010a).
Ponto Group	Baroorangee Creek, Weinteriga Creek, Grassmere, Cannela, Noonthorangee, Koonenberry and Yandenberry Formations	Micaceous metasandstone, phyllitic metasiltstone, metamudstone, calcareous phyllites, felsic tuffs and tuffaceous mudstone, chert, quartz-magnetite rock.	Two stages of Delamerian deformation: 1) steep westerly dipping cleavage associated with strong triaxial strain and steep northerly pitching strain lineation, 2) vertical cleavage associated with extreme flattening, boudinage and isoclinal folding. Early D_1 rotated clockwise 80° about vertical axis in Grassmere Knee Zone. Metamorphosed to greenschist or lower amphibolite grade.	Cambrian. Airfall tuffs in Noonthorangee Formation dated at 508.6 ± 3.2Ma, 512.0 ± 3.1Ma, and 511.7 ± 3.5Ma (U-Pb SHRIMP zircon, Black, 2005).	Deep marine; base of continental slope (Mills, 2010c).
	Bittles Tank Volcanics	Mafic extrusive and intrusive igneous rocks including tholeiitic basalt, gabbro and dolerite.			Oceanic back-arc (Bruce & Vickery, 2010).

Table 13 (continued)

Group	Constituent Units	Lithology	Structure/Metamorphism	Age	Depositional/emplacement environment
Warratta Group	Easter Monday, Jeffreys Flat and Yancannia Formations.	Interbedded siltstone, sandstone and mudstone, local thin impure limestone and diamictite.	Rocks contain a penetrative foliation, inclined folding and reverse faulting – east vergent in Jeffreys Flat and Easter Monday Formations and west vergeint in Yancannia Formation. Kink folding and ductile drag folding overprint earlier deformation in Waratta Inlier. Metamorphosed to lower greenschist facies.	Late Cambrian-Early Ordovician, 497.2 ± 2.6Ma U-Pb SHRIMP date from tuff in Easter Monday Fm. (Webby, 1984; Black, 2006; 2007; Greenfield, 2010a).	Marine shelf to deep marine, represents subsidence and marine transgression following the end of the Delamerian Orogeny (Greenfield, 2010a).
Kayrunnera Group	Morden, Boshy, Watties Bore, Hummock, Cupala Creek, Hummock, and Wheeney Creek Formations, Funeral Creek and Kandie Tank Limestones, and Williams Creek Conglomerate	Variably deformed mudstone, siltstone, sandstone, limestone and polymictic conglomerate. Individual basins exhibit general fining up sequences.	Variably cleaved and folded but deformation differs between basins. Ranges from weak cleavage and open folding to strong cleavage, tight folding and mylonitic fabrics. Regional metamorphism increases from prehnite-pumpellyite in Cupala Creek Basin to lower greenschist facies in Nuntherungie Basin	Late Cambrian-Ordovician. Constrained by timing of Delamerian Orogeny and trilobite and conodont fossils.	Fluvial transitioning to shallow marine, Deep marine (Watties Bore Formation; Greenfield & others, 2010b)
Mutawintji Group	Bilpa and Nuchea conglomerates, Nootumbulla, Rowena and Scropes Range Formations, and Bynguano Quartzite	Predominantly quartzite, pebbly sandstones, basal conglomerates, occasional micaceous siltstones and calcareous beds.	Open folded and weakly cleaved. Metamorphosed to prehnite-pumpellyite facies during Benambran Orogeny.	Late Cambrian-Middle Ordovician. Constrained by conodonts, shelly faunas and trace fossils.	Fluvial to deltaic and shallow marine (Greenfield & others, 2010c).
Pimbilla Tank Group	Yandaminta Quartzite, and Tabita and Pingbilly Formations.	Clean, white quartzite, siliceous mudstone, fossiliferous limestone grading to dolostone interbedded with shales and siltstones.	Outcrop occurs on limbs and core of tight overturned syncline but cleavage is only weak to moderate in fine-grained clastic units.	Late Early Ordovician. Constrained by rich macro fauna.	Shallow marine (Percival, 2010c)

In central areas, the Hungerford Granite, which crops out as small bodies in Queensland (Figure 28) is interpreted to be part of a very large and complex body of intrusions in the subsurface (Figure 38).

The **Tinchelooka Diorite** to the south is slightly magnetic, and described as a quartz diorite based on drilling by Minotaur Exploration Ltd and Platsearch Ltd in 2008 (*in* Glen & others, 2010). It has a preliminary U–Pb SHRIMP zircon age of ~402Ma and inherited zircons from Mesoarchean to ~422Ma (Glen & others, 2010).

Immediately south, the **Utah Lake Plutonic Complex** forms an arcuate belt of non-magnetic granites (Figure 38). A K–Ar date of 389Ma was obtained from the Barrona granite which occurs along this belt (Richards & McDougall, 1986; *in* Glen & others, 2010).

The youngest dated intrusion is the highly fractionated, I-type **Midway Granite** which occurs in the eastern southern Thomson Orogen (Burton & others, 2007). U–Pb

SHRIMP (zircon) geochronology indicates that a small granite stock (235 ± 1.4Ma) and a swarm of porphyry dykes (237.1 ± 1.4Ma) associated with Sn and Cu skarn mineralisation from the unit are both Triassic in age (Burton & others, 2007).

MINERALISATION

The northern Thomson Orogen has been exploited for minerals since the mid 19th century. The first major discovery was the Clermont Goldfield in 1861 followed by the Cape River Goldfield (1867), the Ravenswood Goldfield (1868) and the most productive field, the Charters Towers Goldfield, in 1871. Production in the Charters Towers Goldfield peaked in 1899 at 12t for the year dwindling to 369kg in 1920. Mining in the region continued through the first half of the 20th century assisted by government subsidies for sinking shafts at low levels of production.

After the Second World War, interest renewed in exploration with modern techniques, initially focussed on base metal exploration and expanding into gold, leading to a series of significant discoveries. In the 1960s exploration in the Greenvale area identified nickel and cobalt resources and mining began in 1974. In 1986 the Mount Leyshon deposit was reopened and produced 95t of gold before closure in 2002. During this period, the Thalanga (1989) (zinc, copper, lead, silver, gold), Highway–Reward (copper, gold, silver), Ravenswood (gold), Disraeli, Black Jack, and Far Fanning mines all entered production and several are still active.

The northern Thomson Orogen region hosts volcanic-hosted massive sulphide (VHMS) deposits and nickel–cobalt–scandium laterite deposits that are related to the emplacement of early Paleozoic rocks. Other deposits hosted by sedimentary, metasedimentary and igneous rock emplaced within the Thomson Orogen are related to the Pama, Macrossan and Kennedy Igneous Associations which extend throughout eastern Australia, Torres Strait and Papua New Guinea.

The first group of mineral deposits in the Thomson Orogen were emplaced post Rodinia break up in a magma-poor rifted margin setting. These include:

- the Peak Downs copper deposit associated with the Bathampton Metamorphics (Anakie Metamorphic Group),
- primary nickel mineralisation in the Sandalwood Serpentinite (Boiler Gully Complex of the Halls Reward Metamorphics) and the Argentine Metamorphics, subsequently weathered to form nickel–cobalt–scandium rich laterite at the Minamoolka, Kokomo, Bell Creak, Lucky Break, Greenvale and Lucknow deposits, and
- podiform chromite mineralisation within fault slivers of the Gray Creek Complex (Gray Creek North and Gray Creek South).

These deposits are significant but are a small component of the economic mineralisation of the Thomson Orogen.

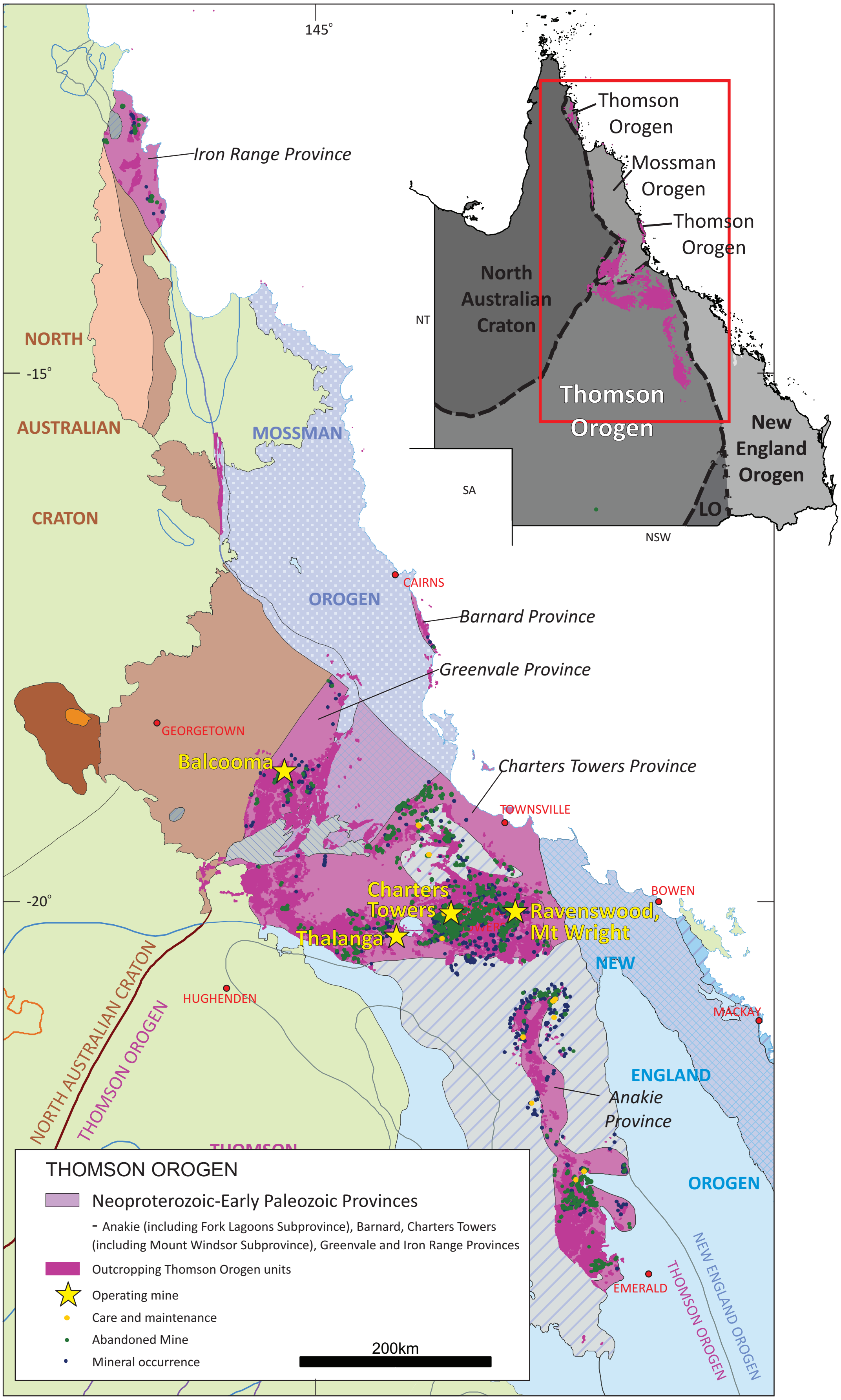


Figure 45. Distribution of known mineralisation (symbolised by status) throughout the outcropping Thomson Orogen

Transition to an active margin environment during the Delamerian–Tyennan–Ross Orogeny in the mid to late Cambrian was followed by extension early in the Benambran Cycle (Kositcin & others, 2009). During this time, the Balcooma Metavolcanic Group and Seventy Mile Range Group were deposited. These host two clusters of copper–lead–zinc–gold–silver bearing VHMS deposits centred on the major Balcooma and Thalanga mines. These have been the major producers of base metals in the Thomson Orogen and are economically significant. The Late Ordovician–early Silurian Benambran Orogeny terminated this period of mineralisation.

Emplacement of the Pama Igneous Association which includes elements of the Ravenswood, Reedy Springs, Lolworth, Retreat and Cape York Batholiths, occurred during a subsequent extension event in the Silurian to Devonian. Large amounts of gold were emplaced throughout the Thomson Orogen during this time including the Charters Towers Goldfield and deposits at Cape River, Lolworth, and Mount Remarkable. Historically, these are the most important deposits within the Thomson Orogen and hold significant resources of gold.

Subsequent magmatism throughout the mid-Carboniferous to mid-Permian (Kennedy Igneous Association) produced a similar volume of identified gold mineralisation to the earlier Pama Igneous Association. The mineralisation is dominantly gold in porphyry associated systems emplaced into metasedimentary and intrusive rocks of the Thomson Orogen. The most significant deposit is Mount Leyshon which yielded over 90t of gold.

DEFINITION

The Thomson Orogen is a complex four dimensional geological domain which is most often portrayed in plan (2D) view. This led to difficulty in defining the mineralisation to be considered in this review. For simplicity we have reviewed mineralisation that:

1. occurs within the spatial extent of the Thomson Orogen (Figure 2)
2. is associated with or hosted by rocks emplaced prior to or during the Benambran Orogeny. This event may be less prominent in Queensland so a late Silurian age may instead be considered.

The 21 815km^2 of exposed Thomson Orogen rocks contains 2327 mineral occurrences out of 21199 in the state (Figure 45), including 1770 of 8597 gold occurrences. To put this in perspective, 1.2% of the total land area of Queensland contains 20% of the gold occurrences.

Mineral deposits in this section are broadly divided by commodity, deposit model and age, although it should be noted that significant uncertainty exists in the formation ages of many deposits and their host rocks.

VOLCANIC-HOSTED MASSIVE SULPHIDES

Volcanic-hosted massive sulphide (VHMS) deposits are formed at or just below the seafloor and are related to mixing of seawater with magmatic hydrothermal fluids in a range of volcanically active tectonic environments. ‘Black smokers’ found at mid-ocean ridges reflect modern examples of VHMS mineralisation processes but have poor preservation potential. Continental back-arc basins (Figure 46) have greater preservation potential and the majority of ancient VHMS deposits are associated with these settings (Huston & others, 2010). The majority of the economic deposits of copper–lead–zinc and a significant portion of the gold and silver from the Thomson Orogen, occur in VHMS deposits.

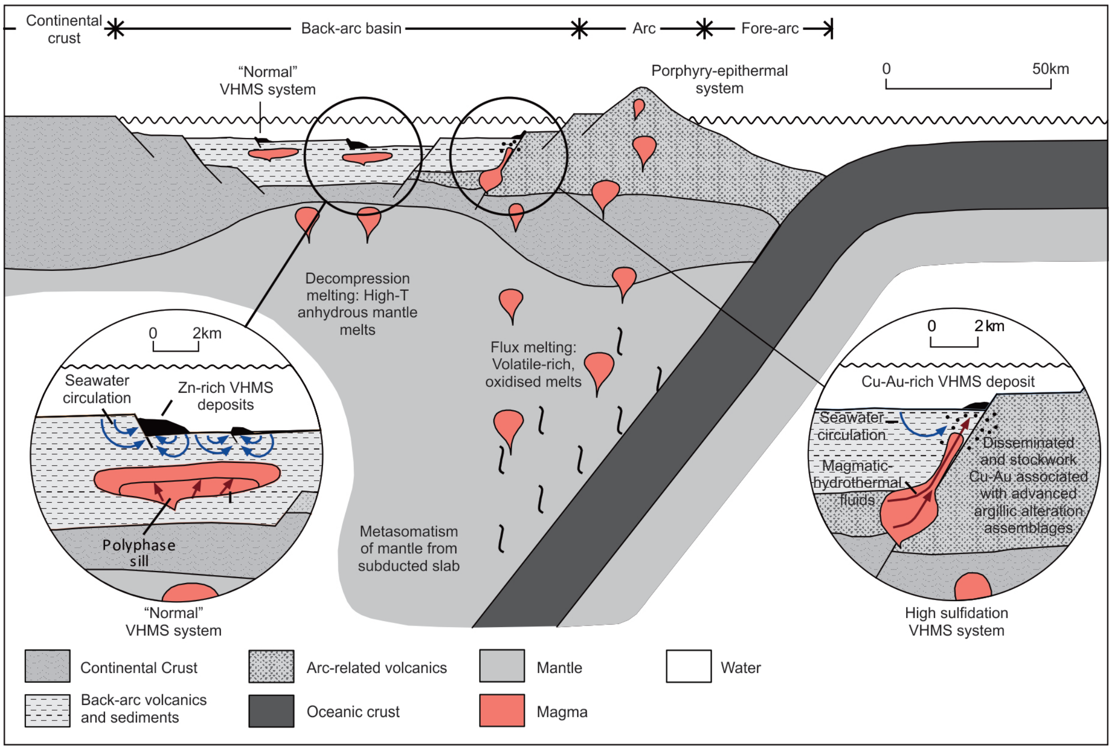


Figure 46. Possible settings of some VHMS deposits within an idealised convergent margin. The figure also shows the dominant influence of magmatic hydrothermal fluids on higher temperature copper gold rich VHMS deposits in contrast to a greater influence of seawater circulation in zinc rich deposits (from Huston & others, 2010).

Three types of VHMS deposits are defined (Cyprus, Besshi and Kuroko) based on associated igneous rocks and mineralogy (Cox & Singer, 1986). Kuroko-type deposits are associated with felsic igneous rocks and pyritic massive sulphide deposits enriched in copper, zinc, lead and barium which contain sulphates. Cyprus-type deposits are hosted by ophiolitic pillow basalts and are enriched in copper ± zinc and lack sulphates. Besshi-type deposits are associated with interlayered igneous and sedimentary rocks are enriched in copper ± zinc and lack sulphates. Excluding the Peak Downs deposit, which is classified as Besshi-type, the majority of known VHMS deposits in the Thomson Orogen are classified Kuroko-type.

A more recent classification scheme (Franklin & others, 2005) divides deposits into five lithostratigraphic types or settings:

1. bimodal-mafic — incipient rifted suprasubduction oceanic arcs,
2. mafic — primitive oceanic back-arcs, typified by ophiolite sequences,
3. pelite-mafic — mature oceanic back-arcs with subequal pelite and basalt,
4. bimodal-felsic — incipient rifted supra-subduction continental arcs with 35-70% felsic volcaniclastic strata, and
5. siliciclastic-felsic — mature continental back-arcs with continent-derived and volcaniclastic strata.

In this scheme, the Peak Downs deposit falls into the pelitic-mafic category while the remainder of Thomson Orogen deposits are classified as bimodal-felsic.

Structural controls on VHMS deposits are variable, but centre around fluid pathways. Mineral deposits may occur in the plumbing system or on the seafloor as fluids are expelled through sediments and volcanic rocks. The alteration associated with VHMS deposits is a result of the mixing of sea water with magmatic fluids and takes place at relatively low temperatures and low pressures. The morphology, mineralogy and geochemistry of alteration associated with VHMS mineralisation are variable. Alteration associated with Australian VHMS deposits, including those within the Thomson Orogen are thoroughly described through AMIRA project P439 (e.g. CODES, 1998).

In the Thomson Orogen, VHMS deposits were dominantly formed within the Cambrian–Ordovician back-arc setting of the Seventy Mile Range Group and equivalents in the Greenvale Province (Figure 47a,b). The Peak Downs deposit is an exception, being hosted in the Neoproterozoic to Cambrian Bathampton Metamorphics (Anakie Metamorphic Group) in a rifted margin setting (Fergusson & others, 2009).

The settings and geometries of VHMS deposits are also variable (Figure 46). The tabular Thalanga and related deposits have similarities to the ‘normal’ VHMS system of Huston & others, 2010, while the Highway and Reward deposits are more comparable to the copper–gold rich system with a more advanced argillic alteration and disseminated nature. This is consistent with their geographic locations; Highway Reward is some 50km east of the Thalanga deposit towards the hypothesised magmatic arc (Fergusson & others, 2007b).

Neoproterozoic–Cambrian

Known Neoproterozoic to Cambrian VHMS mineralisation in the Thomson Orogen is restricted to the Clermont copper mining area hosted by the Bathampton Metamorphics of the Anakie Metamorphic Group. The Peak Downs copper mine was the largest on the field. Comstock and West Copperfield which produced small

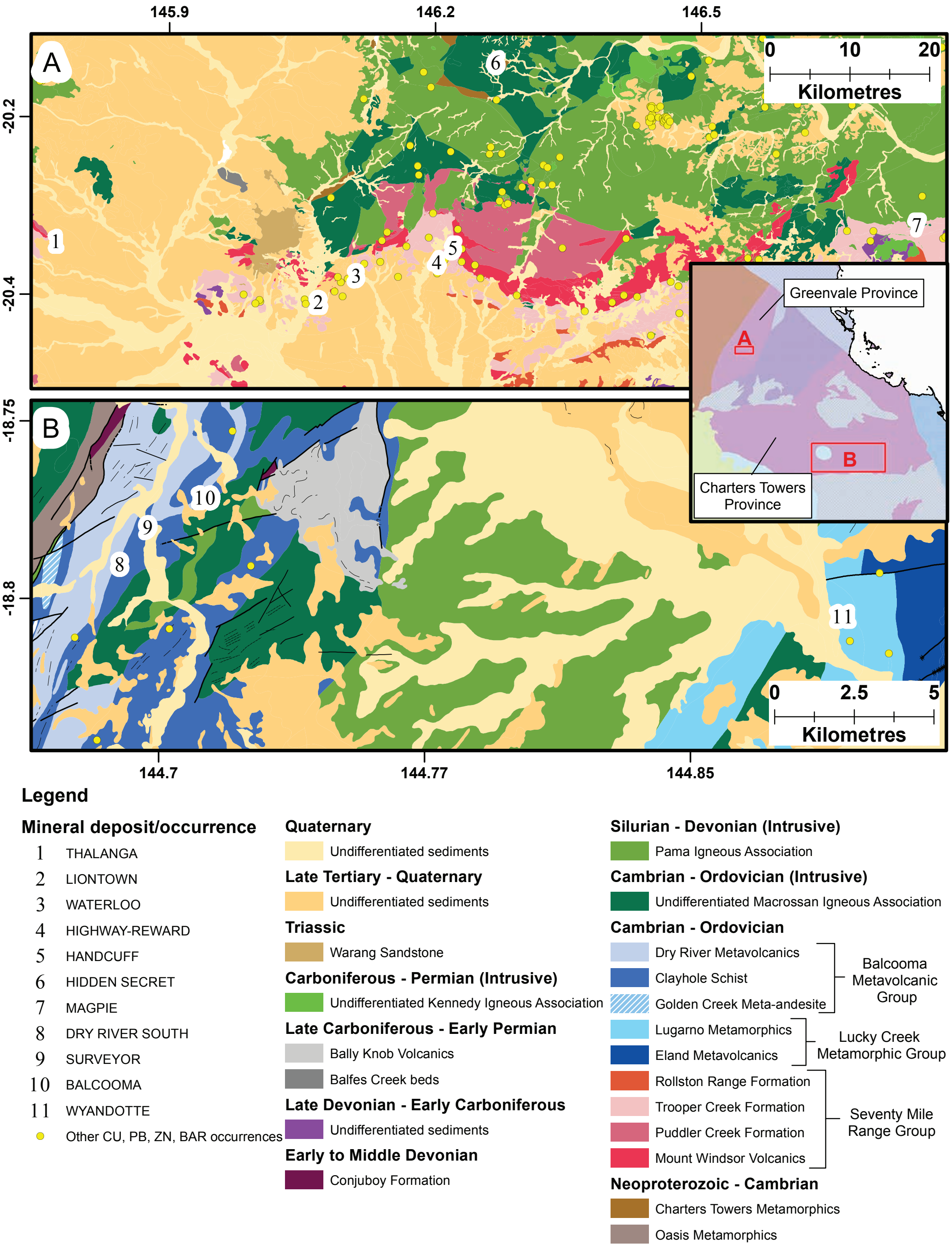


Figure 47. Location of VHMS deposits in the northern Thomson Orogen: a) VHMS deposits occur in a belt in the southern Charters Towers Province hosted by units of the Seventy Mile Range Group; b) VHMS deposits also occur in the central part of the Greenvale Province hosted by the Lucky Creek Metamorphic Group.

amounts of copper also fall into this group but are historical workings with no recorded production. Production of high grade copper ore prior to 1900 exceeded 100 000t, grading 17% copper. The Peak Downs mine extended over 500m in strike length and was worked from four shafts to a maximum depth of approximately 100m. Periodic attempts to reopen the mine have failed (Lam, 2005). The known resources currently total 6.8Mt of ore at 0.42% copper (Jerkovic, 1999).

The deposit is hosted by muscovite–quartz schist and chlorite–quartz schist of the Neoproterozoic Bathampton Metamorphics. Mineralisation occurs dominantly within a siliceous ironstone layer with some mineralisation within chlorite–quartz schist. The deposit comprises a pyrite–chalcopyrite lode with secondary chalcocite, and azurite and malachite present in the oxidised upper portion. Mineralisation is localised in a shear zone and concentrated within a strongly chlorite-altered zone. The mined parts of the deposit were significantly enriched by supergene processes. The primary ore averaged less than 4% copper, while secondary ore, dominantly comprising malachite and azurite in a siliceous ironstone gangue, averaged 17%.

The mineralisation at Peak Downs and surrounding deposits falls into the copper–gold high-sulphidation style suggested by Huston & others (2010) (Figure 46) or the Besshi style as suggested by Rees (1993). The classification schemes are not exclusive. Rees (1993) interpreted the mineralisation to have formed in a VHMS setting, and remobilised by later faulting with ore deposition in dilatational zones. Oxygen and sulphur isotopes indicate a significant input from sedimentary and metamorphic water to the ore forming hydrothermal system. The sulphur isotopes are enriched in ^{34}S which is indicative of a sedimentary/metamorphic or primary magmatic source and eliminates the possibility of input from biogenic sources (values $\delta^{34}S$ 6.5–11.3 %). Gold-bearing and barren quartz veins associated with the deposit both have $\delta^{18}O$ values between 13.8–15 %. The consistency of ^{18}O values indicates a long lived uniform source, consistent with a sedimentary metamorphic source (Wilson & Golding, 1984).

The age of the Peak Downs copper deposit is constrained by detrital zircon ages and K–Ar metamorphic ages from the Bathampton Metamorphics and the assumption that mineralisation was penecontemporaneous with host rock deposition. Mineralisation thus occurred between ~585Ma (MDA of the Bathampton Metamorphics) and a metamorphic cooling age of ~510Ma. Significantly these deposits pre-date the Delamerian Orogeny in Queensland (Withnall & others, 1995).

Although VHMS deposits of this age are not described elsewhere in the Thomson Orogen, several Neoproterozoic to Cambrian units include metavolcanic sequences and may be prospective.

Cambrian–Ordovician

The known Cambrian–Ordovician VHMS deposits of the Thomson Orogen are confined to rocks of the Seventy Mile Range Group in the Charters Towers Province and equivalents in the Greenvale Province. An extensional setting, following the Delamerian–Tyennan–Ross Orogeny, is interpreted for the Seventy Mile Range group. Extension has been interpreted as within a back-arc setting with an arc invoked to the east (Henderson, 1986; Stolz, 1995; Fergusson & others, 2007a,b) or by a non-subduction related episode of continental extension (Hutton, 2004). This period coincides with significant mineralisation throughout the Tasmanides including the 455–440Ma lode gold deposits in the Victoria, 450–440Ma porphyry copper-gold and related epithermal gold deposits in the Macquarie Arc of central New South Wales and the Tasmanian VHMS field (see Huston & others, 2006). The Seventy Mile Range Group and equivalents are the most significant mineralisation in the Thomson Orogen from this age range (Kositcin & others, 2009) and fall within a major peak of global VHMS deposit generation between 510 and 460Ma (Huston & others, 2010).

Charters Towers Province

Within the Seventy Mile Range Group, VHMS mineralisation occurs within the upper Mount Windsor Volcanics and overlying Trooper Creek Formation (Figure 47a). Both units include submarine volcanics and volcaniclastic deposits with compositions ranging from rhyolite-dacite in the Mount Windsor Volcanics to andesite-basalt in the Trooper Creek Formation. Volcano-sedimentary facies within the Trooper Creek Formation in particular, provide controls on the distribution and geometry of several important deposits (e.g. Highway–Reward, Thalanga) (Doyle & McPhie, 1999).

The age of the Seventy Mile Range Group and mineralisation is constrained by U–Pb zircon dates from the Mount Windsor Volcanics (481 ± 5 and 485 ± 5Ma; Perkins & others, 1993) and by fossil evidence in the Trooper Creek Formation (Lancefieldian 2 and 3 stages) and overlying Rollston Range Formation (Bendigonian) (Henderson, 1983). Mineralisation is effectively bracketed within a 5my window.

The **Thalanga** deposit occurs at the contact between the Mount Windsor Volcanics and the Trooper Creek Formation and was the largest tonnage deposit identified in the Seventy Mile Range Group (6.35Mt at 1.7% copper, 1.35% lead, 4.6% copper, 0.46g/t gold and 44.3g/t silver). Between 1991 and 2000, 35 6678t zinc, 87 833t lead and 79 403t of copper were produced from the main orebody at Thalanga. The deposit consists of several interconnected stratiform, tabular sulphide lenses hosted primarily by rhyolite (Figure 48). The primary deposit at Thalanga is three kilometres long with a total vertical dimension of 400m. Mineralisation strikes east-south-east and dips variably throughout. Lenses which host ore are up to 25m wide. Ore is dominantly sphalerite–pyrite–galena–chalcopyrite with significant but variable barite and alteration is localised on the deposit.

Syn-volcanism seafloor deposition is interpreted for the deposit. The footwall host sequence comprises rhyolitic lava flows and domes with subordinate rhyolitic breccias and volcaniclastic deposits. The hanging wall consists of porphyritic to aphyric dacite and minor basaltic andesite with minor volcaniclastic components which increase westward. Alteration is stronger in the footwall and involves strong silicification and propyllitic and sericitic alteration. The hanging wall has quartz sericite ± pyrite ± chlorite alteration. Chlorite, tremolite, dolomite and calcite rock is identified within the body of the deposit and has immobile element ratios that are strikingly similar to the host rhyolite. These horizons are interpreted as strongly altered rhyolite recrystallised by subsequent regional metamorphism (Herrmann & Hill, 2001). Rare ironstones which occur in the distal parts of the Thalanga ore lenses are considered to be true exhalites.

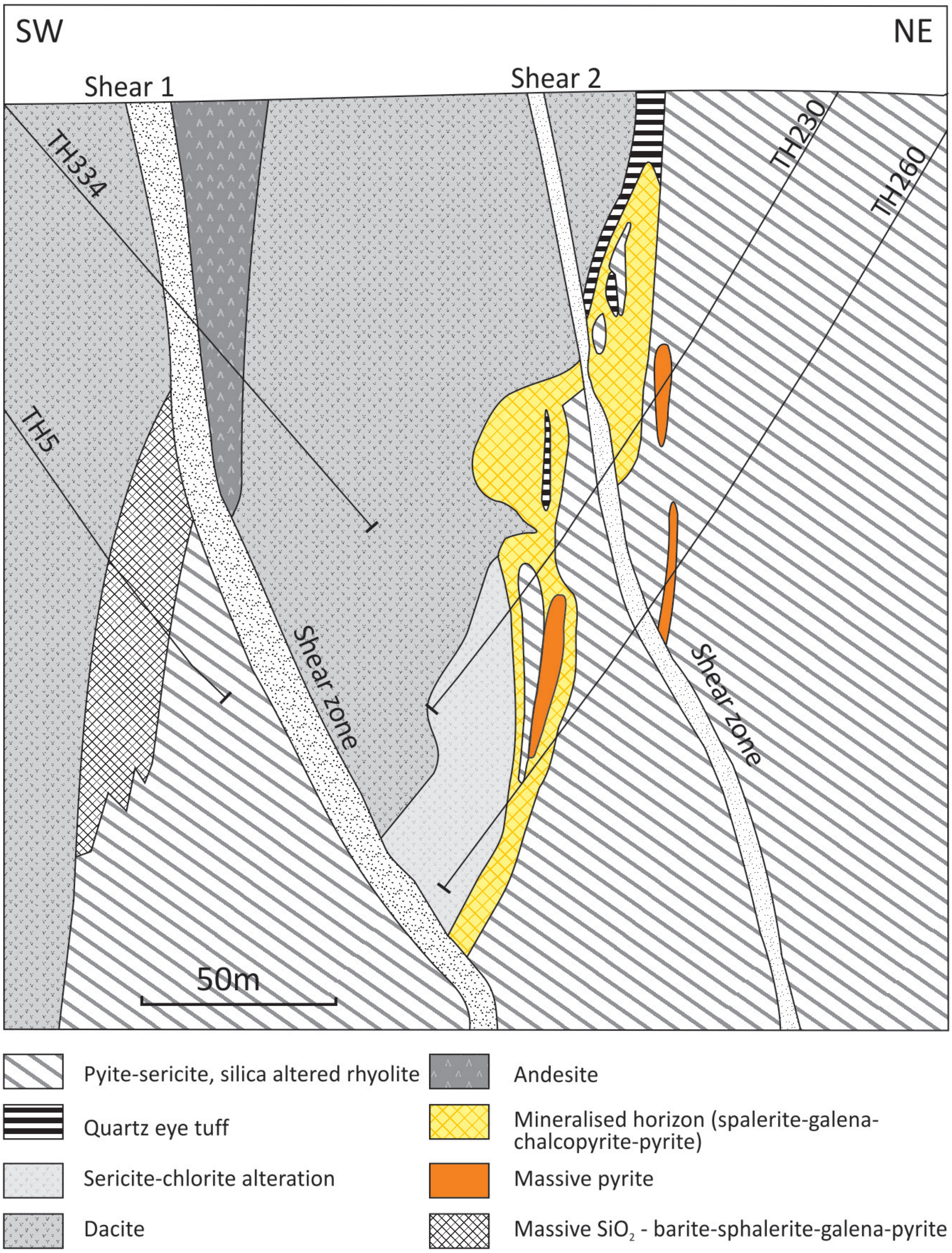


Figure 48. Cross-section of the central portion of the Thalanga deposit showing the relationships of ore and host rocks (from Berry & others, 1992)

Thalanga is flanked by several satellite deposits; the **West 45**, **Vomacka** and **Orient** deposits which are similar in character and stratigraphic position, but smaller than the main deposit. The **East Thalanga** and **Far East** deposit is under cover of the Tertiary Campaspe Formation.

Liontown is the most significant in a group of VHMS deposits located 42km south-south-west of Charters Towers (Figure 47a). The deposit was mined between 1951

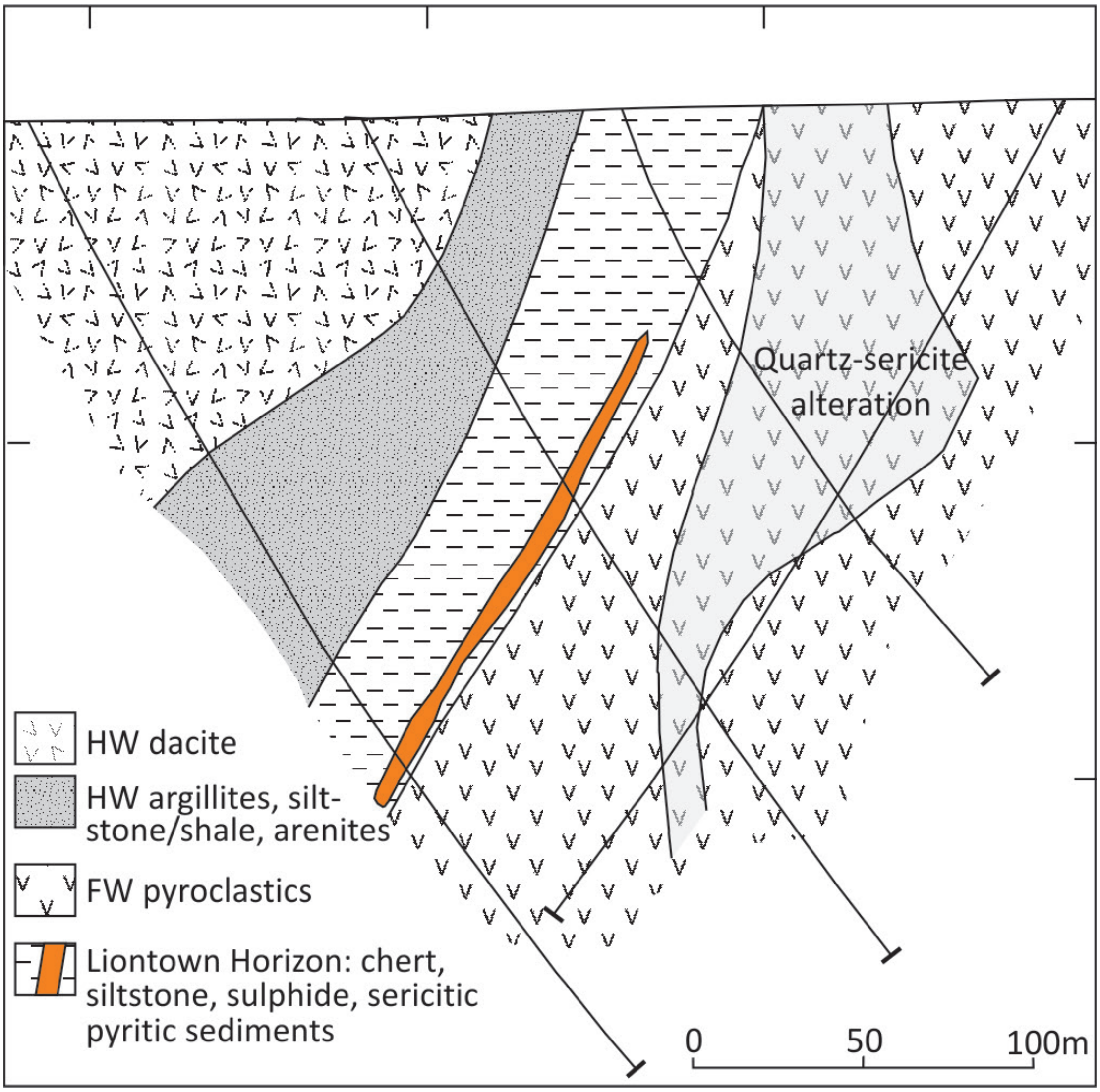


Figure 49. Cross-section showing distribution of sulphides, alteration and geology of the Liontown VHMS deposit (from Berry & others, 1992).

and 1961 and produced 93kg of fine gold, 1678kg of matte silver and 528t lead. Liontown has identified resources of 1.845Mt at 0.57% copper, 7.5% zinc, 2.5% lead, 0.4g/t gold and 28.3g/t silver (Appendix 4). The Liontown deposit occurs at the top of the Trooper Creek Formation at the contact with the overlying Rollston Range Formation. The deposit is hosted by cherty sediments that overlie schistose, quartz-sericite altered rhyolitic volcanics (Figure 49). The deposit consists of: stringer quartz veins (dominantly in the volcanics), which carry copper and gold; semi-massive to massive sphalerite-galena ± chalcopyrite pods which replace dacitic tuff; and finely bladed semi-massive sulphides within the cherty sediments (Berry & others, 1992). Secondary covellite, azurite and malachite occur within the weathered gossan of the deposit.

Waterloo is a small, high grade VHMS deposit 5km to the north-east of Liontown with an identified primary sulphide and transitional to oxide resource of 707 000t at 1.9% copper, 11% zinc, 1.6% lead, 50g/t silver, 1g/t gold and a smaller oxide resource (Appendix 4). It is hosted by the Trooper Creek Formation, but occurs under

20–50m of Tertiary Campaspe Formation cover. The footwall alteration zone consists dominantly of pyritic sericite schist and subordinate pyritic quartz-sericite schist. Protoliths are interpreted as andesite and andesitic volcaniclastic rocks respectively. The hanging wall comprises greywacke, argillite and chert. The mineralised zone is a subvertical lens up to 8m wide, 400m long and 200m thick dominated by chalcopyrite–pyrite–sphalerite with minor galena–arsenopyrite–tennantite and galena, secondary, covellite and chalcocite. The deposit also contains tellurides of silver, gold and lead (hessite, calaverite, petzite and altaite) and primary gold and electrum. The **Agincourt** deposit, an extension of the Waterloo system 1km to the north-west, is rich in barite but lacks a resource (Huston & others, 1995).

Magpie is an unmined VHMS deposit in the Dreghorn area, 70km south-east of Charters Towers. It is hosted within a rhyodacite–dacite, basalt, subvolcanic intrusion within the Trooper Creek Formation and overprinted by post mineralisation dolerite

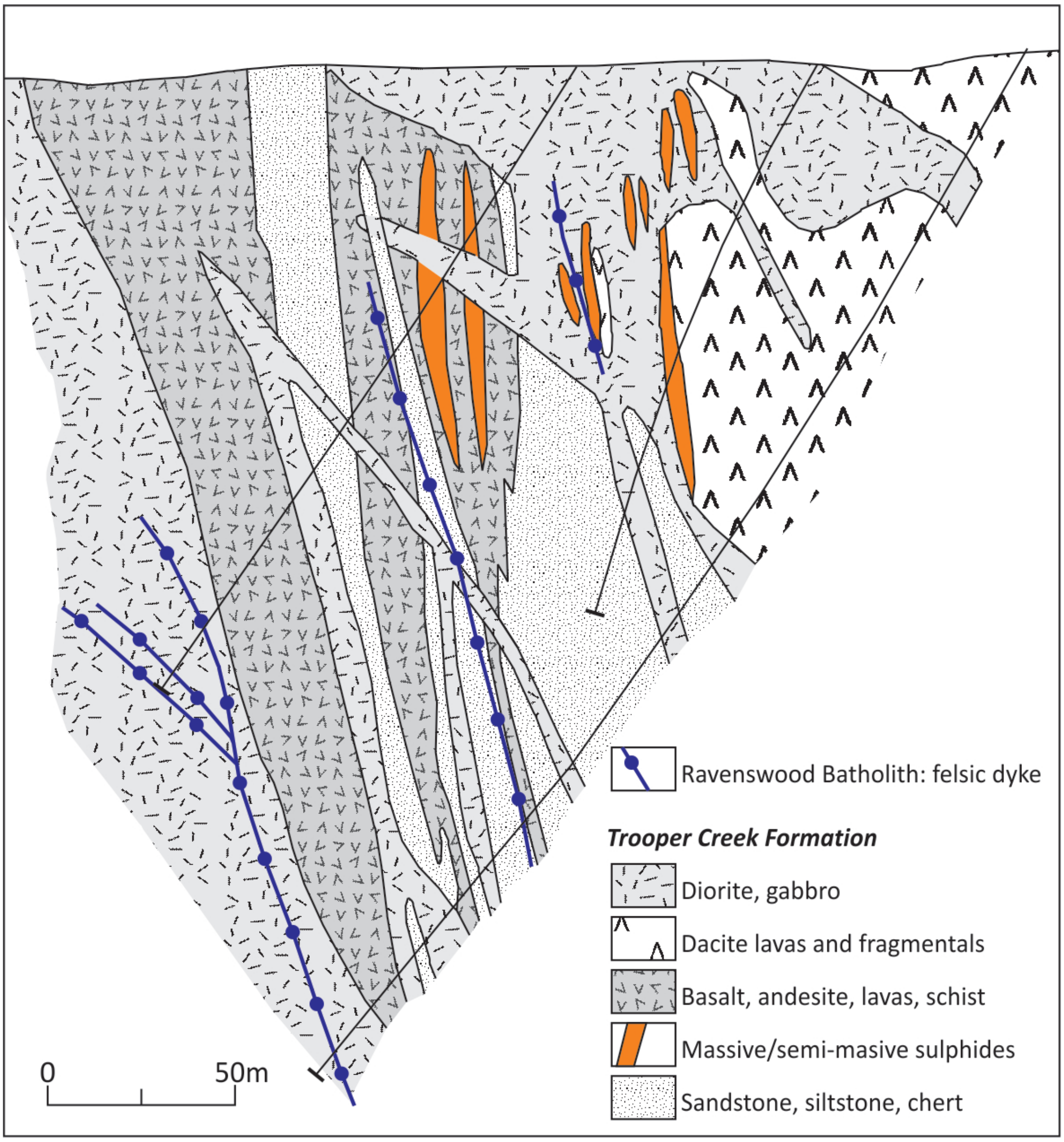


Figure 50. Geology of the unmined Magpie VHMS deposit showing massive/semi-massive sulphides in a series of stratigraphic subvertical lenses dipping southwards; no location or orientation data given (from Berry & others, 1992)

and gabbro (Figure 50). It has been altered by emplacement of the Ravenswood Batholith (Monecke & others, 2006). There are three lenses of mineralisation identified which range in thickness from 1 to 5m. The ore mineralogy is dominated by sphalerite and pyrite with less abundant chalcopyrite and galena. The sulphides have been recrystallised by subsequent metamorphism. Alteration is characterised by cordierite–andalusite hornfels facies metamorphism (Hutton & Withnall, 2007). The deposit forms a series of subvertical lenses (Figure 50) and is interpreted to have formed at or near the sea floor in a deep marine to moderately deep marine environment (Mulholland, 1991). Deposition was associated with development of an explosive dacitic cryptodome, which is altered in the same style as the mineralisation host rocks.

The **Highway–Reward** deposit was discovered in 1953 by Messrs Olsen and Thorne, who detected gold in a road scraping. Subsequent investigations were completed by Mount Isa Mines. The deposit is hosted by the Trooper Creek Formation. Lithofacies associated with the deposit are grouped into three associations (Doyle & McPhie, 1999):

1. volcanogenic sedimentary facies, including turbidites that indicate submarine, below storm wave base conditions,
2. primary volcanic facies including coherent rhyolite to dacite and associated breccias (autoclastic breccia and peperite),
3. resedimented, syn-eruptive facies including monomictic breccia (resedimented autoclastic breccia/peperite) and graded lithic-crystal-pumice breccia and sandstone.

Together, these define a submarine, shallow intrusion-dominated volcanic centre. Interestingly at least 10 different porphyritic intrusions are identified, the majority of which have peperitic upper margins indicating emplacement into wet unconsolidated sediments.

The geometry of the Highway–Reward deposit is complex and consists of two major pyrite–chalcopyrite pipes and several smaller north-north-east-trending pyrite–chalcopyrite pipes which are separated by strongly altered volcanic and sedimentary units (Figure 51). Alteration is pyrite ± quartz ± sericite stringer-type veining that extends 150m into the footwall and at least 60m into the hanging wall which is exposed at the surface. Metal ratios in the Highway–Reward deposits are characterised by high copper and low lead and zinc indicating a more mafic fluid source than other deposits of the Seventy Mile Range Group (Franklin & others, 2005). The deposit has a significant supergene component, dominantly comprised of chalcocite, and is partially buried by the Campaspe Formation (Beams & others, 1998).

Handcuff is a small, unmined lenticular orebody located 1.5km north-east along strike of the Reward deposit. It comprises a barite–chalcopyrite–anhydrite–sphalerite–galena–pyrite orebody with sericitic alteration and has a resource of 1Mt inferred at 0.4% copper, 7.4% zinc, 0.2% lead, 8.8g/t silver and 0.2g/t gold.

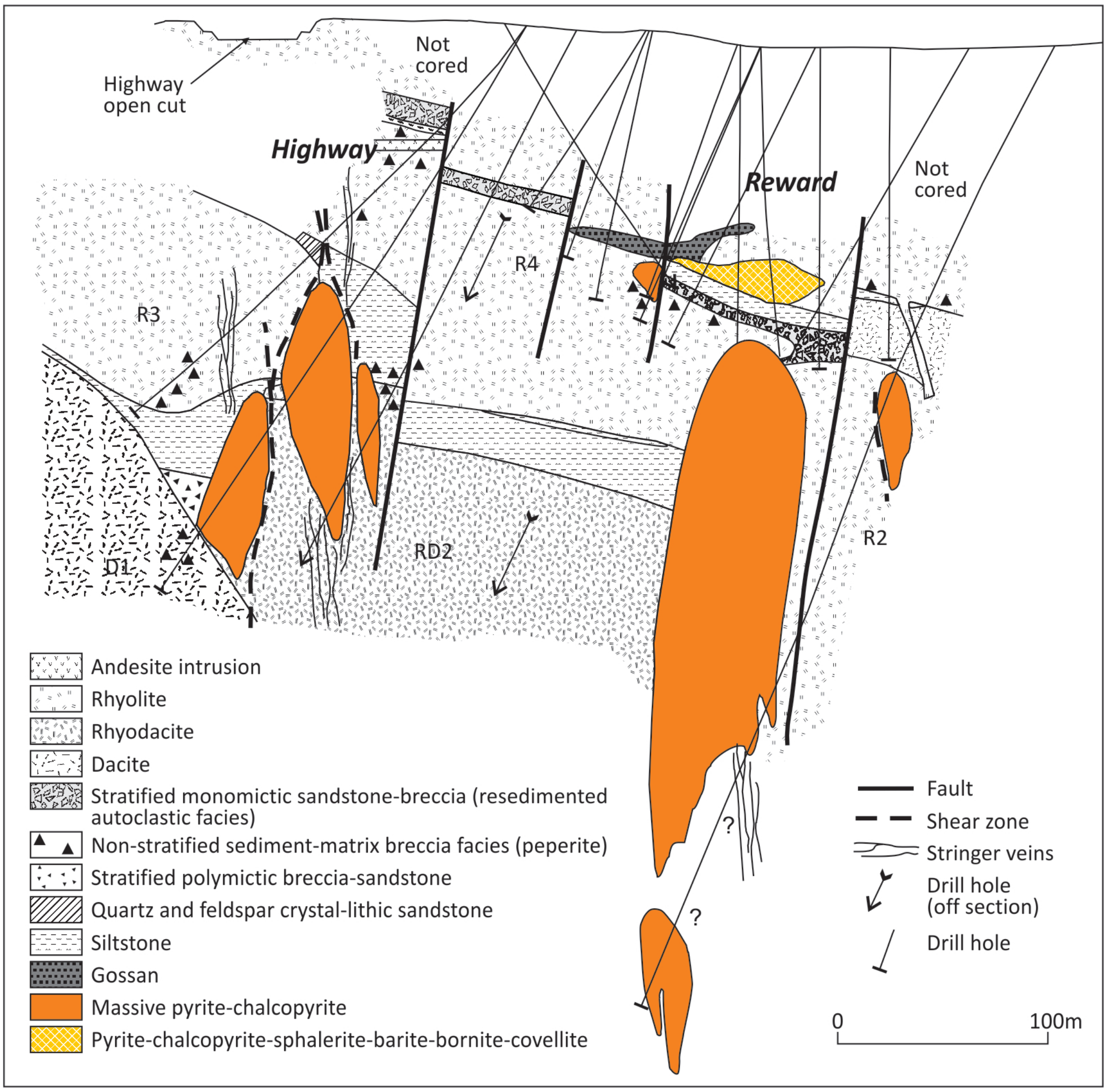


Figure 51. Simplified cross-section of the Highway–Reward deposit showing two main sulphide pipes hosted by various volcano-sedimentary facies of the Trooper Creek Formation (from Doyle & McPhie, 1999)

Greenvale Province

To the north, in the Greenvale Province, VHMS mineralisation is hosted by the Balcooma Metavolcanic Group and Lucky Creek Metamorphic Group (Figure 47b). These groups include rhyolitic metavolcanics and metasediments with minor mafic volcaniclastics and lava. They are considered equivalent to the Seventy Mile Range Group on the basis of lithological and geochronological similarity (Hutton & Withnall, 2007). Major deposits include Balcooma, Surveyor, and Dry River in the Balcooma Metavolcanic Group, and the Wyandotte copper deposit in the Lugano Metavolcanics of the Lucky Creek Metamorphic Group. A minimum age of mineralisation is given by a dyke that intrudes the Balcooma Metavolcanic Group (~471Ma, Withnall & others ,1991). The age of the Lugano Metavolcanics is poorly constrained.

The **Balcooma**, **Surveyor** and **Dry River South** deposits occur at the same stratigraphic level within the Balcooma Metavolcanic Group (Figure 47b). All three

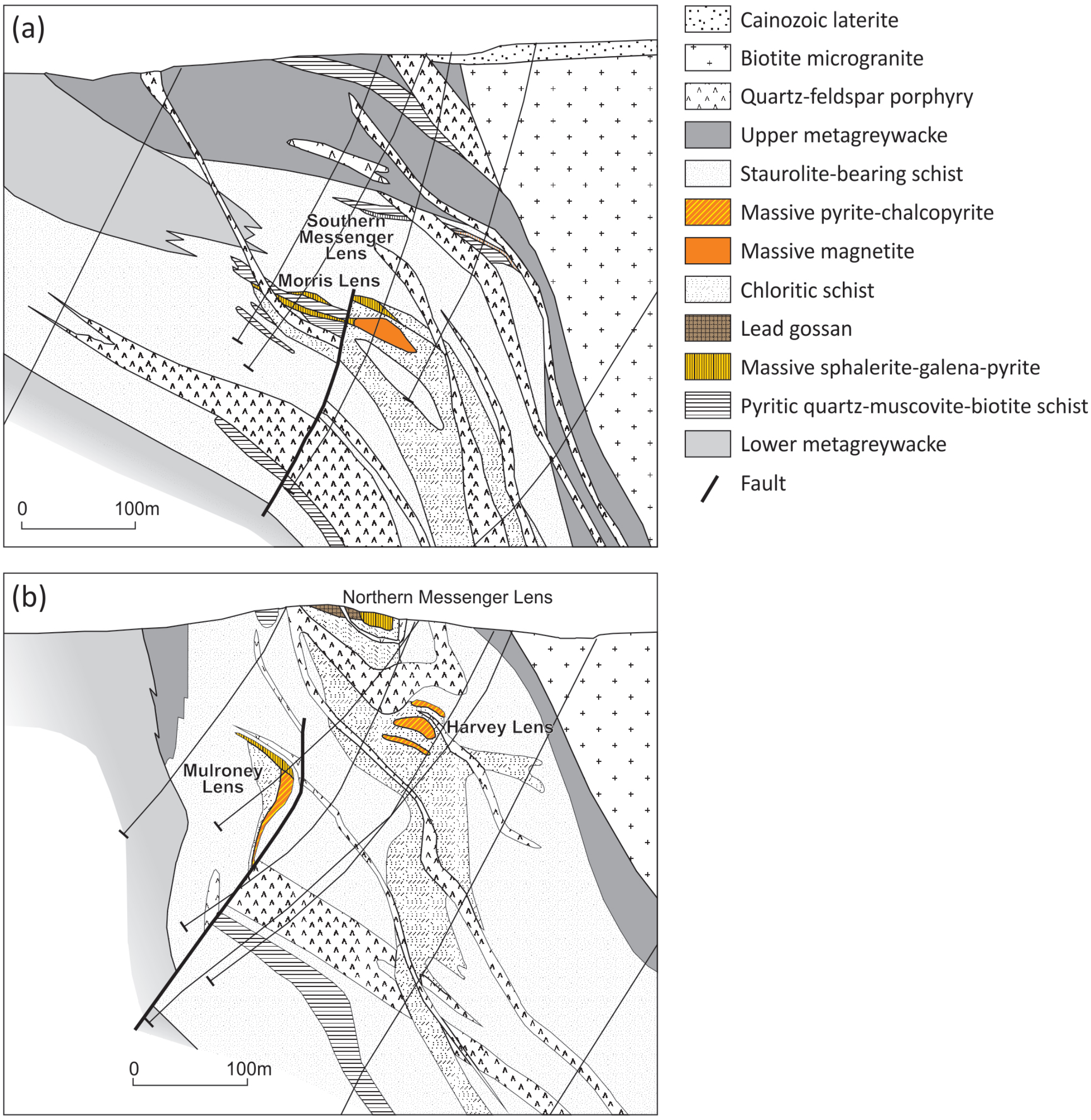


Figure 52. Cross-sections of the Balcooma VHMS deposit showing several copper, lead and zinc-rich horizons hosted by the Balcooma Metavolcanic Group, and drill holes used to constrain the cross-section (from Huston, 1990)

deposits have been mined, but the specifics of production from each mine is not recorded because reporting is rolled up with output from the Thalanga Copper Plant, and the Mount Garnet Plant which also includes production from other mines in north Queensland (e.g. Mungana and Mount Garnet). Production from the Thalanga Plant included 177 319t copper concentrates between 2006 and 2009, and 13 965t copper concentrate and 13 040t zinc concentrate in the 2010–2011 financial year. The Mount Garnet Plant produced 707.2kg gold, 61610t copper, 80720kg silver, 185 125t zinc and 33 525t lead between 2005–2010, and 104t lead, 40 125t zinc, 10 747t copper, 8.3kg gold and 900kg silver between 2010–2011. The deposits still host significant resources with a combined total of 2.3Mt at 1.06% copper, 2.5% lead, 5.8% zinc, 0.45g/t gold and 43g/t silver (Appendix 4).

The characteristics and age of these deposits are similar to the Thalanga deposits. **Balcooma** is hosted by a metapelite lens within a meta-arenite intruded by felsic sills (Figure 52). The mineralisation is divided into two zinc–lead-rich horizons and a

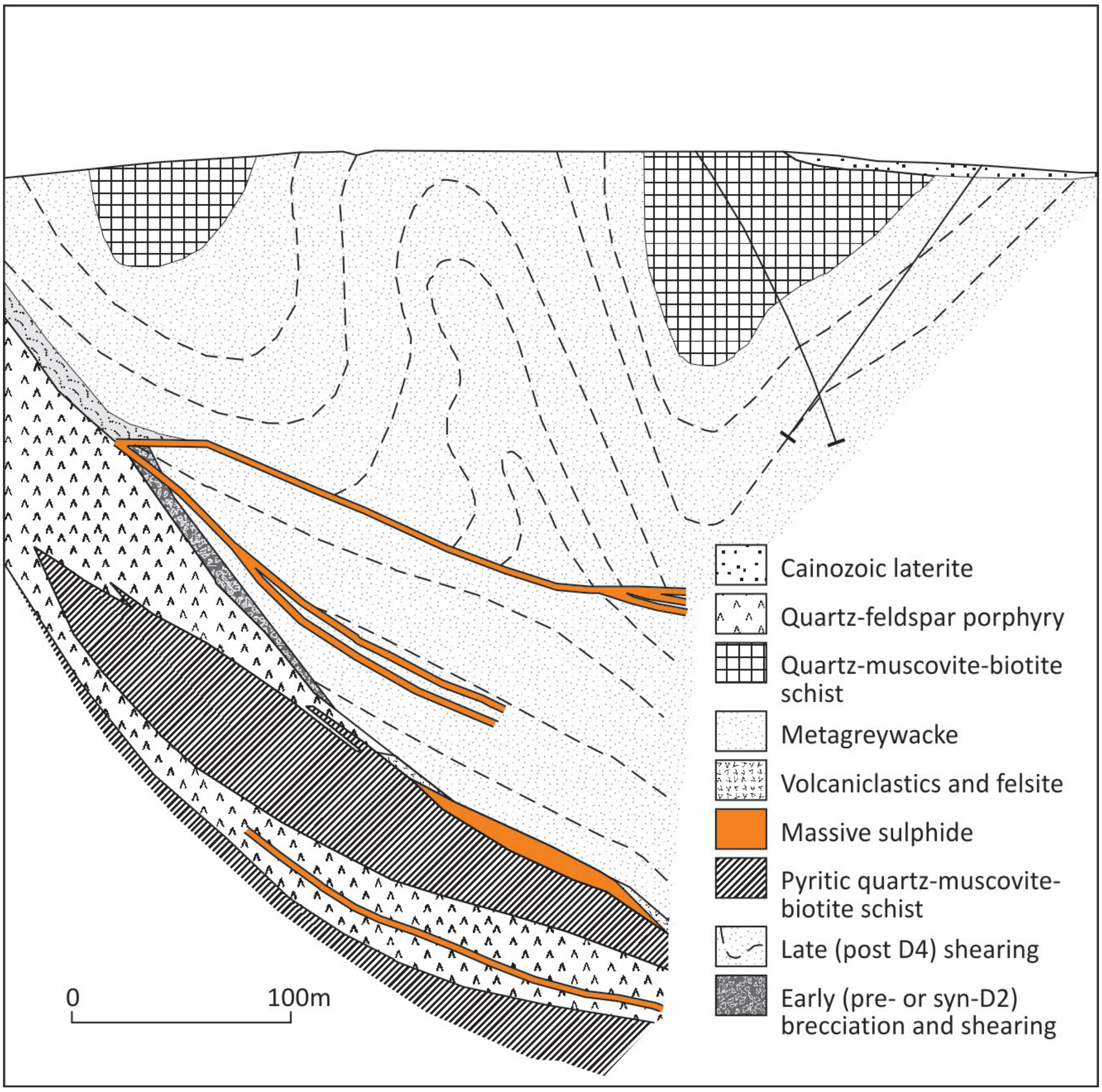


Figure 53. Cross-section showing the distribution of lithologies and sulphides associated with the Dry River South VHMS deposit (from Huston & others, 1992).

third copper-rich horizon. The copper-rich body is massive pyrite–chalcopyrite and magnetite with an alteration envelope of chloritised, staurolite-bearing metapelite which abuts a deformed quartz–feldspar porphyry. The zinc–lead mineralised horizons are associated with pyritic quartz–muscovite schist and consist of sphalerite–galena–pyrite–chalcopyrite. A gahnite-bearing quartzite adjacent to the deposit is interpreted as an exhalite (Huston, 1990). Metal ratios at Balcooma are variable with some parts of the deposit carrying high copper values and no lead or zinc, and other parts carrying similar ratios to Thalanga.

The **Dry River South** deposit occurs at the contact between altered volcanics and meta-arenite, quartz–feldspar porphyry and quartz–muscovite–biotite schist (Figure 53). The deposit is tabular in form, 1km long and up to 200m wide, trending south-south-west and dipping to the east. The mineralogy of the deposit is divided into two types: pyrite–chalcopyrite and pyrite–sphalerite–galena. Massive magnetite occurs as a facies equivalent to the massive sulphides. Footwall alteration adjacent to the mineralised horizon contains disseminated pyrite, biotite and staurolite. This alteration halo extends for up to 100m into the footwall. The deposit is significantly folded and faulted (Huston & others, 1992).

Surveyor is similar to Dry River South in mineralogy and occurs in the same stratigraphic position. The deposit consists of a lens ~300m long and up to 23m thick. The ore is sphalerite–galena–pyrite–chalcopyrite with some arsenopyrite, pyrrhotite, tetrahedrite, cerussite, anglesite, chalcocite and pyromorphite.

Huston & others (1992) considered that the copper deposits at Balcooma formed from high temperature volcanogenic fluids (>300°C), whereas lower temperature zinc-rich fluids (200–300°C) formed the zinc rich lens at Balcooma and the Dry River South and Surveyor deposits.

The **Wyandotte** copper deposit is a stratiform chalcopyrite–pyrite deposit hosted by an east–dipping epidote–amphibole schist within the mafic–ultramafic Lugano Metavolcanics. Limited data is available on the deposit, but 175 000t at 2.3% copper is indicated (Lachlan Resources NL, 1996).

SEDIMENTARY IRON

Schists with high iron content are found in the Iron Range Province, Barnard Province, Charters Towers Province and Anakie Province. The high iron content is likely related to the initial composition of the sedimentary protolith and thus these schists are interpreted as metamorphosed banded-iron-formation (BIF). Little work has been completed on these sedimentary iron deposits in the Thomson Orogen. None are currently economic but production has occurred from the **Mourilyan Harb**our deposit in the Barnard Province which was worked during the early 20th century (Morton, 1937). This is a Lake Superior type deposit dominated by hematite and hosted by schist of the Barnard Metamorphics. It consists of country rock with interlayers of hematite cut by quartz veins. Samples collected by Morton (1937) ranged from 45–58.3% iron. This deposit has affinities with deposits in the Iron Range Province further north.

Numerous small iron ore and manganese deposits were identified in the Iron Range by Broken Hill Pty Co. Ltd in the late 1950s and early 1960s (see summaries in Canavan, 1965; Brooks, 1970; Willmott & Powell, 1977; Bruvel & Morwood, 1992). These are hosted by the Sefton Metamorphics and form prominent hills in a north-north-west trending belt ~38km long and up to ~3km wide. The deposits are described as Lake Superior type and comprise steeply dipping lenses of hematite- and magnetite-rich schist and quartzite and the enriched weathering products. Two types of deposit were identified (Canavan, 1965):

1. Black Hill or northern-type deposits composed of magnetite quartzite with lesser hematite, manganese oxides, rhodochrosite, calcite, pyrite and pyrrhotite with an economically important residual capping with a high manganese content. The residual capping at Black Hill averages 3.3m thick with ~60% iron and manganese underlain by a less oxidised zone 15–30m thick.

2. Lammond Hill or southern-type deposits comprise hematite-quartz schist. They commonly lack a residual capping and contain little manganese.

Indicated reserves of 1Mt at 54–62% iron and manganese and inferred reserves of 305 000t at 45–55% iron and manganese are suggested for these deposits.

In the Argentine Metamorphics, ironstone is best developed about 8km east-south-east of Mount Podge. It was investigated by Poseidon Exploration Ltd as a possible source of magnetite and as a potential host for Starra-type gold deposits (Goulevitch *in* Evans, 1987). Quartz-hematite rocks with minor magnetite crop out as a series of elongate discontinuous zones up to 100m long and up to 10m wide (although scree around the outcrops generally extends much further). The rocks are locally banded (up to 5cm). Assays of core from shallow drillholes averaged 34% Fe and <1g/t Au. The ironstone is interbedded with laminated amphibolite and mica schist. Metachert, consisting of fine-grained saccharoidal quartz, and up to 15% Fe as hematite, may be a siliceous variant of the ironstone (Withnall & McLennan, 1991).

In the Anakie inlier, BIF is identified within greenstone units of the Bathampton Metamorphics. Exploration to date has focussed on gold and base metals associated with BIF rather than iron. Ironstone bodies up to 600m long occur at **Peak Downs, Comstock, Beefwood** and **Area K prospect** (Lam, 2005). The ironstone at Peak Downs for example is ~600m long and 2.5m thick. It is associated with copper and localised along an east-striking shear zone that dips gently south. It is massive, rich in hematite, goethite and magnetite, locally banded and interlayered with quartz (Lam, 2005).

ULTRAMAFIC

Lateritic nickel

Lateritic nickel deposits form where tropical weathering of mafic and ultramafic rocks concentrates mobile heavy elements in to the lower part of the regolith profile. In the Thomson Orogen, known lateritic nickel deposits (Figure 54) are derived from the Boiler Gully Complex (particularly the Sandalwood Serpentinite) of the Halls Reward Metamorphics, and the Argentine Metamorphics. These units include varying proportions of metamorphosed mafic and ultramafic rocks including amphibolite, metagabbro, and clinopyroxenite. They are Neoproterozoic to Ordovician but the age of exhumation and therefore laterite formation is unclear.

The **Lucknow** and **Greenvale** nickel deposits are near Greenvale and developed on serpentinite of the Sandalwood Serpentinite (Boiler Gully Complex) and in the Gray Creek Complex. The deposits comprise unevenly distributed, complex hydrated silicate lenses in lateritised serpentinite (Figure 55). Ore mineralogy is népouite, goethite, magnesite, chrysoprase, smectite and manganiferous wad. Between 1974 and 1992 428 762t nickel and 35 776t cobalt were produced from 39Mt of mined material. Significant resources remain and have recently been discovered to carry significant scandium. The remaining identified resources comprise 16.2Mt at 0.73% nickel,

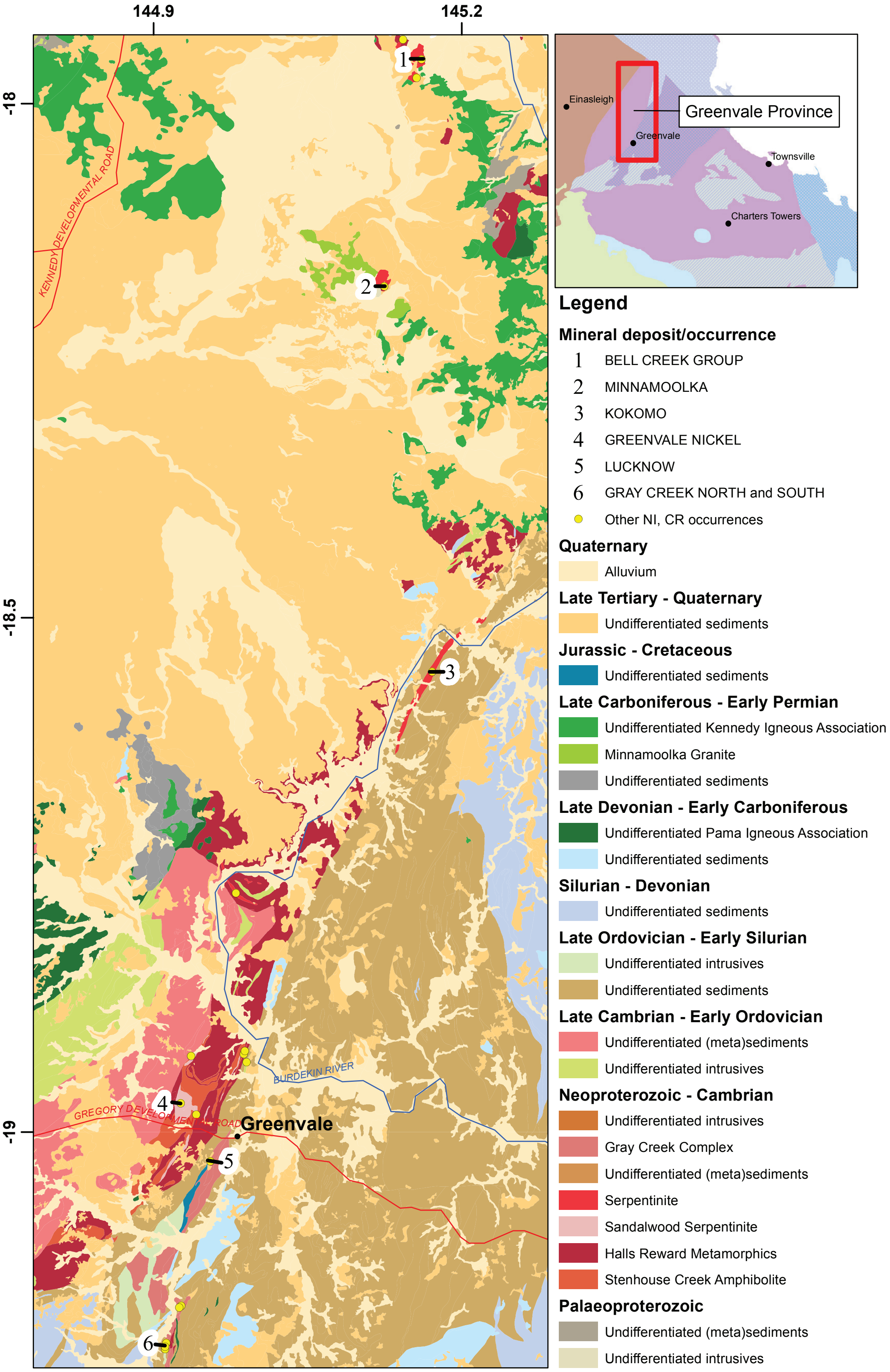


Figure 54. Distribution of major lateritic nickel deposits and podiform chromite along the eastern margin of the Greenvale Province in the Thomson Orogen

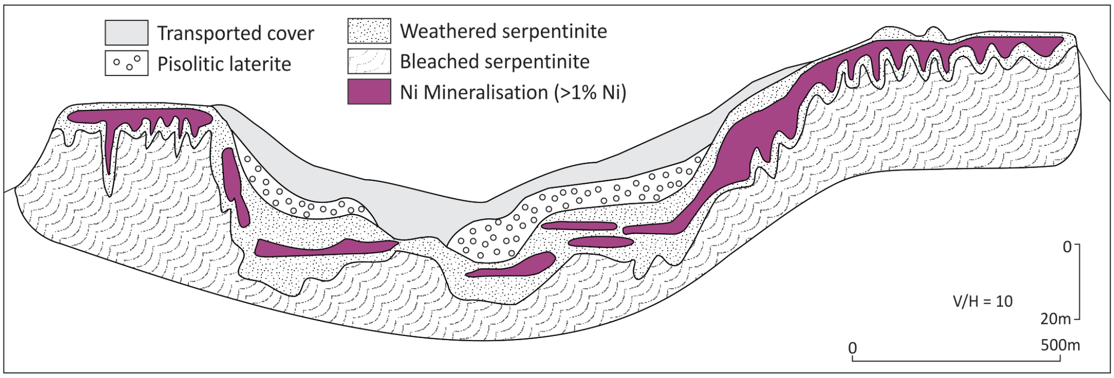


Figure 55. Schematic section showing the distribution of nickel mineralisation and relationship to the laterite weathering profile at Greenvale (from Burger, 1979)

0.05% cobalt, and 38g/t scandium at Greenvale and 13.8Mt at 0.31% nickel, 0.07%, cobalt, 116g/t scandium at Lucknow.

The **Kokomo** deposit, 52km north-north-east of Greenvale is developed within an extensive exposure of the Sandalwood Serpentinite that has been tectonically emplaced into the Ordovician Wairuna Formation. The total identified resource at Kokomo consists of 29.5Mt at 0.49% nickel, 0.08% cobalt, and 55g/t scandium. The deposit is also anomalous in platinum group elements but no resource has been established.

The **Minnamoolka** deposit is 42km north of Kokomo and 54km south of Mount Garnet. It occurs within a window of Sandalwood Serpentinite and the Carboniferous to Permian Minnamoolka Granite in an area dominated by Tertiary sediments. The deposit forms a series of shallow, thin, irregular to tabular bodies with narrow linear zones of high grade enrichment (Zeissink, 1977). The resource comprises 5.5Mt at 0.82% nickel and 0.04% cobalt (Appendix 4).

Further north, the **Bell Creek Group** of deposits (Bell Creek South, Bell Creek North, Bell Creek Northwest, The Neck) is 32km south-south-east of Mount Garnet. It is hosted by another window of Sandalwood Serpentinite through Tertiary sandstone and basalt. Resources total 12.9Mt at 0.91% nickel and 0.06% cobalt (Appendix 4). The mineralogy is presumed to be similar to the Greenvale deposit.

Lucky Break is another nickel laterite within the Thomson Orogen and occurs to the east, within the Argentine Metamorphics. The deposit is within heavily sheared, fractured and weathered, lateritised and silicified ultramafic rocks. Trial production was carried out in 2006 by Metallica Minerals but no records of tonnages are available. The current identified resource at Luck Break is 1.49Mt at 0.76% nickel and 0.04% cobalt.

Although serpentinite is known from the Anakie Province, such as at Grasstree Mountain, unlike the Greenvale area to the north, little to no supergene enrichment due to lateritisation has occurred.

Podiform chromite

Chromite deposits occur as pods within ultramafic rock packages. Details of deposits within the Gray Creek Complex (**Gray Creek South** and **Gray Creek North**) (Figure 54) were summarised by Lam (1998). They occur through an area of 7km^2 in several zones 2–3m wide and 100m long dipping 40°–90° west. Two ore types are identified; massive chromite lenses (41.0% Cr_2O_3, 17.6% Fe_2O_3, 24.9% Al_2O_3, 15.5% MgO), and disseminated chromite aggregates (41.3% Cr_2O_3, 15.8% Fe_2O_3, 26.6% Al_2O_3, 15.6% MgO). These form bands that are conformable with the host serpentinite foliation. A non-JORC-compliant resource estimate of 20 000t chromite was made at Gray Creek South in the 1950s. A combined resource of 290 000t chromite was made in the 1980s but problems with high silica content have inhibited further investigation (Lam, 1998).

Within the Anakie Inlier, lenses of chromite occur at **Grass Tree Mountain** in a 2m x 100m zone of serpentinite. Minor disseminated chromite associated with serpentinite also occurs at **Arsenic Ridge** (Lam, 2005).

OROGENIC GOLD

Orogenic gold deposits are associated with regionally metamorphosed terranes in which ore has formed during compressional or transpressional deformation processes at convergent plate margins at depths up to 20km. They are characterised by quartz-dominant vein systems with ≤3–5% sulphides and ≤5–15% carbonate material with strong vertical continuity and relatively high gold grades (5–30g/t). Deposits are commonly hosted by second or third order structures associated with major, often transcrustal, compressional structures. Fluids associated with orogenic gold systems are typically low salinity. Temperatures and pressures are in the range of 200–650°C and 1–5kb (i.e. midcrustal) and derived from regional events inherent along convergent margins. Alteration can be widespread due to the broad nature of the systems, and varies in style with wall rock chemistry and crustal level. Outward zonation from the veins is commonly observed on a scale of metres (Goldfarb & others, 2001). Gold deposits in Queensland with these characteristics have historically been classified as mesothermal or plutonic style gold deposits (e.g. Peters, 1987; Sillitoe & Thompson, 1998).

Orogenic gold deposits within the Thomson Orogen and throughout the Tasmanides are related to the development of the margin of Gondwana (Goldfarb & others, 2001; Haeberlin, 2002) (Figure 56). The long history of compressional and extensional deformation associated with the development of this margin and recorded by rocks of the Thomson Orogen make them particularly amenable to orogenic gold mineralisation. Relationships may also exist on a broad scale between orogenic gold deposits and granitic batholiths throughout the Thomson Orogen. The Charters Towers Goldfield, for example, is mostly hosted by granites of the Ravenswood Batholith.

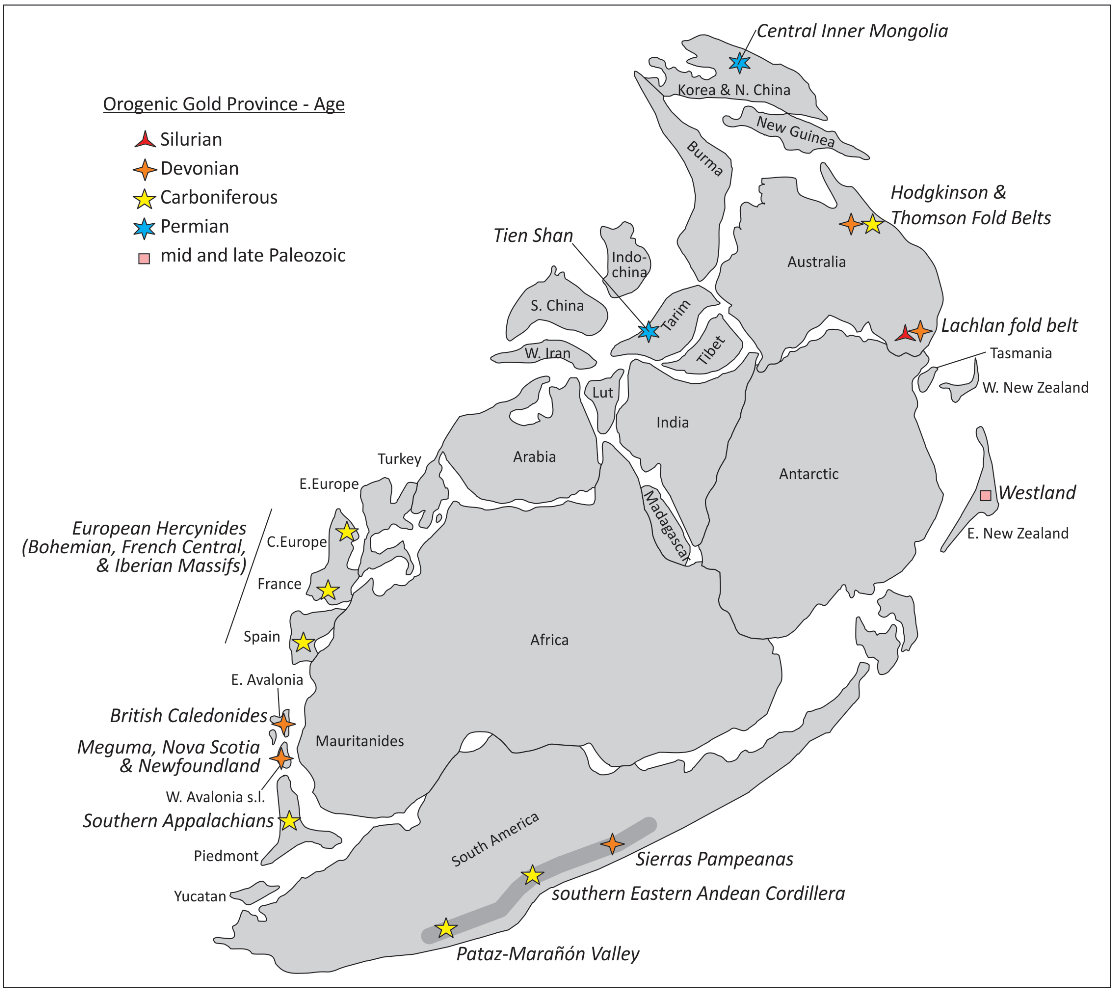


Figure 56. Distribution of orogenic gold provinces relative to a middle Cambrian reconstruction of the Gondwana supercontinent. Belts of mineralisation occur along the margins of the supercontinent (from Haberlin & others, 2002).

Known orogenic gold mineralisation is widespread in the Thomson Orogen, occurring in the far north (Iron Range Province), abundantly in the Charters Towers Province, and extending to the far south at Granite Springs, and in northern New South Wales at Tibooburra. However, it should be noted that assignment of deposits to the orogenic gold style is sometimes uncertain and the origin of many deposits, particularly those within the Anakie Inlier, are poorly constrained. In this section we also describe alluvial and deep lead deposits that may be associated with orogenic gold protores. These are economically important deposits, particularly around Clermont.

Silurian–Devonian

While the age of some host rocks are known, the ages of orogenic gold mineralisation in the Thomson Orogen are poorly constrained. Dating of alteration at Charters Towers indicates a Late Silurian – Early Devonian age and it is likely that most orogenic gold mineralisation was emplaced in the Silurian–Devonian.

Charters Towers

The Charters Towers Goldfield is the most productive goldfield in the Thomson Orogen and in Queensland. It hosts Queensland's largest known resources of gold with over 146t inferred gold resources (Denaro, 2011). The Charters Towers Goldfield is considered orogenic in style due to the wide geographic spread of similar mineralisation with orogenic characteristics outlined above. Mineralisation in the Charters Towers Goldfield is dominantly hosted by the Ravenswood Batholith. It is broadly coincident in time and style to significant gold mineralisation within the Proterozoic Etheridge Province, which abuts the Thomson Orogen, and from which over 20t gold has been extracted (Kreuzer, 2005).

The Charters Towers Goldfield (Figure 57) consists of several hundred workings. Deposits are dominantly hosted by quartz veins (with various orientations) within Silurian–Devonian and Ordovician granites and granodiorites of the Ravenswood Batholith. A minor component occurs within mafic intrusives and metasediments of the Charters Towers Metamorphics. The main veins broadly strike south-east to east with a shallow northerly dip but exceptions are common; there is a significant amount of north-striking veins which dip to the east at moderate to steep angles.

Mineralisation is commonly associated with potassic, propylitic and sericitic alteration and aplitic dykes are commonly associated with mineralised zones. Gold occurs as free gold or within pyrite and is commonly very small (40µm–80µm) (Kreuzer, 2005), although some deposits (e.g. Mary Lou) are renowned for spectacular leaf gold associated with galena and other sulphides. Tellurides have been reported, and fluorite and barite occur rarely in the southern lodes of the field such as the Lower Light House. Fluid inclusion studies from the Queen, Day Dawn and Brilliant lodes yield

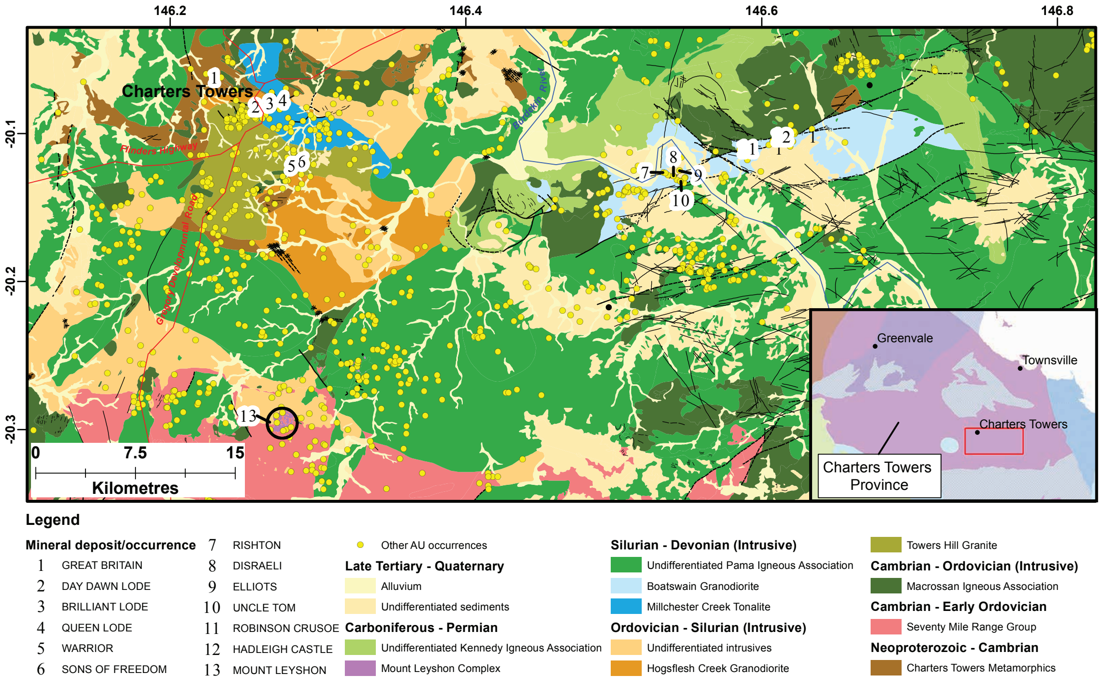


Figure 57. Distribution of abundant gold occurrences in the Charters Towers Province. Clusters of major deposits occur at Charters Towers (Charters Towers Goldfield) and at Rishton and Hadleigh Castle to the east. Location of Mount Leyshon to the south of Charters Towers is also shown.

values of 5.3–11wt% NaCl equivalent, at trapping temperatures of 240–300°C, with an expected formation depth of 2.5–3.5km. Sphalerite–galena isotope fractionation data indicate a 310°C fluid (Peters, 1987; Peters & Golding, 1989).

The great number of orogenic gold deposits in the Charters Towers field precludes more than a general reference to each except where some special feature has to be described, although in isolation these deposits would warrant significant attention.

The **Brilliant Lode** was discovered in 1889 as a blind orebody along with Day Dawn. It is the most significant lode on the field with production of 51t gold between 1879 and 1917. It is hosted by the Hogsflesh Creek Granodiorite and the Millchester Creek Tonalite. The deposit mineralogy comprises free gold hosted by a quartz–calcite vein with galena–pyrite–sphalerite–arsenopyrite–chalcopyrite and rare molybdenite. The vein is 0.75m wide on average, strikes east–west and dips 30–40° north. The deposit was mined to a maximum depth of 928m and an identified resource of 1.5Mt at 13g/t remains. Sericitic alteration associated with the Brilliant Lode within the Millchester Creek Tonalite is dated at 414.8±1Ma (^{40}Ar/^{39}Ar, Perkins & Kennedy, 1998).

The Brilliant East Lode was intersected at 1320m from the surface by CT5000, a collaborative drill hole between the Queensland Government and Citigold. At this depth the reef carried only 0.1g/t gold (Morrison & Lancaster, 2009).

The **Day Dawn** has a similar mineral assemblage to the Brilliant lode and is hosted by the Towers Hill Granite and the Hogsflesh Creek Granodiorite. The deposit strikes 100° and dips 50° to the north. It was mined to a maximum depth of 914m between 1873 and 1919 and produced 38.7t of gold from 1.6Mt of ore.

The **Great Britain** mine, hosted by the Charters Towers Metamorphics, produced 90kg of gold from 3259t of ore, and has a resource of 1.5Mt at 2.2g/t gold. It was mined to 144m between 1875 and 1910. It is the largest deposit on the field to be hosted by the Charters Towers Metamorphics.

The Charters Towers mining field was consolidated in 1985 by J.J. Lynch, Charters Towers Mines N.L. and Great Mines Ltd. Citigold Corporation subsequently took control and small-scale production has occurred since 1987. Initial production was from the Black Jack area which hosts the current treatment plant. The Imperial was then mined by opencut, followed by underground mining of the Warrior and Sons of Freedom reefs.

The **Warrior** gold mine is the operating portal via a decline from the base of the mined out Imperial pit, located 6km south-south-east of Charters Towers. This is used for accessing the south-western reefs of the Charters Towers Goldfield including the **Warrior** and **Sons of Freedom** deposits. The Warrior deposit has a known resource of 1.944Mt at 13.5g/t gold (Appendix 4). Production from the Warrior group since re-opening in 2006 is 2920.3kg of gold bullion. The mineralogy of the deposit is not significantly different from the Day Dawn or Brilliant Lode.

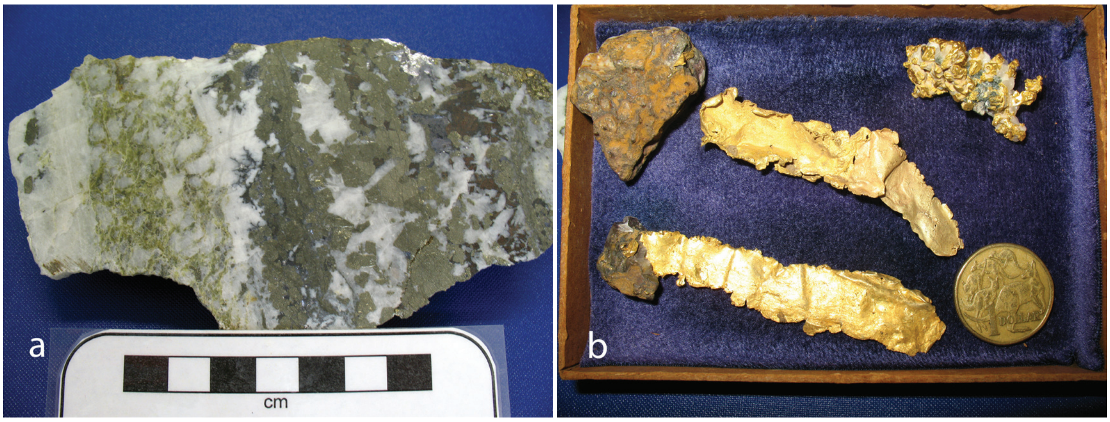


Figure 58. a) Typical gold mineralisation from the Charters Towers Field: pyrite-galena-chalcopyrite-sphalerite-quartz-epidote-calcite vein with flecks of gold. b) crystalline gold with quartz (top right) from the field and leaf gold (bottom) from the Mary Lou Mine.

Hadleigh Castle and Rishton Group

To the east of Charters Towers, the **Hadleigh Castle** and **Rishton group** of deposits (including **Disraeli)** are hosted by the east-north-easterly-trending Mosgardies Shear Zone (Kreuzer, 2005), which hosts several Permian–Carboniferous gold deposits (Hodkinson, 1998). Links exist between the Charters Towers and Hadleigh Castle belt, based on similarity of alteration ages, ore geology and emplacement along a major geophysical lineament (Kreuzer, 2005).

The **Hadleigh Castle** mine is 36km east of Charters Towers within the Boatswain Granodiorite, which consists of several granodiorite and diorite intrusions. The deposit consists of gold bearing quartz–sulphide veins located within a regional shear zone. Mineralisation is localised at the intersection of this major corridor, which trends east-north-east, and cross structures, which trend north–south and north-west–south-east. This confluence is the focus of intense alteration and shearing associated with gold mineralisation (Hodkinson, 1998). The major orebody is about 300m long, 80m wide and mined to 200m vertical depth from surface. It strikes 50–55° and dips 30–50° south-east. The actual width of the veins is generally less than 3m. Between 1874 and 2005, the mine produced 10 639kg of gold bullion from 2.3Mt of ore. **Robinson Crusoe** is a satellite deposit with similar geology, which was mined historically, and then by opencut in 1993–1994. It produced 379kg of gold from 187556t of ore.

The **Rishton** mining area is on the southern banks of the Burdekin River, 37km west of Ravenswood. After small scale historical mining between 1881 and 1942, this group of deposits were investigated by North Queensland Resources and an opencut and treatment plant were established. The latter also treated ore from the nearby **Hadleigh Castle** mine. The major opencut was the **Disraeli** and later the **Joe’s Delight**, but historical production also includes the **Rishton**, **Uncle Tom** and **Elliots** mines. Between 1881 and 1990 this group of deposits produced 2480kg of gold bullion from 1.1Mt of ore. The gold is in quartz sulphide veins hosted by the Boatswain Granodiorite. The Disraeli deposit comprises seven subparallel lenses

3–5m wide over total width of up to 50m. The area is partially covered by Tertiary sandstone as well as unconsolidated sediment deposited by the Burdekin River.

Cape River

The Cape River Goldfield and the **Pentland Deep Lead** (Figure 59) were discovered in 1867 by Richard Daintree and gazetted soon after. The **Pentland Deep lead** is a significant alluvial deposit, having produced over 1710kg of gold (Garrad, 1996). Gold is commonly waterworn and coarse with nuggets up to 2.8kg. It occurs in the lower 0.5m of the alluvium and is associated with quartz, schist and clay. The possibility of the gold being primary was considered in early reports (Annual Reports to the Department of Mines in 1894 and 1898) but was discounted by Garrad (1996). The source may have been to the north-west along Sandy Creek where the Cornelia Orthogneiss, amphibolites of the Cape River Metamorphics and the Bulgin Creek Granite crop out, but more evidence is required to establish the source of this significant alluvial goldfield. The area has undergone significant erosion and deposition throughout the Cenozoic so current landforms and drainage may be misleading in the search for the source of the alluvial gold deposits.

The **Gorge Creek** area of the Cape River Goldfield is a less substantial alluvial gold producer with some recent production of 114.571kg gold in 1980–1989. The field was mainly developed on alluvial gold but there are some small reefs known as the **Great Australian**, **Wheel of Fortune** and **Greens Reef.** The reefs are hosted by the Mount Elvan Granite and the Cape River Metamorphics. These deposits consist of gold-bearing quartz–sulphide veins which were multiply reactivated and contain potassium feldspar and sulphides. Various textures are consistent with the multiple reactivation of the veins: quartz matrix in silica–sericite alteration zone; crackle and fracture zone; networks of irregular quartz veins; and a strongly sheared footwall. A grunerite–magnetite–garnet quartzite horizon in the Cape River Metamorphics hosts the majority of deposits.

In the **Greens Reef** deposit gold is hosted within kaolinite with little quartz associated. This deposit is at the contact between granite of the Fat Hen Creek Complex and the Cape River Metamorphics. Gold is generally fine and associated sulphides are restricted to pyrite. The workings are on a north-westerly trending structure which is subparallel to the major fabric of the Cape River Metamorphics in the area.

By contrast, in the Mount Davenport area, two significant mines (**General Grant** and **Union)** exhibit mineralisation that is perpendicular to the foliation in the Cape River Metamorphics. The veins are narrow and variable in thickness and hosted by amphibolite with psammite, pegmatite masses and sericite schist. A narrow zone of sericitic wall-rock alteration is adjacent to the veins. Quartz is translucent with stylotised laminae, large dilational zones are typically unmineralised, and pyrite, galena and arsenopyrite occur rarely in the veins.

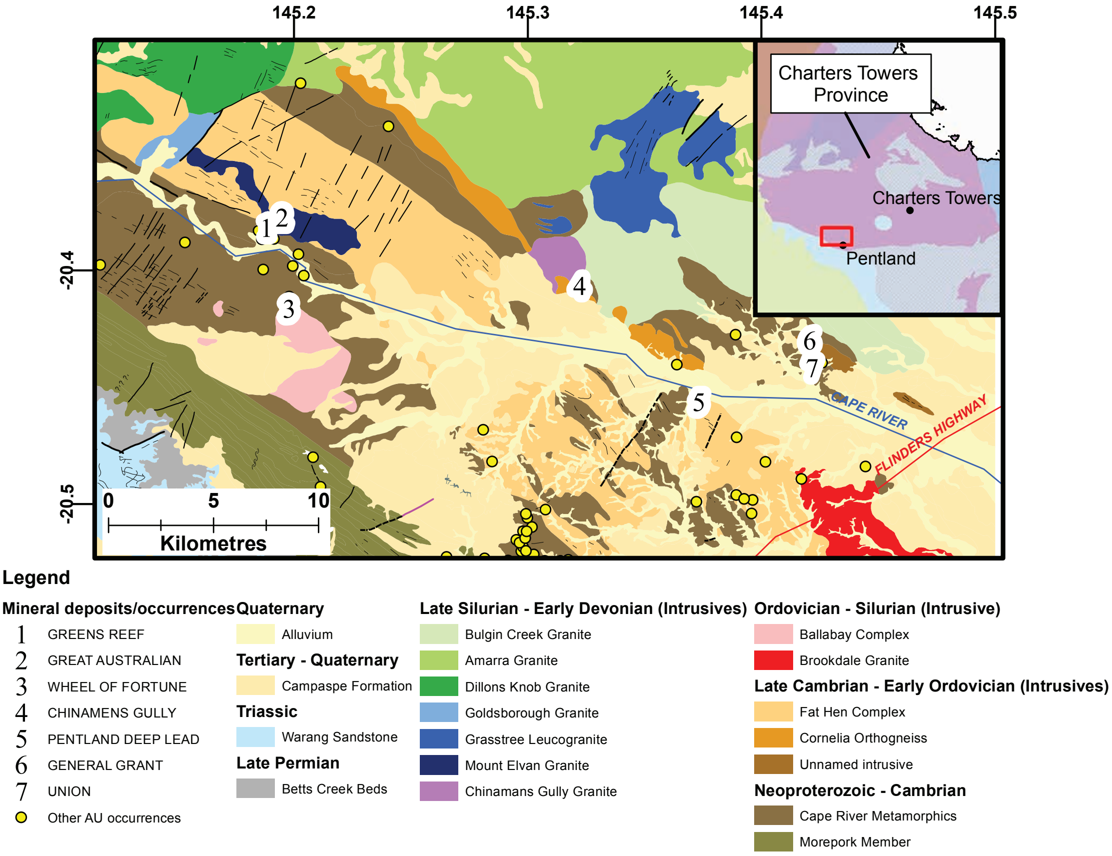


Figure 59. Distribution of primary and deep lead gold occurrences associated with the Cape River Metamorphics in the south-west of the Charters Towers Province

Chinamans Gully is a minor alluvial field with gold sourced from one reef associated with a dolerite dyke that is hosted by granite and amphibolite of the Cape River Metamorphics.

Greenvale Province

The Lucky Creek Goldfield in the Greenvale Province is hosted by the Lucky Creek Metamorphic Group and is associated with intrusion of Silurian granitoids. The **Steam Engine** mine was the major producer on the field with 11.7kg of gold produced between 1905 and 1911, and has a resource of 280 000t at 2.5g/t of gold remaining to a depth of 50m. The gold is associated with disseminated pyrite and arsenopyrite within silicified biotite–carbonate–sericite schist with 10% chalcopyrite, pyrrhotite, rutile, magnetite and tourmaline.

Argentine

In the Argentine Mineral Field gold was worked from the 1870s but deposits were generally regarded as small and low grade. Recorded production totals 1727.2t of ore for 39.78kg of gold bullion (Levingston, 1971; Morwood & others, 2001), but records are scarce because the field was mainly worked by mineral freehold tenures. The discovery of silver in 1881 led to a burst of activity and development including the **Hero, Ard Righ, Colorado** and **Northbrook** mines (Figure 60). Since 1886

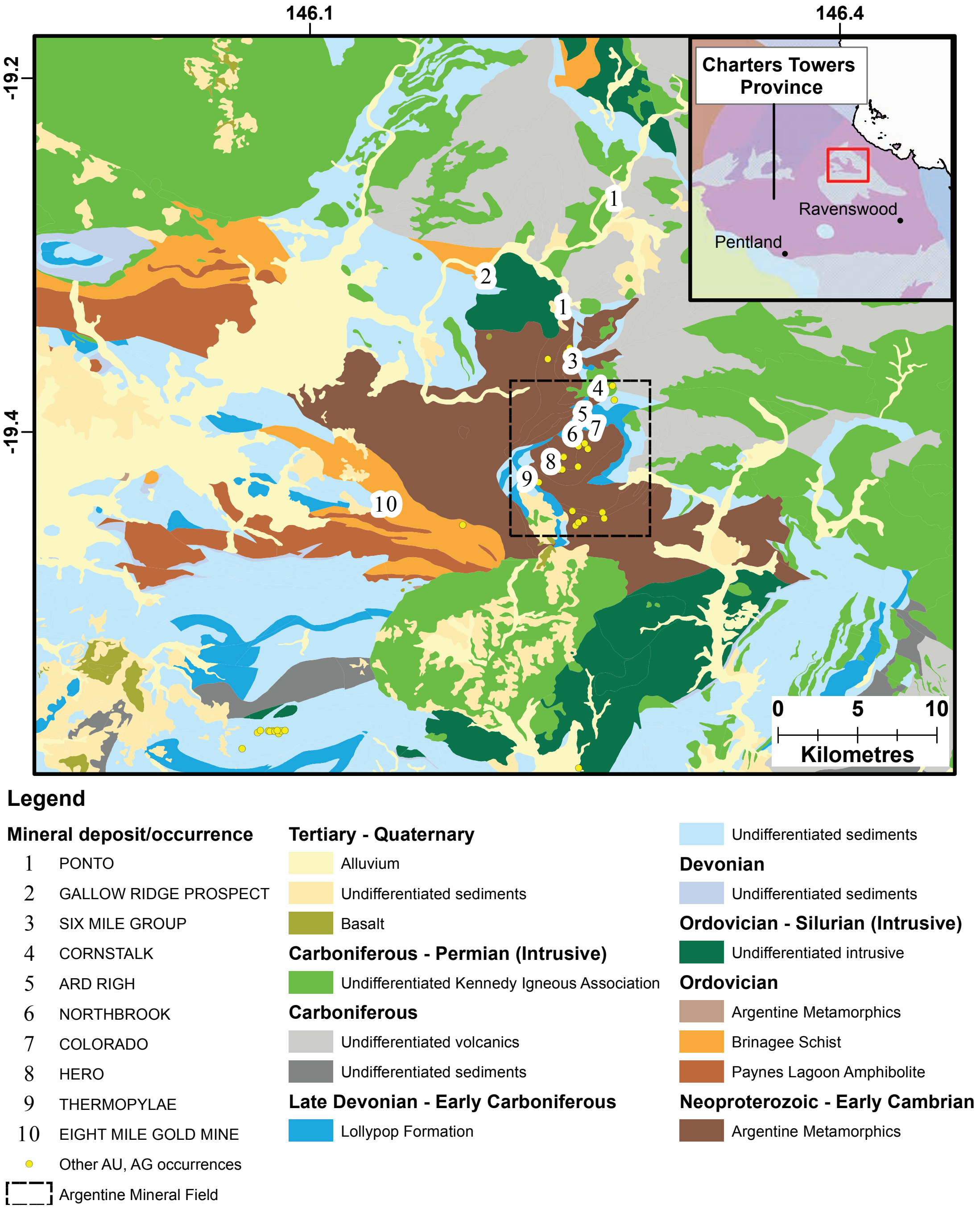


Figure 60. Distribution of orogenic gold mineral occurrences in the Argentine Mineral Field

the field has been abandoned. Lodes are <1m wide, trend north and west parallel to major faults, and are mostly hosted by the Argentine Metamorphics with some veins continuing into the Carboniferous Keelbottom Group (Withnall & McLennan, 1991).

The more significant of the gold deposits in and around the Argentine Mineral Field (Figure 60) are **Thermopylae, Ponto, Cornstalk, Gallow Ridge,** the **Eight Mile Gold Mine,** and the **Six Mile Group** of mines. Some of these deposits are briefly described in regional reporting (e.g. Levingston, 1971; Withnall & McLennan, 1991; Morwood & others, 2001) but in general, the nature of mineralisation is poorly known. Host units include the Brinagee Schist, Paynes Lagoon Amphibolite, undivided Argentine Metamorphics, Lollypop Formation and minor intrusive units.

Thermopylae occurs near the Argentine township and comprises a large quartz lode, carrying some galena, which was worked for gold prior to commencement of silver mining. **Ponto** was also an early gold producing area. Weak gold mineralisation here occurs in a zone up to 60m wide and 1km long, in steeply dipping shears and minor quartz veins hosted by ferruginised mica schist and gneiss. Mineralisation at **Cornstalk** comprises arsenopyrite in quartz stringers that are developed in a silica-sericite alteration zone <1m wide hosted by a small Permian granodiorite pluton. Three parallel mineralised structures can be traced over a strike length of 300m. The **Six Mile Group** of mines is just north of the Argentine Mineral Field. Mineralisation is associated with sericitisation and some silicification and occurs in north-trending shears in altered ultramafic rocks, quartz-feldspar porphyry and mafic dykes near the contact between amphibolite and migmatite. To the north-west, gold at **Gallow Ridge** is related to quartz veined shear zones within altered granitic gneiss and schist. Shear zones outcrop over an area 1.4 x 1km and range from 0.3–5m in width. Most of these deposits are now within the Army Training Area and access is limited. Further to the west, the **Eight Mile gold mine** was a small alluvial mine worked in the 1980s with coarse and commonly nuggety gold. An origin in quartz reefs within shear zones adjacent to chert to the north of the treatment plant is suggested.

Anakie Province

Gold was first discovered in the Anakie Province in 1861 in gullies south of Clermont township and this sparked one of Queensland major gold rushes. Up to 1993, ~14 000kg of gold is estimated to have been extracted (Withnall & others, 1995). Four different settings for the gold mineralisation are suggested (Withnall & others, 1995):

1. Lode gold deposits, mostly quartz reefs in the Anakie Metamorphic Group, principally the Bathampton Metamorphics (e.g. **Belyando, Lucky Break, Star of Hope**)
2. Permian conglomerate, either along the unconformity with the Anakie Metamorphic Group, or in ‘false bottoms’ above the unconformity (e.g. **Black Ridge, The Springs, Miclere, McMasters, Hurley’s and Leo’s Flat**)
3. Older alluvium or leads, probably mainly late Tertiary, consisting of linear belts of poorly consolidated sediments cutting across the present drainage pattern (e.g. **Cumberland lead, Clermont Surface lead, Deep Creek lead**)
4. Quaternary alluvial deposits along the modern drainage system (e.g. along creeks draining the east and west sides of the Drummond Range, at **Western Reefs, Birimgan** and **Cockatoo Dam areas,** and in **Brigalow, Sandy, Expedition, Oaky, Rolfe, Gregory** and **Eastern Creeks**).

The vast majority of gold has been produced from basal sections of Permian conglomerate that were worked from the 1870s to ~1920 and from 1931–1956. The origin of this gold, however, is uncertain and several contrasting hypotheses ranging from an alluvial origin (i.e. the deposits are deep leads) to mixing of thermally and chemically contrasting fluids are presented in the literature. Although it is possible that this gold was derived from lode deposits hosted by the Anakie Metamorphic

Group (and therefore part of the Thomson Orogen), a detailed description of these deposits and the younger deep lead and alluvial gold is beyond the scope of this document. Below we focus on the lode gold and the reader is instead referred to the detailed reviews of Lam (2005) and Withnall & others (1995).

Although relatively minor in terms of production (accounting for ~27% of total production), known lode gold deposits are scattered throughout the Anakie Province (Figure 61). Many of these, including the more significant deposits (Belyando), have characteristics consistent with an orogenic gold model. However, it should be noted that the majority are poorly studied and designation to the orogenic gold style is tentative. Some deposits included here may be porphyry-related.

The lode gold deposits in the Anakie Province are structurally controlled and occur in either discrete shear zones or in broad corridors of shearing. The abundant deposits and prospects south of Clermont, for example, comprise reefs that dominantly strike east–west. These occur within an extensive east-south-east-trending zone suggesting that they are *en echelon* and related to a sinistral strike slip fault zone (Withnall & others, 1995).

The mineralised shear zones occur within mica schist or chlorite schist of the Anakie Metamorphic Group and are locally associated with carbonate, chlorite or silica alteration. Gold generally occurs in fine quartz veins, occasionally with sulphides.

The age of mineralisation is uncertain but some deposits appear to have a spatial and temporal relationship with microdiorite dykes. These may be related to the Retreat Batholith (Middle Devonian) and it may have provided a heat source for fluid flow and remobilisation and concentration of gold in structurally favourable sites.

Oxygen isotope studies (Wilson & Golding, 1984) indicate $\delta^{18}O$ values higher than 16 per mil for gold-bearing quartz veins suggesting a metamorphic fluid origin. However, host phyllites have lower values and a different fluid source is therefore suggested.

Some general characteristics of lode gold deposits in the Anakie Province are shown in Table 14. The more significant and more recently discovered deposits of Belyando and Lucky break are discussed below.

The **Belyando** gold deposit, also known as **Hill 266,** lies approximately 70km north-west of Clermont in an isolated inlier surrounded by Cenozoic deposits (Figure 61). The deposit produced 2289kg of gold between 1989 and 2009, and a low grade stockpile of 1.8Mt at 0.32g/t gold remains. The deposit consisted of several sub–parallel lensoidal quartz bodies which formed a low hill 300m long and 100m wide of fine grained quartz–muscovite schist that is part of the Anakie Metamorphic Group. The mineralisation occurs as cryptocrystalline quartz with pyrite and arsenopyrite. The deposit may be associated with Devonian intrusives under cover, and was considered to be a plutonic lode style deposit by Morrison & Beams (1995). However, Mustard (1990) favoured an orogenic gold model due to the fluid characteristics and timing of mineralisation with respect to metamorphism.

Table 14. Characteristics of lode gold deposits in the Anakie Province (summarised from Withnall & others, 1995; Lam, 2005)

Region/ Group	Deposit/Prospect	Description
South of Clermont	Bedford	Workings sunk on boundary of iron-rich calc-silicate hangingwall and clayey phyllite footwall; country rock is schist with reticular quartz leaders every 1m or so dipping S.
	Star of East	Quartz reef with east strike and near vertical dip; production from 1882–1883 was 255t ore for 3.9kg gold.
	Star of Hope	Discovered 1896; underground workings reached 60m in 1902 and produced 1500t ore with 28g/t gold; vertical lode strikes 085°, extends over 4.8km to W; lode crosscuts phyllite of Anakie Metamorphic Group and occurs in a fracture zone, shear is up to 120m wide with most intense shearing adjacent to quartz, limonite/pyrite, arsenopyrite, gold veins; average grade of lode 32g/t, surface to 20m; quartz contains minor pyrite and sphalerite and averaged 31g/t gold; 20–40m quartz yielded 18g/t gold; below 40m quartz contains abundant pyrite and arsenopyrite which yielded ~15g/t gold
	Biddy Walsh	Workings sunk on a quartz vein trending 070°
	Somersetshire	Most extensively worked lode in the group of workings east of the Clermont–McDonalds Flat Road; numerous deep shafts over 450m sunk on silvery-white to purplish ferruginous and micaceous phyllite; lode appears to follow a shear or fracture zone crosscutting foliation of country rock; quartz is massive, white and some contains traces of boxworks and stains of sulphides, gossanous phyllite crops out nearby; drilling in 1993 intersected 1m from 21–22m with 233.5ppm gold
	Gricks	Two shafts sunk over 50m along 105° trend; mullock is brown phyllite, brecciated quartz reef crops out to the north
	Welcome	Reef traced over 500m long and 0.7m wide, strikes E and dips 20° S; consists of white quartz; shaft intersected high grade gold-bearing quartz (100g/t avg) from surface to 15m.
	Palm Tree, Crown	Lodes consist of open-space filled texture with symmetric quartz veins up to 0.3m wide on fissure walls, brecciation and healing of quartz veins has occurred; forms part of an *en echelon* system of lodes in metasediments of the Anakie Metamorphic Group
	Croydon	Lode crops out over 50m along 100° strike, dips 70° SSE, 0.4m wide
	Robertson's	Reef forms two parallel bodies of quartz ~2m apart, strikes 110°, dips 30° S; up to 150g/t gold recovered; mullock consists of brown phyllite, minor breccia quartz and calcrete
	Homeward Bound	Discovered around 1869; lode extends over 175m, strikes 320°, dips 30° SW; hosted in mica schist of Anakie Metamorphic Group; average width of lode 0.6–0.9m with average grade of 32–40g/t gold
	Others including Dingo, Doctor, Christmas, Bismarck, Saint Patrick, Unnamed (649700, 659711, 659712, 669703, 671702, 657708)	Gold bearing quartz reefs in WNW-trending belt from McDonalds Flat to near Peak Downs copper mine; most reefs are planar sheets in fracture-openings which crosscut schistosity, reefs up to 2m wide and pinch and swell, range from single quartz veins to series of thin quartz veinlets, wider portions generally barren; most reefs strike ~E, dips range from 45° to subvertical; quartz is associated with pyrite, arsenopyrite, sphalerite, galena, calcite and siderite; distinction between barren and auriferous lodes unclear.
North of Clermont	Venus	Lode structure is >500m long x 170m wide with N strike; hosted by Hurleys Metamorphics; lode contains fracture-healed, brecciated quartz with clayey cement; past mining indicates grades up to 120g/t gold

Table 14 (continued)

Region/ Group	Deposit/Prospect	Description
North of Clermont (continued)	Apsley	Discovered 1881, two rich gold-bearing quartz leaders dipping into large lode
	Marjorie (Miclere)	Discovered in 1963, mined out within 3 years, lode trends NNW over 300m; hosted by Anakie Metamorphic Group; ~4.5kg gold obtained from 190t ore, other small lodes occur to the S
West of Clermont	Southern Cross (Hurleys)	Discovered in early 1930s, intermittent mining 1932–1951, 1140t ore yielding 81kg gold, deposit strikes 125°, dips 50–55° SW, lode ranged up to 0.6m wide (avg 0.15m), W pitching shoots containing up to 30g/t gold, high gold mainly in massive grey quartz with disseminated galena and sphalerite, lodes occur in E and SE-trending shear zones in mica schist
	Petersens prospect	Discovered 1917, averaged 23g/t gold; anomalous gold and arsenic associated with E-trending silicified zone in quartz-mica schist intruded by microdiorite dykes; patchy gold mineralisation occurs in propylitised, silicified schist and in brecciated contact margins of dykes
	Smeagol's workings	8kg gold won from reef to depth of 5.5m between 1901–1903, further 3kg 1916–1917 from 50t ore; workings spread over three lode formations in mica schist adjacent to large serpentinite body, lodes 0.6 to 1.5m wide, comprise networks of quartz leaders enclosed in brecciated formation, average yield 30g/t gold
	Fig Tree Mine	Discovered in 1901, gold mined from quartz veins associated with E-trending shear/fault zones crosscutting bed of red and green quartz-mica schist with interlayers of finely laminated, saccharoidal, fine-grained quartzite
	Goldfinger	Prospect outlined from panned concentrate stream sediment sampling assaying up to 11.71ppm gold; quartz outcrop containing visible gold, mineralised structure of sheared and brecciated quartz-muscovite-sericite schist with 5–15% fine-grained disseminated to weakly banded pyrite and arsenopyrite; prospect has been costeaned and drilled with intersections including 6.25m with 3.63g/t gold from 23.5m
	Midas	Anomalous gold associated with intensively silicified and carbonate altered zone within an E-trending tight fold of intercalated quartz-muscovite schists and chlorite schist, minor galena, arsenopyrite and pyrite present in narrow auriferous quartz veinlets <50mm wide; rock chip samples of mineralised vein up to 56.2g/t gold
	Clyde (Clyke) Creek	High gold and arsenic assay values obtained from N-trending dolerite dyke in intercalated muscovite-quartz schist and minor chlorite schist dipping 40°W
	Fingerprint	Zone of anomalous gold-tungsten in a NW-trending chlorite schist near contact with mica schist, discreet scheelite, pyrite and chalcopyrite grains identified in quartz stringers
	Others including Wee Five, Little Finger, Roulette, Keno prospect, Benny workings, Hillview, K-2, Two Up, Pinkie, Rolfe Creek, Leo Grande	Dominantly quartz veins hosted in shear zones in quartz-mica or chlorite schists

Table 14 (continued)

Region/ Group	**Deposit/Prospect**	**Description**
Moorlands prospect	Moorlands prospect	Very large but low-grade prospect discovered 1989; E-striking quartz stockwork zone 750m long x 50m wide dipping steeply S, hosted by Monteagle Quartzite; drilling to 90m indicates resource of 8.5Mt at average 0.3g/t, best intersection 44m at 0.7g/t including 4m at 2.7g/t
Western Creek area	Western reefs	3 parallel NW-trending shear zones with gold and sulphide bearing quartz veins cutting schist and quartzite of Bathampton Metamorphics
	Ladlode prospect	Siliceous hematite gossan at contact of medium-grained granodiorite and metasediments of Anakie Metamorphic Group, lode and granodiorite exhibit pervasive carbonate alteration with outer chloritised zone
	BT, QA	Small quartz lodes with low tonnage potential
Dingo Range area	Vanguard Creek,	Associated with a small siliceous ironstone outcrop, area of Monteagle Quartzite
	Monteagle, Rosewood	Brecciated quartzite intruded by rhyolitic feldspar porphyry dykes; gold mineralisation occurs in hairline fractures in quartzite.
Belyando and Lucky Break	Belyando	Originally investigated as Hill 266 prospect occuring as a quartz blow above soil-covered plains; mining commenced 1989, ceased mid-1993, 1.968Mt ore for 1558kg gold and 595kg silver; hosted by multiply deformed phyllite, mineralisation localised within and adjacent to tabular siliceous body 300m long x 140m wide, strikes E, dips N at 50–70°, 3 brecciation events, gold associated with comb quartz veins consisting of white euhedral crystals and grey infill, interstitial sulphides include pyrite, galena, chalcopyrite, arsenopyrite and minor sphalerite and tennanite, irregular gold grains from 1µm to 0.35mm along pyrite and galena boundaries, along fractures or as blebs in pyrite
	Lucky Break, Frankfield Ridge/ Byjingo, Frankfield Hill	Lucky Break: worked between 1987 and 1988 for 90 000t at 2.4g/t gold; mineralised zone 0.5 to 8m wide comprising two quartz reefs dipping moderately to steeply W with arcuate trend from NNE in N to WNW in S; along with Frankfield Ridge/Byjingo and Frankfield Hill it is classified as Anakie-style — simple mineral assemblage of gold, pyrite and minor arsenopyrite, mineralisation spatially associated with massive north-trending ven systems, hosted by quartzite and pelites of Anakie Metamorphic Group, generally concordant with local foliation, veins consist of buck white to glassy blue-grey quartz, mineralisation associated with finer vein stockworks infilling fractures in vein system
Capella-Retro area	Kettle's shaft, Arbor prospect	Narrow veins up to 2cm wide along two intersecting, steeply dipping fracture sets in altered biotite granite; quartz contains disseminated arsenopyrite and copper staining; assay in 1990 indicated maximum gold grade of 1.06g/t; source of mineralisation is probably residual fluids from host granite. Arbor prospect is similar.
	Prairei peak	Rhyolite dykes cut by extensive sheeted quartz-sulphide vein systems with low gold values
	Ayres Rock prospect	Altered (chloritised and sericitised) rhyolitic volcaniclastic (possibly ignimbrite) veined by quartz and chalcedony
	Retro prospect	System of steeply dipping quartz veins up to 2.5m wide traced as linear zone ~2km long in poorly exposed phyllitic metamorphics; smaller reefs up to 100m long located adjacent to main zone
	Nanya prospect	Gossanous quartz vein material cutting sericitised granite

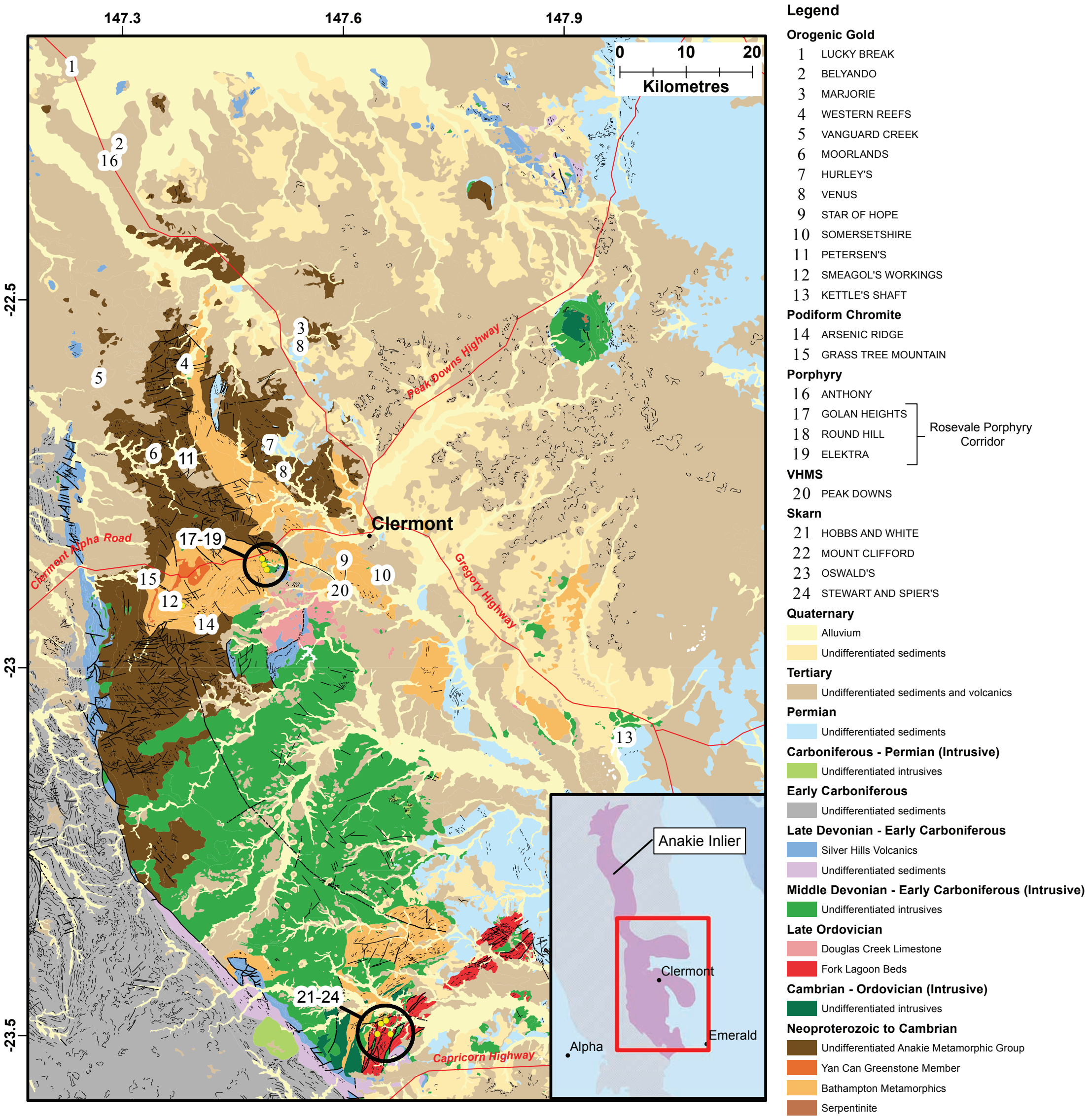


Figure 61. Distribution of mineralisation in the southern Anakie Inlier. Orogenic gold deposits are associated with the Anakie Metamorphic Group and occur predominantly in the north, including areas of shallow cover; podiform chromite and VHMS deposits are exclusively hosted by the Bathampton Metamorphics; skarns are associated with the Fork Lagoons beds in the south; and porphyry-related deposits occur throughout.

The **Lucky Break** deposit, which is about 80km north-north-west of Clermont (Figure 61), was mined in 1987–1988 and produced 216kg of gold from 90 000t of ore at 2.4g/t gold. The deposit is hosted by schist and quartzite of the Anakie Metamorphic Group. The gold occurs in brecciated, silicified, hematitic, quartz–sulphide–chalcopyrite–arsenopyrite–stibnite veins within a shear zone. Gold is located in the coarse hematite grains (which replace pyrite cubes), dendrites within the oxidised zone or finely disseminated. Only the oxide ore was mined. The age of mineralisation is not well constrained. Gold at the Lucky Break deposit was considered to have been sourced from the intrusion of the Retreat Batholith into the Anakie Metamorphic Group by Kretchmer (1986). Mackay (1988) grouped Lucky Break with smaller nearby prospects such as **Frankfield Hill** and **Byjingo** into an ‘Anakie Style’ classification. The general characteristics of this style are (Withnall & others, 1995):

1. simple mineral assemblage — coarse gold, pyrite and minor arsenopyrite
2. spatial association with massive north-trending vein systems
3. hosted by the Anakie Metamorphic Group and concordant with local foliation
4. veins consist of buck white to glassy blue-grey quartz
5. mineralisation is associated with finer vein stockworks infilling fractures in the vein system.

Iron Range

Gordon's and **Johnson's** are hydrothermal gold deposits in the Iron Range Province in far north Queensland (Figure 62). Gordon's produced 11 503t of ore between 1935 and 1952 yielding 217.5kg of gold. At Gordon's, a resource of 36 000t at 28g/t gold remains, and a resource of 250 000t at 2.03g/t gold has been identified at Johnson's. Both resources are within the Iron Range National Park. The deposits are hosted by the iron-rich schists of the Sefton Metamorphics. The mineral assemblage comprises gold, magnetite and quartz and alteration includes argillic, carbonate–sericite alteration, chloritic alteration and pervasive silicification. The Johnson's orebody has a strike length of 250m and Gordon's has a strike length of 300m comprising sheared iron-rich slate and quartz. The deposits are considered to be mesothermal, structurally-controlled epigenetic mineralisation and to have formed during the emplacement of the Cape York Batholith (Bruvel & Morwood, 1992). Within both deposits there is a strong positive association between ironstone/hematite schist and gold grades. The nature of the deposits and tectonic environment in which these deposits were emplaced is not well constrained.

Southern Thomson

The small areas of granite outcrop in the Eulo Ridge area, which represent the only outcrop in the southern Thomson Orogen area in Queensland, host a gold occurrence at **Granite Springs**. The mineralisation is confined to narrow north-east-trending, iron-stained, gold-bearing quartz veins. No production data exists, but the workings include several deep (>20m) shafts (Figure 63). Exploration interest has recently been renewed in this area.

Although not in Queensland, the Tibooburra Goldfield in northern New South Wales is also worthy of note here, because it occurs in the far southern extent of the Thomson Orogen and attests to the widespread nature of this style of deposit. Tibooburra and the surrounding inliers are described as an orogenic gold province (Greenfield & Reid, 2006). Primary mineralisation occurs in syn-D_1 quartz vein networks (~440Ma) hosted by late Cambrian, greenschist facies metasediments (Waratta Group) (Figure 64). The primary ore averages grades up to 25g/t (e.g. at Pioneer Reef) but little exploration of this primary ore system has been completed since the 1880s gold rush. The majority (85%) of gold from the region was produced from nuggets in the quartz-rich basal lag deposits of overlying (Cretaceous) sediments (Greenfield & Reid, 2006; Brown & others, 2006). A total of 1700kg of gold was won from Tibooburra between 1881 and 1901.

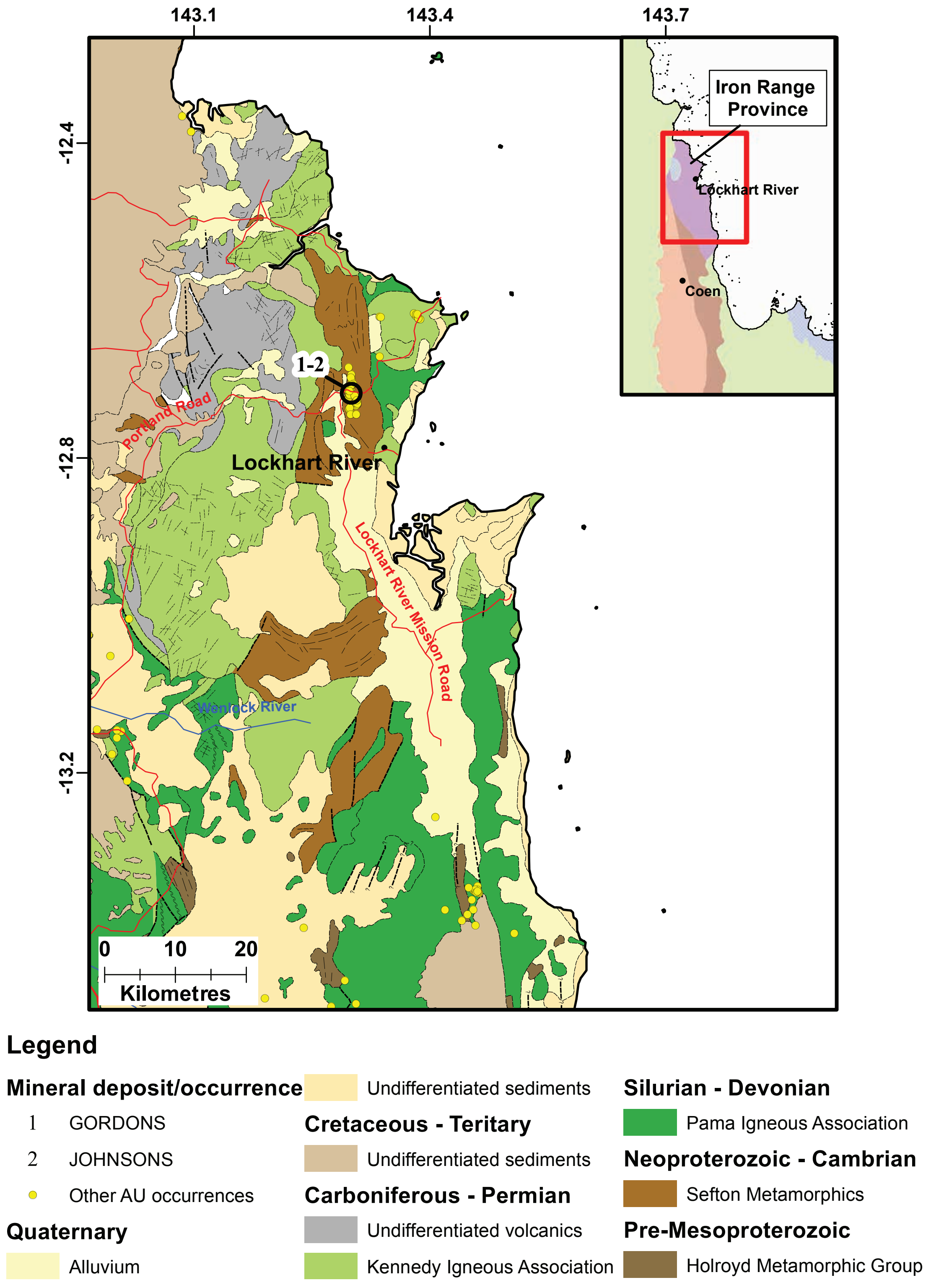


Figure 62. Distribution of Iron Range Province gold deposits

Figure 63. Deep shaft in the Granite Springs Granite at Granite Springs

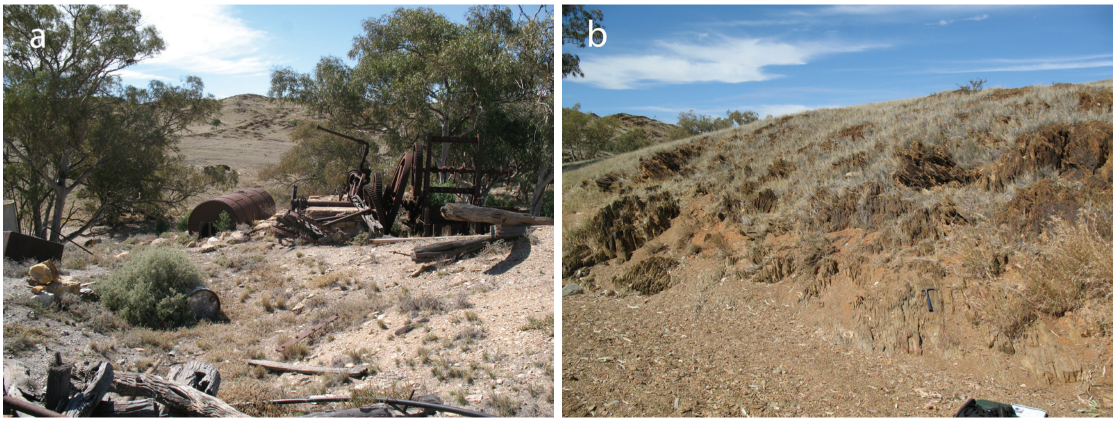


Figure 64. a) Remnants of mining equipment at the Pioneer Reef workings developed in the 1880s; b) Host rocks of the Pioneer Reef comprise fine-grained metasiltstone and sandstone of the Jeffreys Flat Formation (Waratta Group).

PORPHYRY ASSOCIATED SYSTEMS

Mineralised porphyry systems have a strong genetic association with convergent plate margin settings, but may also develop after subduction has ceased (Baker, 2002). Periods of extension within an overall compressive tectonic regime can allow for development of gold-copper porphyry systems above a shallowly dipping lithospheric slab. The deposits are often formed in response to variation in the tectonic setting (e.g. arc-continent collision or subduction of an aseismic ridge) (Bierlein & others, 2002). Porphyry style mineralisation occurs deeper than 1.5km with saline mineralising fluids typically between 300–400°C and alteration occurring at approximately 500°C. The composition of associated intrusive rocks can span low-K calc-alkaline diorite, through high-K quartz monzonite to alkaline syenite, monzonite and shoshonite (Bierlein & others, 2002).

Rhyolitic to trachytic dykes, plugs, stocks and breccias associated with gravity and magnetic anomalies related to underlying plutons and crustal scale faults are typical of porphyry systems (Morrison & Beams, 1998). Alteration systems are typically large-volume (10s to 100s of km^3) and zoned with potassic alteration commonly associated with the core, extending outward at lower temperature and salinity into phyllic and argillic alteration zones.

Mining of porphyry copper ± gold ± molybdenum ± silver and related systems of the northern Thomson Orogen has produced in excess of 158t of gold from 1981 to the present and production is ongoing. The most significant mines are the Mount Leyshon, Ravenswood and Mount Wright deposits. To date the porphyry systems of the Thomson Orogen have mainly produced gold with some by-product silver and copper. The recent discovery of the Anthony molybdenum deposit has identified significant molybdenum resources and potential for copper resources.

The porphyry-related systems in north Queensland, including the Thomson Orogen, occur in a variety of forms including hydrothermal breccias, skarns, veins and stockwork style mineralisation (Morrison & Beams, 1998) (Figure 65). In the Thomson Orogen, known porphyry systems are largely related to emplacement of the Kennedy Igneous Association in the Carboniferous to Permian, and initiation of the Drummond Basin in the Late Devonian. The tectonic environment of porphyry systems in the Thomson Orogen is debatable, but conforming to the typical view of porphyry systems, it is convenient to imagine that they were generated inboard of a west-dipping subduction zone associated with the Connors Arc.

The potential for preservation of porphyry-related systems depends on the level of erosion throughout the Thomson Orogen. Porphyry systems in the Ravenswood area, the northern Ravenswood Batholith area, and in the area of the Argentine mineral field are eroded to their middle or lower levels (Horton, 1978) so the preservation of the epithermal components in these areas is unlikely. By contrast, the upper levels of porphyry systems may be preserved further south at Anthony. Additionally, epithermal deposits of the Drummond Basin may overlie other porphyry-related styles of mineralisation at depth.

Epithermal mineralisation is commonly interpreted as representing the upper levels of porphyry associated systems. Epithermal gold deposits occur near the surface (i.e. generally <1.5km depth) and at temperatures less than 300°C. They are associated with volcanic or shallow intrusive rocks commonly in rift and back-arc tectonic environments (Kesler & Wilkinson, 2009). Modern analogues are observed in many active volcanic regions, particularly in association with felsic magmatism (e.g. Taupo and Yellowstone).

Within the region of the Thomson Orogen, many epithermal gold deposits occur in association with lowermost (Cycle 1, Late Devonian) deposits of the Drummond Basin. The genesis of these deposits is tightly linked to felsic magmatism related to initiation of the basin, and deposits such as Pajingo, Wirralie and Twin Hills and extensive sinter occurrences are well described in the literature (see Denaro & others, 2004 and references therein). These deposits are hosted in the Drummond Basin succession and are not considered in this review. However, potential exists for these types of deposits to be hosted by older successions throughout the Thomson Orogen, particularly in areas that were affected by Late Devonian magmatism associated with the Drummond Basin.

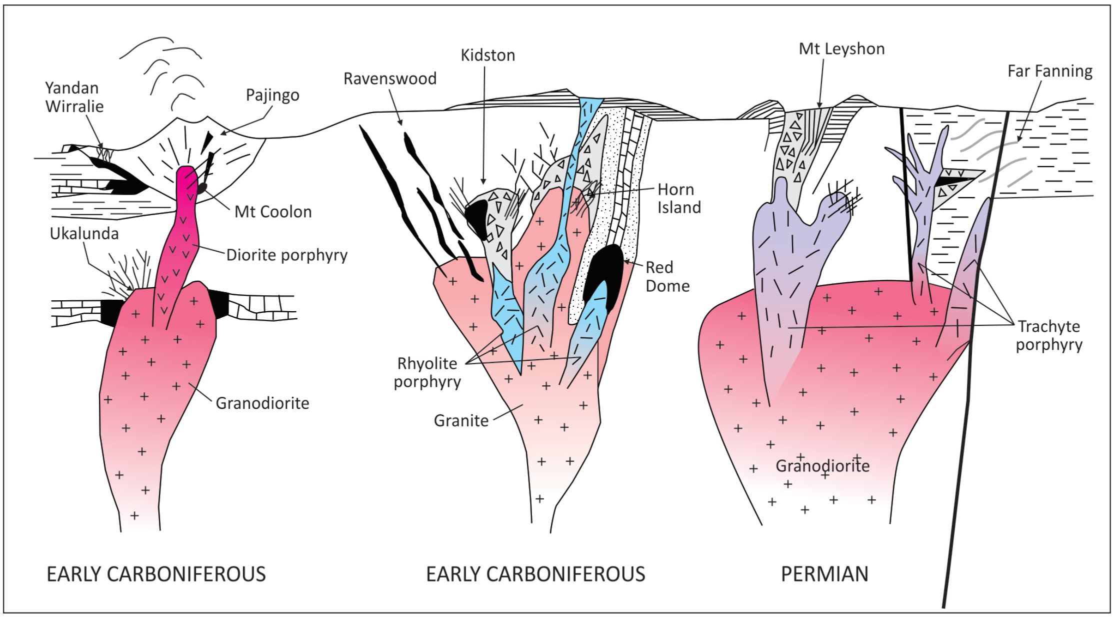


Figure 65. Styles and settings of porphyry and epithermal gold mineralisation in north Queensland (from Morrison & Beams, 1998).

Devonian

The **Rosevale porphyry corridor** (Figure 61) is a 7km by 3km north-north-west trending structural corridor, which hosts a series of blind porphyry copper deposits and breccia hosted silver-lead-zinc-gold mineralisation. These occur where Devonian granitoids and volcanic rocks have penetrated the Anakie Metamorphic Group. No resources have been established and no production has occurred, but the deposits are significant, because of their high potential for new large tonnage copper discoveries. Multiple intrusive phases have been intersected at the **Round Hill, Elektra** and **Golan Heights** prospects within the corridor. These include porphyritic quartz monzonite, monzodiorite, dacite, and rhyolite. To date drilling has intersected some broad zones of sub-economic porphyry-related copper–molybdenum and breccia hosted silver–lead–zinc–gold mineralisation. Observations of disseminated and micro-vein, fracture-related bornite–chalcopyrite–pyrite in quartz monzonite porphyry are also recorded (Diatreme Resources Limited, 2010).

Carboniferous–Permian

The Carboniferous to Permian Kennedy Igneous Association in north Queensland, which comprises extensive intrusive and extrusive, predominantly felsic igneous rocks, is associated with development of gold, copper, zinc, lead, tin, tungsten, uranium and molybdenum mineral deposits. This section will review mineral deposits associated with this igneous association and hosted by Thomson Orogen sediments, metasediments, volcanics and intrusive rocks. The Thomson Orogen hosts significant amounts of primarily gold mineralisation emplaced at shallow to mid crustal depths. Mount Leyshon and Ravenswood are the most significant examples and are generally classified as gold-rich porphyry or porphyry-related systems.

Ravenswood and Mount Wright

The Ravenswood goldfield (Figure 66) comprises a group of over 200 gold mines and workings hosted by the Ravenswood Batholith and centred on the town of Ravenswood. The initial discovery of gold at Ravenswood was by stockman Thomas Aitken who discovered alluvial gold in Elphinstone creek in 1868. This led to a gold rush and subsequent mining of deep reefs. Mining up to 1950 produced 10 794kg of gold bullion and fine gold at an average grade of 18g/t from over 100 separate workings. In 1987, Carpentaria Gold began systematic modern exploration and discovered a series of very large low-grade deposits. At the time of writing, mining has ceased but there are plans for a further cut-back at Sarsfield, and processing of low-grade stockpiles and ore currently being mined at Mount Wright. Identified resources and reserves remaining at Sarsfield are 66.37Mt at 0.78g/t gold. The history of the field was summarised by Collett & others (1998).

The Ravenswood gold system is designated a porphyry copper–gold related system but there are difficulties in distinguishing deposits as porphyry or plutonic systems (Morrison & Beams, 1998). Mineralisation is hosted by the Silurian–Devonian

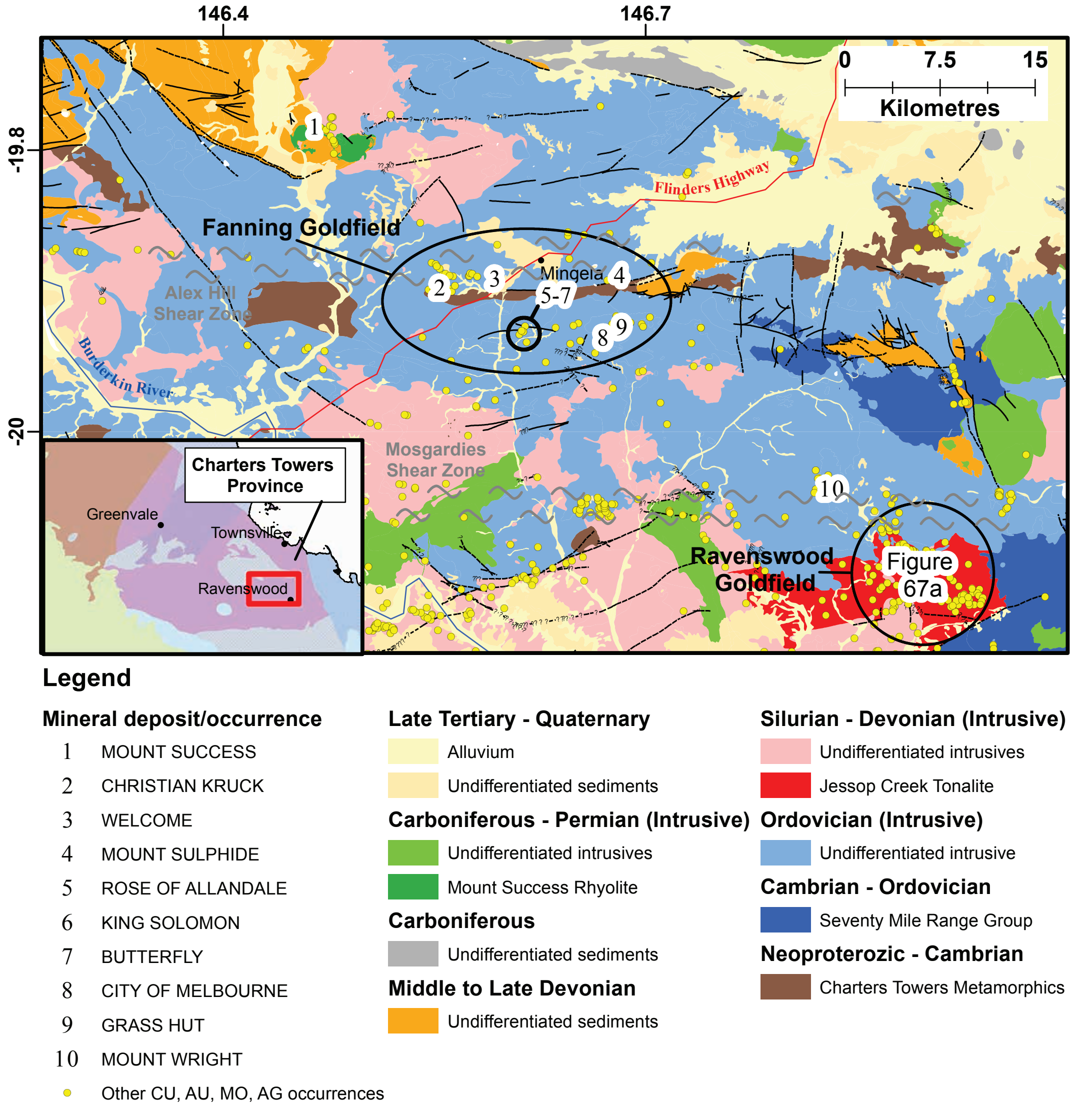


Figure 66. Distribution of porphyry-related gold mineralisation in the Ravenswood region

Jessops Creek Tonalite (Figure 66), and is focussed along the northerly striking Jessops Creek Fault Zone (part of the more extensive Ravenswood Lineament), which intersects the easterly trending Mosgardies Shear Zone. The Mosgardies Shear Zone is at least 43km long and up to 10km wide. This shear zone has been multiply reactivated throughout the Paleozoic. It is well-defined in Ordovician granites but is also evident in the Silurian–Devonian granites as primary igneous layering or isolated shear zones (Hutton & others, 1994).

Modern mining operations are located on second-order structures associated with the Mosgardies Shear Zone. Individual deposits are Nolans, Buck Reef West and Sarsfield (Figures 67; 68) (encompassing the historical **Slaughteryard Creek**, **Opencut Area**(**OCA**), **Area 4** and **Area 5** mines). These deposits are considered below as an entity.

Two major mineralisation styles are recognised (Switzer & others, 1998):

1. Low-angle, multiphase, quartz–sericite–pyrite veins and stockworks with open space-filling comb quartz and a high sulphide content (pyrite–sphalerite–chalcopyrite). Several elemental associations are exhibited (copper–arsenic, copper–lead–zinc, bismuth–arsenic–antimony–tellurium–silver). Alteration is chloritic with a biotite halo and patchy sericite–pyrite and silica alteration.

2. Chlorite–carbonate–base metal breccia hosted within tonalite and diorite of the Ravenswood Batholith. This style occurs at Buck Reef which is dominant throughout the major low-grade deposits in the Ravenswood area (**Nolans**, **Sarsfield**, **Buck Reef West**). Mineralisation forms pipe- or sheet-like bodies with breccia-fill replacement. Biotite alteration is dominant, and quartz is not always present, (Hartley & Dash 1993).

Complexity of the multiple preferred directions of mineralisation and complex reactivation are evidence for a porphyry setting rather than a plutonic/orogenic setting. The Duke, Grant and Sunset vein are a series of large fissures in the **Buck Reef West** pit and dip to the north (Figure 67). Sunset is the most extensive vein on the field at 900m long, 3m wide and intersected at least 250m below the surface. The Keel structure in the Sarsfield pit is a multiveined structure 15–25m thick (Figure 67). Dating of biotite and sericite associated with Buck Reef West yielded Carboniferous dates of 330 and 310Ma (Perkins & Kennedy, 1998).

Copper Knob, 1.3km North of Ravenswood, was worked sporadically between 1906 and 1943 and produced 3t of copper and 6kg of gold. The deposit was drilled and a resource of 2.16Mt at 0.08% copper, 0.049% zinc, 0.23g/t gold, 1.2g/t silver was defined in 1999 by Haoma Mining (Appendix 4). The Copper Knob deposit is a shear zone-hosted gold deposit with accessory copper–zinc–silver within the Jessops Creek Tonalite. The age of the mineralisation is unknown, but it is likely a distal part of the Carboniferous Ravenswood porphyry system.

The **Mount Wright** gold deposit is 9km north-west of Ravenswood (Figure 66). It is related to a Carboniferous–Permian rhyolite which intrudes the Early to Middle

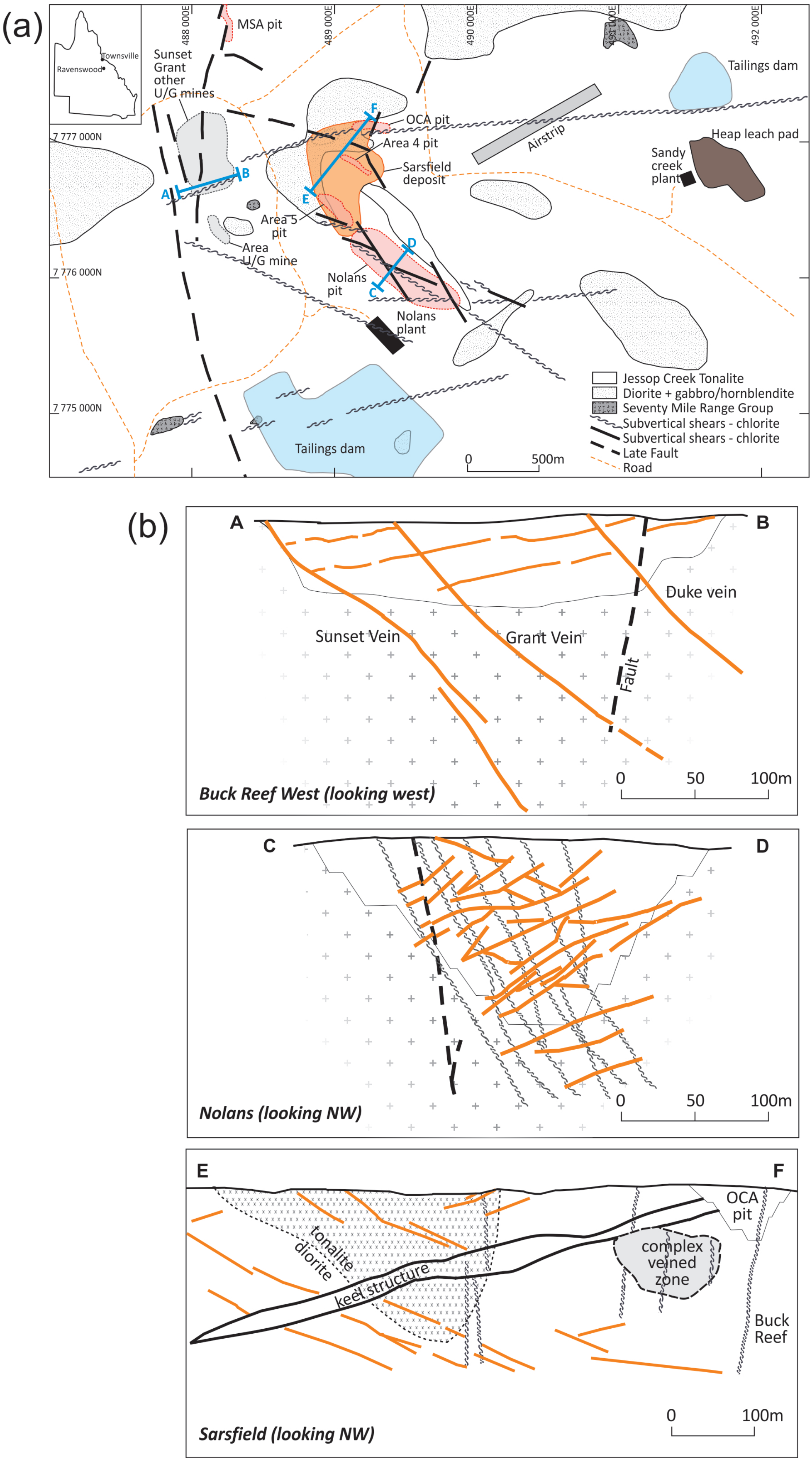


Figure 67. Plan view (a) and cross-sections (b) of the Nolans, Buck Reef West and Sarsfield deposits of the Ravenswood Goldfield, showing distribution of mineralised structures (from Collett & others, 1998)

Figure 68. View of Sarsfield pit from the northern edge looking south

Ordovician Glenell Granodiorite and Millaroo Granite of the Ravenswood Batholith, part of the Macrossan Igneous Association. The gold mineralisation is hosted dominantly by rhyolite breccia and to a lesser degree by granite breccia with minor vein mineralisation. Mafic and rhyolitic dykes transect the Ordovician granitoids. The deposit is divided into two sections, the Main Orebody and the Mother Lode. The Mother Lode was mined historically between 1917 and 1942, and by Carpentaria gold in 1992–1993 producing 570kg of gold bullion. Subsequently, the main Mount Wright deposit, a blind orebody, was discovered 200m to 500m below the surface (Figure 69).

The main orebody is pipe-like and comprised of strongly altered and brecciated rhyolite and granite surrounded by a halo of altered granite. The gold mineralisation is hosted by the rhyolite and by breccia directly adjacent to the rhyolite. Harvey (1998) divided the breccia into two types: a volcanic breccia related to the explosive emplacement of the breccia pipe and consisting of angular rhyolite, andesite and granite fragments in a fine matrix of rhyolitic fragments, dominantly in the upper part of the deposit and above the mineralised zone; and secondly, a breccia comprising flow banded strongly sericitised granite, rhyolite and andesite fragments, which is dominant at depth.

The alteration assemblage at Mount Wright consists of strong, texturally destructive sericite, siderite and silica alteration within the brecciated zone, which extends into the country rock as a halo and along fractures, and potassic alteration in the core of the alteration system (Harvey, 1998). Gold mineralisation is accompanied by sulphides, sericite, quartz and siderite and occurs in interclast spaces and fractures in the breccia. Mineralogy of the sulphide ore infill within the breccia is marcasite–pyrite–siderite–quartz–sphalerite–arsenopyrite–chalcopyrite–native bismuth-bismuthinite. Dating of sericite alteration and zircons from a rhyolite dyke, which is contemporaneous with the gold mineralisation, yielded ages of 305 and 303.0 ± 3.8Ma respectively (Perkins & Kennedy, 1998). Current resources and reserves total 5.84Mt at 2.58g/t gold (Appendix 4).

Fanning mineral field

The **Fanning mineral field** (Figure 66) is hosted by the Ravenswood Batholith and contains the **Welcome** deposit and the **Butterfly**, **Christian Kruck**, **King Solomon**, **Rose of Allandale, Grass Hut, Mount Sulphide** and **City of Melbourne** historical

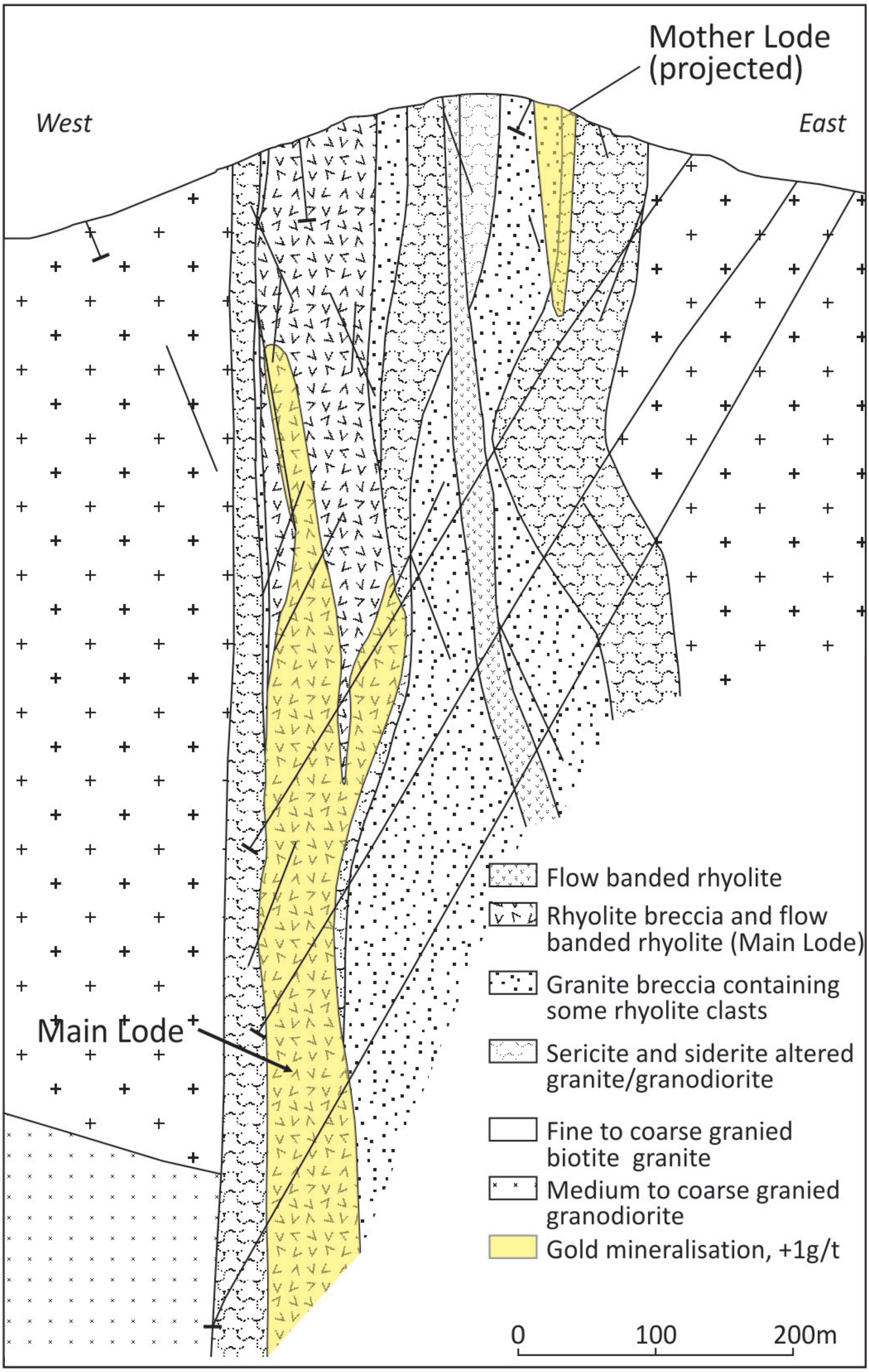


Figure 69. Cross-section looking north of Mount Wright, showing distribution of major rock types and gold mineralisation (from Harvey, 1998).

mines which all recorded some production. The field has produced up to 7300t for 185kg gold bullion estimated to contain 139kg gold, and an additional 35.7kg recovered from smelting and cyanidisation of mullock. The majority of this ore was from the Christian Kruck and Welcome deposits.

The Fanning Mineral Field is in the Alex Hill Shear Zone. This east-trending structure is 100km long and up to 7km wide with a sinistral sense of movement, and is defined by distinct tectonic layering in outcrop. Shearing is well-defined in Ordovician granites but is absent or poorly defined in Silurian–Devonian granites. Active shearing during the emplacement of the Mingela Granodiorite is evident along the shear zone (Hutton & others, 1994). The Fanning Mineral field is reported to carry mesothermal veins at Christian Kruck, Chas Madge and Evening Star (GSQ Mineral Occurrence Data). Mineralisation consists of visible gold with associated galena and minor pyrite and chalcopyrite with secondary copper carbonates.

The **Welcome** deposit or **Welcome Breccia** is a breccia pipe north of Mount Wright and 4km west-south-west of Mingela (Figure 66). The deposit has similar characteristics to the Mount Wright deposit — a breccia pipe hosted by the Ravenswood Batholith with gold mineralisation hosted within breccia fill consisting of sphalerite, chalcopyrite, pyrite and quartz. The deposit was mined between 1906 and 1936 producing 80.9kg of gold from 3657.6t of ore derived from high grade veins. In 1994–1995, 65 200t of ore was mined by SMC Resources for 121.92kg of gold (sourced from fax received from SMC Resources on 28/7/00). Recent drilling by Resolute Mining has identified significant extensions below the mined part of the deposit. The current inferred resource is 2.04Mt at 3.2g/t gold (Appendix 4). The deposit is associated with an unnamed intrusive of unknown age, but probably of similar age and nature to the intrusives at Mount Wright and Mount Leyshon.

Grass Hut, City of Melbourne, Mountain Maid and **Mount Sulphide** are also within the Alex Hill Shear Zone along strike from King Solomon and Rose of Allendale

North-west of the Fanning Mineral Field, the **Mount Success** and **Golden Valley** gold deposits are on the boundary between the Devonian–Carboniferous Burdekin Basin and the Ravenswood Batholith (Figure 66). These deposits are described as a porphyry-related, hydrothermal breccia mineralisation suite. They occur in breccia pipes associated with Carboniferous to Early Permian microgranite, microgranodiorite and granophyre.

Mount Leyshon

Mount Leyshon is a large gold deposit 23km south of Charters Towers and was mined between 1986 and 2002. The deposit has been interpreted as a volcanic vent breccia that intruded the Ravenswood Batholith and the Seventy Mile Range Group in the early Permian. The discovery of the deposit was in 1872 by Mossman, Clarke and Fraser and therefore predated the Charters Towers Goldfield. The deposit was worked on a small scale until 1916. Exploration by Noranda Pacific Limited and Mount Isa

Mines in the 1960s identified copper in the deposit. Noranda entered a joint venture with Marathon and then listed as Pan Australian Mining which in joint venture with Noranda published an initial reserve of 6.3Mt at 1.79g/t gold (Campbell & Kay, 1998). The mine produced 98t gold and 69t silver from 73Mt of ore between 1986 and 2002.

Mount Leyshon lies on the Boori Lineament with the Rishton and Hadleigh Castle deposits (Figure 57), which are described in the Orogenic Gold section. The **Main Pipe Breccia** at Mount Leyshon (Figure 70) is dominated by fragments of Ordovician–Silurian Fenian Granite of the Ravenswood Batholith, sediments of the Puddler Creek Formation (Seventy Mile Range Group), and dacite and rhyolite of the Permian–Carboniferous Mount Leyshon Complex. The breccia exhibits an outward progression from well-milled through mosaic to crackle breccia into coherent country rocks. Fragments are affected by propylitic alteration (chlorite–dominated) and potassic alteration (biotite ± magnetite). The geometry of the main pipe is steep with an antler like geometry. Within the main pipe are some early (pre-mineralisation) porphyritic rhyolite dykes which have been dated at 291 ± 4.8Ma (Murgulov & others, 2008).

The **Mount Leyshon breccia** and **Mount Hope breccia** are the major parts of the orebody. They are spatially and temporally related to porphyries of the same names (i.e. the Mount Hope breccia occurs as a carapace on the Mount Hope Porphyry). The

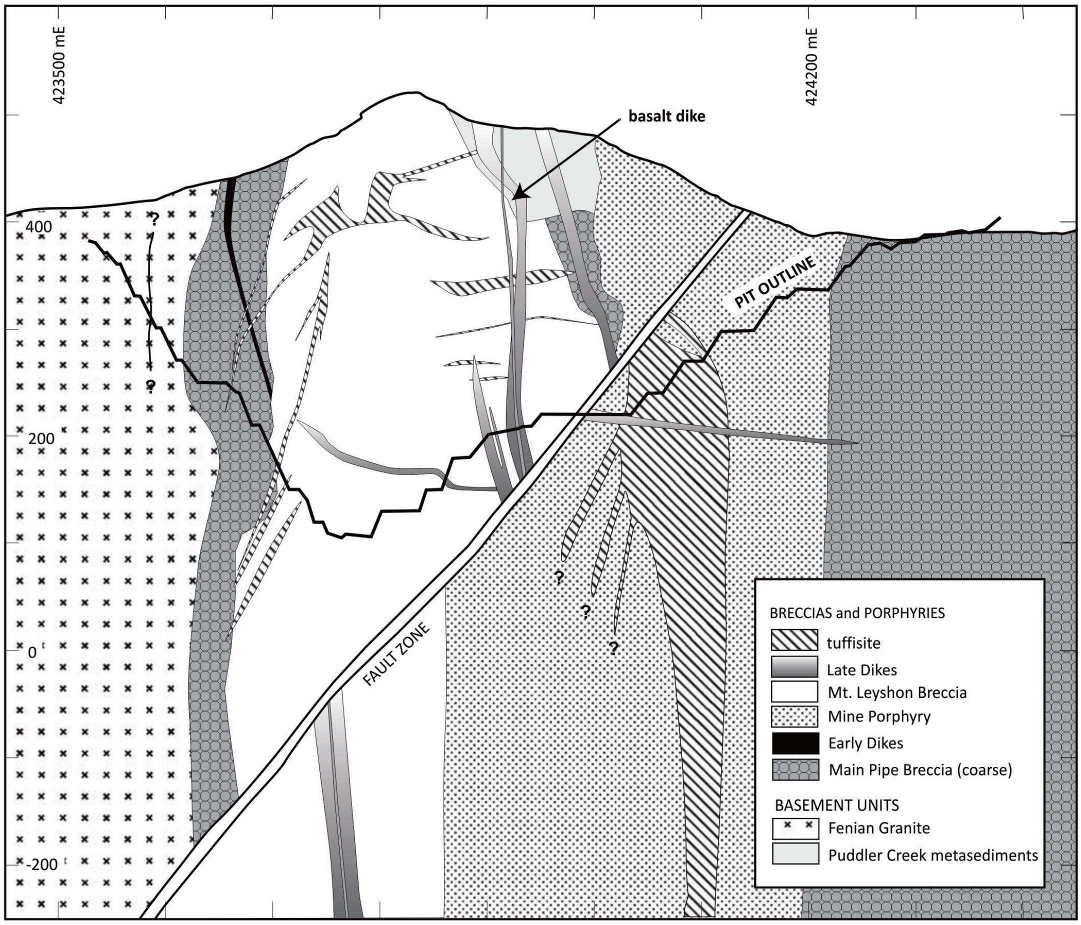


Figure 70. Distribution of rock types and gold mineralisation in an east–west cross-section through the main part of the Mount Leyshon orebody (from Allan & others, 2011)

breccia bodies are broadly similar and comprise clast-supported polymictic breccia of angular to subangular clasts of breccia, porphyritic intrusives and country rocks. Interclastic zones are filled with sand-sized rock fragments. Mineralisation in the Mount Leyshon and Mount Hope breccias occurs in breccia cavities and crosscutting veins and is composed of quartz–chlorite–pyrite–sphalerite–carbonate ± K–feldspar ± fluorite ± chalcopyrite ± galena (Allan & others, 2011). Breccia clasts are typically rimmed by chlorite and prismatic quartz, which are in turn rimmed by magnesian and ferroan calcite, sphalerite, chalcopyrite and galena. Potassium feldspar occurs as cavity fill at depth within the system. Fluorite and magnesian calcite are common as late fill. Quartz–pyrite–sphalerite–chalcopyrite–galena–bismuthinite/aikinite–gold–carbonate mineralisation forms crosscutting cavity fill. These mineralised breccias are cut by late, dominantly andesite dykes with phyllic-altered cores and dated at 288 ± 6Ma by Murgulov & others (2008).

Fluid generation took place in a magma chamber at depth. Crystallisation drove volatile saturation, resulting in over pressure of magmatic fluid and breaching of the magma chamber, and driving porphyry emplacement. This initial event formed the main breccia pipe. This series of events was repeated on smaller scales throughout the life of the system, emplacing the Wallaby Tail, Southern, Mine and Mount Hope porphyries. Fluid inclusion studies suggest that CO_2-bearing fluids introduced the gold into the system, with the fluids infiltrating low permeability zones during late dyke emplacement, such as tuffisites, fractures and residual pore space in the Mount Leyshon breccia, the brecciated porphyry margins and distal fractures. Gold precipitated as the fluid cooled, depressurised and underwent phase separation. Gold values are strongly correlative with narrow zones of intense phyllic alteration and this is consistent with strongly focussed fluids (Allan, 2011 [after Wormald, 1993]).

Pentland

In the Pentland region, a wide cross-section of crustal level is exposed and preserved over a small area, and associated with this is the exposure of a variety of mineral deposit styles which may have formed at a similar time but are now exposed together. The porphyry-related group has not had its age well established but there is no reason why some early Paleozoic porphyry systems may not be preserved in the Cape River Metamorphics, because early Paleozoic VHMS systems are preserved to the east in the Seventy Mile Range Group.

The **Mount Remarkable** area (Figure 71) to the west of Pentland consists of fault controlled veins hosted within a window of Cape River Metamorphics and Fat Hen Creek Complex within significant Tertiary cover. Faults in the area underwent reactivation and multiple fluid input events. The reefs are brecciated and consist dominantly of quartz and milled country rock containing disseminated pyrite, arsenopyrite, galena and minor chalcopyrite. Gold was reported to occur as free gold by Morton (1940). Rich shoots are associated with intersecting structures, bifurcation of the reefs and dilatational sites (Garrad, 1996). The general trend of gold bearing structures is north-east, although workings east of Mount Remarkable are near an east-trending shear rich in cerussite and galena. Recorded production is 287t of ore for 20.13kg of gold, but considering the extent of the workings this is likely to be unrepresentative of the actual amount gold produced. Production is only recorded from the **Barcoo Line** and **Bell–Gay** mines. The nature of deposits has not been conclusively determined, but an investigation of galena lead isotopes (Dean, 1991) indicated that a hydrothermal fluid associated with early Paleozoic granite emplacement was responsible for deposition and interpreted the deposit as a shallow vein. This interpretation is ambiguous in terms of the classification scheme.

Recent exploration in the area has focussed on a buried copper–molybdenum porphyry system under the known gold deposits. The host rock is Ordovician biotite quartz diorite and the probable hydrothermal fluid source is a Carboniferous–Permian quartz–feldspar porphyry (Chevron Exploration Corporation, 1983). Mineralisation occurs as chalcopyrite and molybdenite in quartz–sericite–pyrite ± kaolinite veins. The diorite and porphyry are strongly argillically (kaolinite–montmorillonite–sericite) altered at the surface.

The **Golden Moun**t group of the Cape River goldfield, south-west of Mount Remarkable, is a group of dominantly gold occurrences associated with the Carboniferous–Permian Elimeek Volcanics (a Permian–Carboniferous volcanic breccia complex) (Figure 71). Gold was dominantly recovered from alluvial deposits, coated in manganese oxide, with minor reef mining at what is now known as the **Red, White and Blue** prospect. The gold is hosted by narrow veins of iron-stained quartz and kaolinite, within an irregular, east-trending structure in an ignimbrite of the Elimeek Volcanics. Exploration has revealed a dacitic intrusion which underlies volcanic breccia broadly similar to the Mount Leyshon deposit (Garrad, 1996).

Mount Clearview is a relatively isolated gold deposit south-west of Lolworth in the western part of the Cape River goldfield (Figure 71). It was mined intermittently between 1915 and 1996 to produce 348kg of gold bullion, 10kg of fine gold and 8kg of silver. The deposit is hosted by the Cape River Metamorphics and is crosscut by aplitic and pegmatite dykes. Mineralisation occurs within quartz veins in a dilation zone recognised as a sigmoidal loop (Garrad, 1996). Finely disseminated gold throughout the quartz reef is associated with arsenopyrite and pyrite and there is sericitic, chloritic and silicic alteration. The style of mineralisation is uncertain but the deposit is classified as either porphyry-related or intrusion-related.

Mount Stewart goldfield is 27km north of Pentland (Figure 71). Discovered in 1936, the major mines on the field are the **Brilliant Brumby** and **Surprise**. The field produced just less than 30kg of gold bullion with the majority coming from the Brilliant Brumby. The deposits comprise multiple phases of narrow quartz veins carrying high gold values within the Silurian–Devonian Amarra Granite. Typical mineral assemblages are coarse quartz with arsenopyrite, sphalerite, stibnite, galena and gold. The veins are commonly brecciated, have sericitic and epidote alteration selvages, and mainly trend north to north-east with an easterly dip. Applying a classification to these deposits is difficult, and they are simply described as hydrothermal vein deposits.

Further north, mining commenced in 1926 at the **Lolworth Diggings** (Figure 71). The main mines were; **Midas**, **Crystal Oak**, **Mons Meg** and **Mount Hope**.

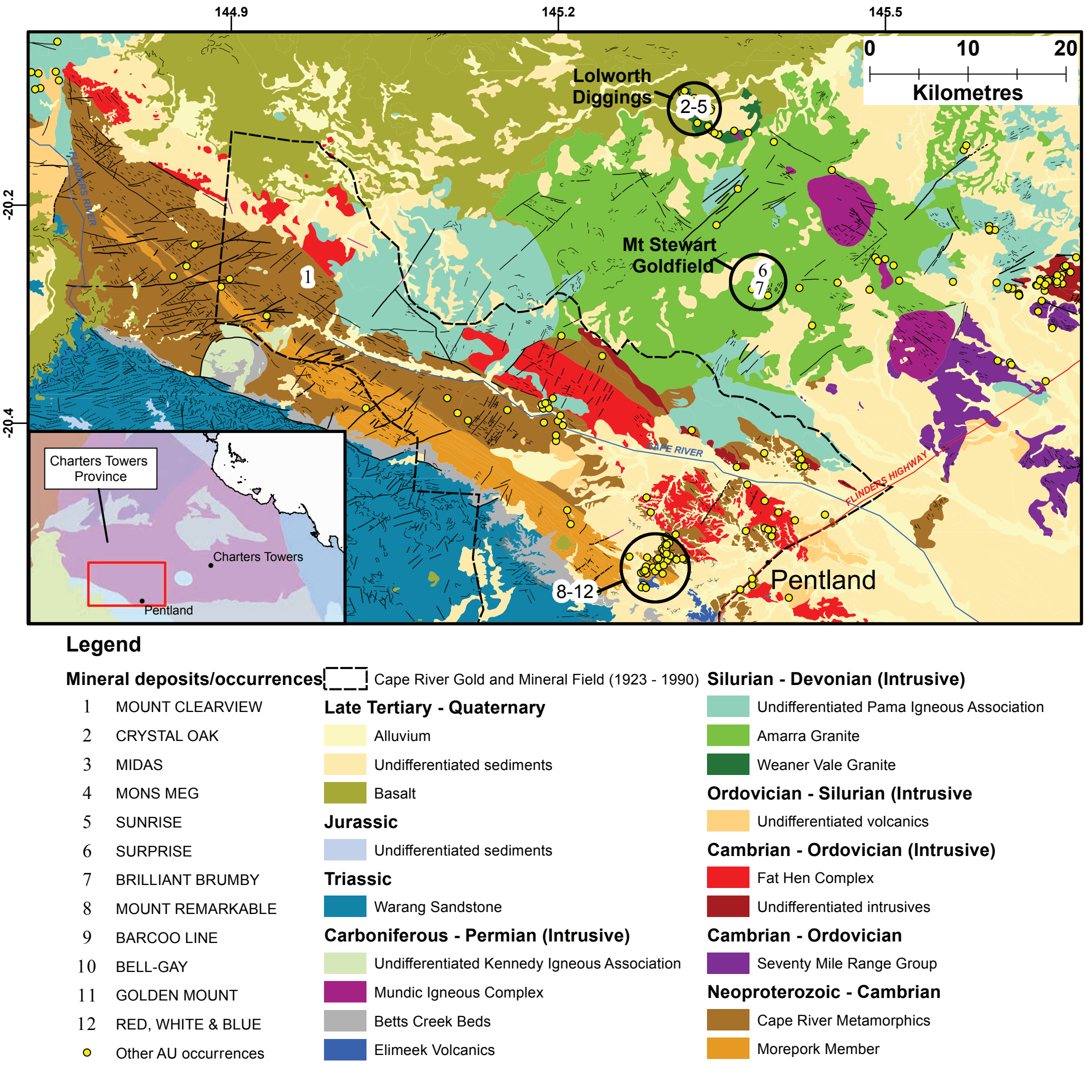


Figure 71. Distribution of porphyry-related deposits in the Pentland region, including the Cape River Gold and Mineral Field, Mount Stewart area, and Lolworth Diggings

Total gold production was 549kg with 48.5kg silver, 6t copper and 5kg wolfram concentrate (Garrad, 1996). Small amounts of copper and gold were also recovered from the Niggers Bounce area prior to 1926. The presence of wolfram suggests that mineralisation in this field is related to highly evolved, possibly Permian, granite.

The deposits occur as small breccia pipes (although some shear-hosted deposits are also present) within medium-grained biotite granite of the Silurian–Devonian Weaner Vale Granite. Although the corridor of deposits is orientated south-south-east, individual deposits typically trend east. Breccia pipes are individually less than 500m^2 in area and typically comprise brecciated, greisenised and sericitised granite, porphyritic dacite, leucogranite and pegmatite fragments. Some flow textures are evident within the breccia pipes. The mineralised breccia is comprised of granite fragments, large (up to 10cm) euhedral quartz crystals, chalcedonic quartz, calcite, dolomite, sulphides, tuffisites and intermediate dyke fragments and sporadic wolframite and scheelite. The sulphide assemblage within the gold-bearing veins and breccia infill is typically pyrite, arsenopyrite, chalcopyrite ± molybdenite, sphalerite, galena and pyrrhotite. Sericitic and kaolinitic alteration is associated with mineralisation, although typically only forms narrow selvages around veins and breccia pipes. Rare potassic alteration of granitic rocks is also present.

Lead isotope studies by Dean (1991) indicate that mineralisation is related to Carboniferous–Permian igneous activity. The breccia host, Weaner Vale Granite, exhibits unidirectional cooling features (brain rock), indicative of variation in magma chamber pressure at shallow depths, but also contains euhedral epidote, which does not support a shallow environment. The Permian Mundic Igneous Complex south-east of the main workings may be part of the igneous activity associated with the mineralisation.

Reedy Springs

The Reedy Springs Batholith (Figure 12) has many affinities with the Ravenswood and Lolworth batholiths including the timing of emplacement. However, known mineralisation is less prominent in the Reedy Springs Batholith. Some important factors may be that plutons of the Reedy Springs Batholith have low water activity and are more evolved, less oxidised and contain less chlorine and more fluorine than those of the Ravenswood Batholith (Reinks & Withnall, 1993). Additionally, different crustal source reservoirs may exist across the Reedy Springs – Lolworth – Ravenswood batholith areas (Hutton, 2004).

The main area of mineralisation within the Reedy Springs Batholith is the **Mount Emu Diggings,** west-north-west of Lolworth (Figure 72). Mining began in 1910 at the Granite Castle mine and the field has produced 57kg of gold and 189kg of silver. The bulk of production came from the Granite Castle Mine with smaller contributions from **The Diecon**, **Sunday School**, **King George**, **Little Wonder** and **White Ant** deposits. Host units include the Upland Granodiorite and Big Bore Granite.

Granite Castle is the major deposit and has a resource of 847 078t at 2.9g/t gold, and 56.2g/t silver. The deposit is hosted by greisenised Upland Granodiorite and comprises quartz veins within shear zones which persist along strike for up to 1.5km. The Upland Granodiorite contains large blocks of metasediments suggesting that the deposits are located in the roof zone or margin of the pluton. The mineralised reefs intersect the metasedimentary blocks in places and have a thin alteration selvage (sericitic with an outer argillic alteration zone). The dominant strike of the reefs is west-north-west with a relatively strong conjugate set striking north. The dominant sulphide minerals are galena, pyrite, sphalerite with stibnite, chalcopyrite and arsenopyrite with silver and gold.

Garrad (1996) suggested that the greisen, low-temperature alteration, restricted distribution of mineralisation and sulphide assemblage indicate that the mineralising fluid was derived from the cooling of the host pluton at shallow depth.

On the edge of the field, the **Edwards** antimony deposit is at the contact of the Bombarri Granodiorite and Big Bore Granite. This deposit produced 310t of stibnite-rich ore.

Anakie

The Anthony molybdenum deposit is a large, low grade porphyry deposit, located 68km north of Clermont (Figure 61). The current global resource is 318Mt at 390ppm molybdenum, of which a significant portion (65Mt) is within the oxidised or transition zone (Zamia Metals Limited. 2012).

The Anthony deposit is ring- or cup-shaped around a central barren intrusion and is hosted by a group of dioritic to granitic intrusions informally termed the Dead Horse Bore intrusive complex. Three phases of magmatism associated with mineralisation are identified: equigranular monzonite, biotite–feldspar porphyry and quartz–biotite porphyry containing globular quartz. Within the quartz–biotite porphyry unidirectional solidification features (wrigglite) are present, indicating volatile escape

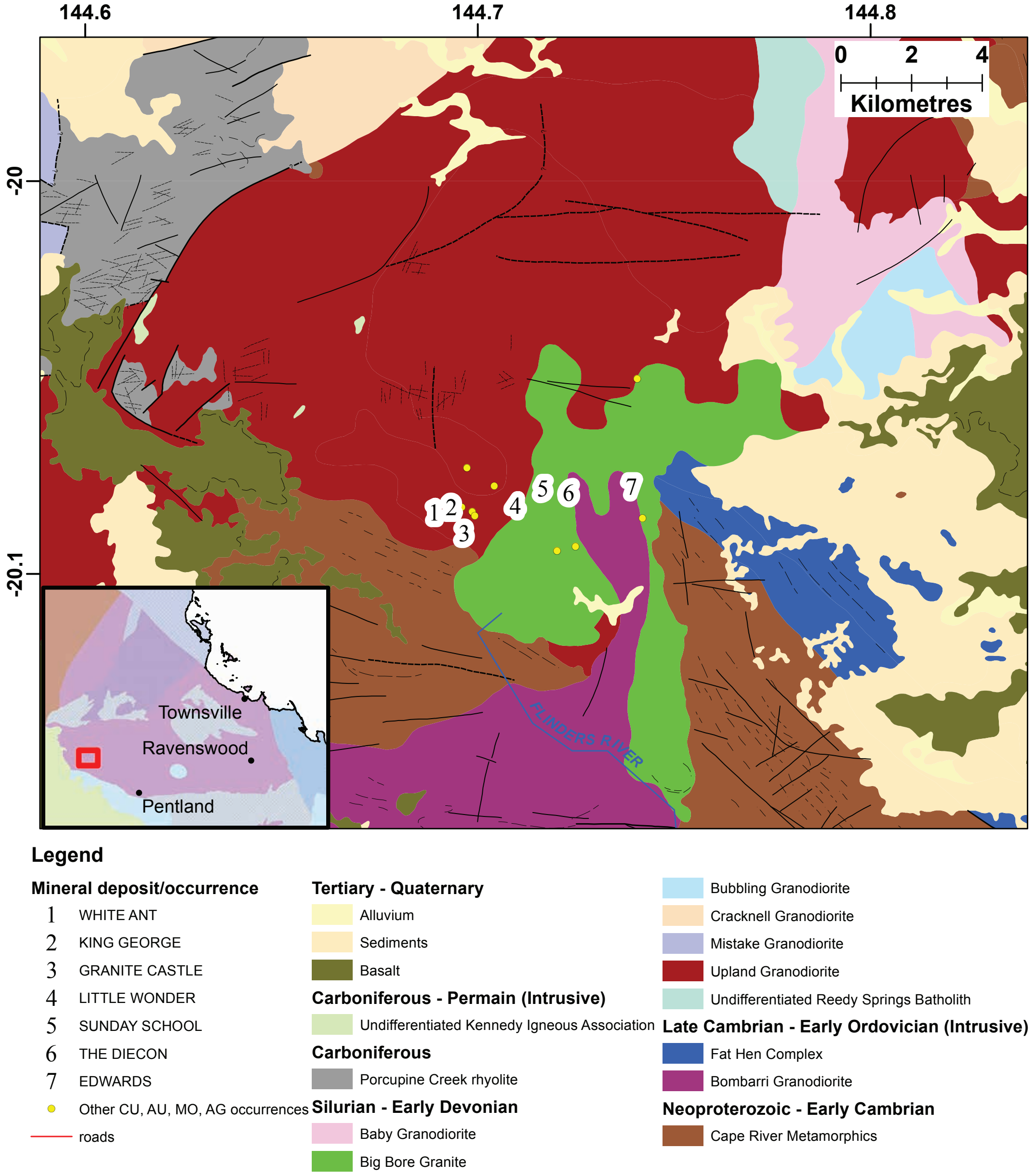
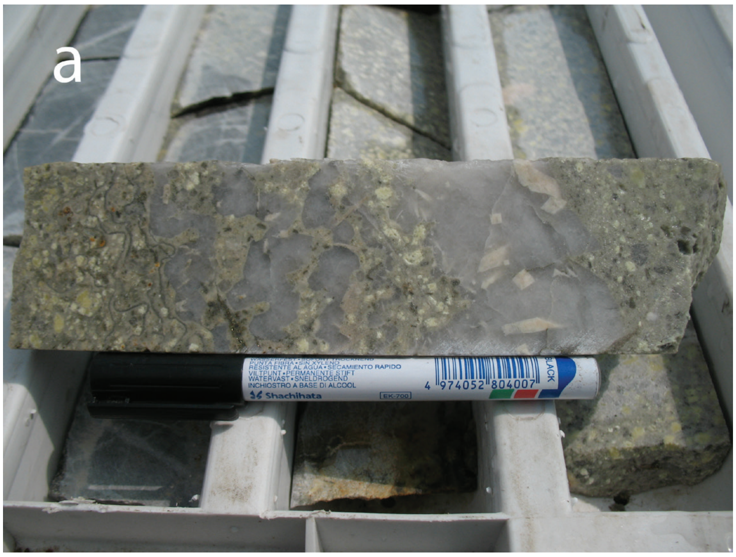


Figure 72. Distribution of porphyry-related systems in the Reedy Springs Batholith



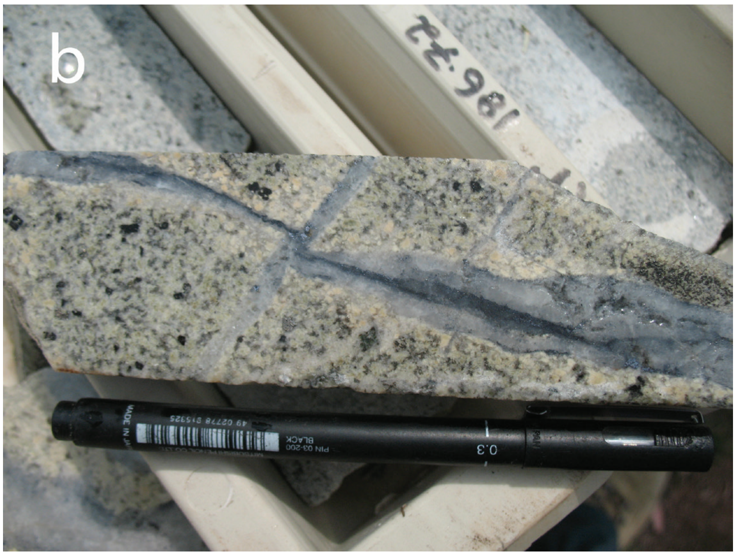


Figure 73. a) Indicators of magmatic/hydrothermal fluid transition associated with a porphyritic intrusion in drill core from the Anthony molybdenum deposit,
b) molybdenite in quartz vein from the Anthony molybdenum deposit

during crystallisation (Figure 73). This is postulated to be the major mineralising phase due to its apparent higher volatile content.

The ore mineralogy at Anthony is dominantly molybdenite associated with pyrite and strong sericite and chlorite alteration. Three generations of veins are identified: quartz–molybdenite–pyrite veins accompanied by potassic alteration; quartz–pyrite veins with sericitic–pyritic alteration; and quartz–pyrite veins accompanied by chlorite, white mica and silica alteration. The orientation of the mineralised veins is chaotic.

SKARN

Known skarn deposits are relatively sparse within the Thomson Orogen. However, given the long history of magmatism and the observed presence of calcareous, shallow marine successions in the outcropping (e.g. Fork Lagoons beds, Carriers Well Formation) and undercover (e.g. Warburton Basin) areas, significant potential remains for this deposit style.

Gold- and copper-bearing skarn in the Fork Lagoons beds is associated with intrusions of the Retreat Batholith (Figure 61). Mount Clifford (Figure 74) was described by Garrad & Lam (1993). It is the main deposit in this area and the only one with production records. The deposit was mined between 1892 and 1898 and then intermittently in the 1900s and 1920s with total production of 12.268kg gold from 2868t of ore. An inferred resource of 10 000t at 6g/t gold exists. The deposit is associated with a roof pendant of Fork Lagoons beds within diorite. It comprises five main reefs — Rainbow (Mary), New Find (Fahey's), King, Eastern, and Queen — which trend north and dip steeply west. Rainbow is the largest reef and contains the main workings. It is 1.3m wide and traceable over 18m at a depth of 13m with diffuse margins. Mineralisation occurs both within the Fork Lagoons beds and the diorite. A two-stage model is suggested (Garrad & Lam, 1993): 1) intrusion of diorite into the carbonate-rich beds causing strong alteration; and 2) intrusion of a second, possibly dyke-like diorite which was responsible for sulphide and gold mineralisation within the metasediments.

Other deposits in this area include **Oswald's**, **Hobbs and White,** and **Stewart**. Each appears to be associated with calcareous units of the Fork Lagoons beds and dioritic intrusions. Shafts were mainly sunk into garnetiferous and ferruginous gossan cappings.

Skarns are also present further north in the area around and north of Mount Coolon, associated with intrusions such as the Manamam Granodiorite and Percy Douglas Granodiorite. For many of these prospects, however, (e.g. TPM, Mount Carmel, Relner) it is unclear if the country (host) rocks are part of the Anakie Metamorphic Group (i.e. Thomson Orogen) or the Early Devonian Ukalunda Formation which is known to include significant calcareous intervals.

The **TPM** copper skarn near Mount Coolon is the best known of these and is a current prospect. The deposit was explored initially as a source for coal washing magnetite, and later a resource of 319 000t at 1.17% copper and 0.28g/t gold was established. A representative sample taken in 1921 by H. Jensen yielded 56.8% iron and 8.6% silica. Mineralisation trends for 4.8km north along a contact between the Manaman Granodiorite and quartzite and schist country rocks (Denaro & others, 2004). Four lenticular north–trending orebodies are defined comprising: 1) quartz magnetite rock with massive euhedral magnetite; 2) pure magnetite–garnet rock; 3) massive magnetite rock with crystalline quartz; and 4) a quartz–magnetite reef in garnet–epidote hornfels (Denaro & others, 2004).

TIN

Tin is common throughout the Kennedy Igneous Association. The deposits are either magmatic in nature and primarily cassiterite which crystallised in highly evolved granite, or within veins related to the emplacement in these intrusives. Many deposits are placers, where tin has been concentrated by fluvial action.

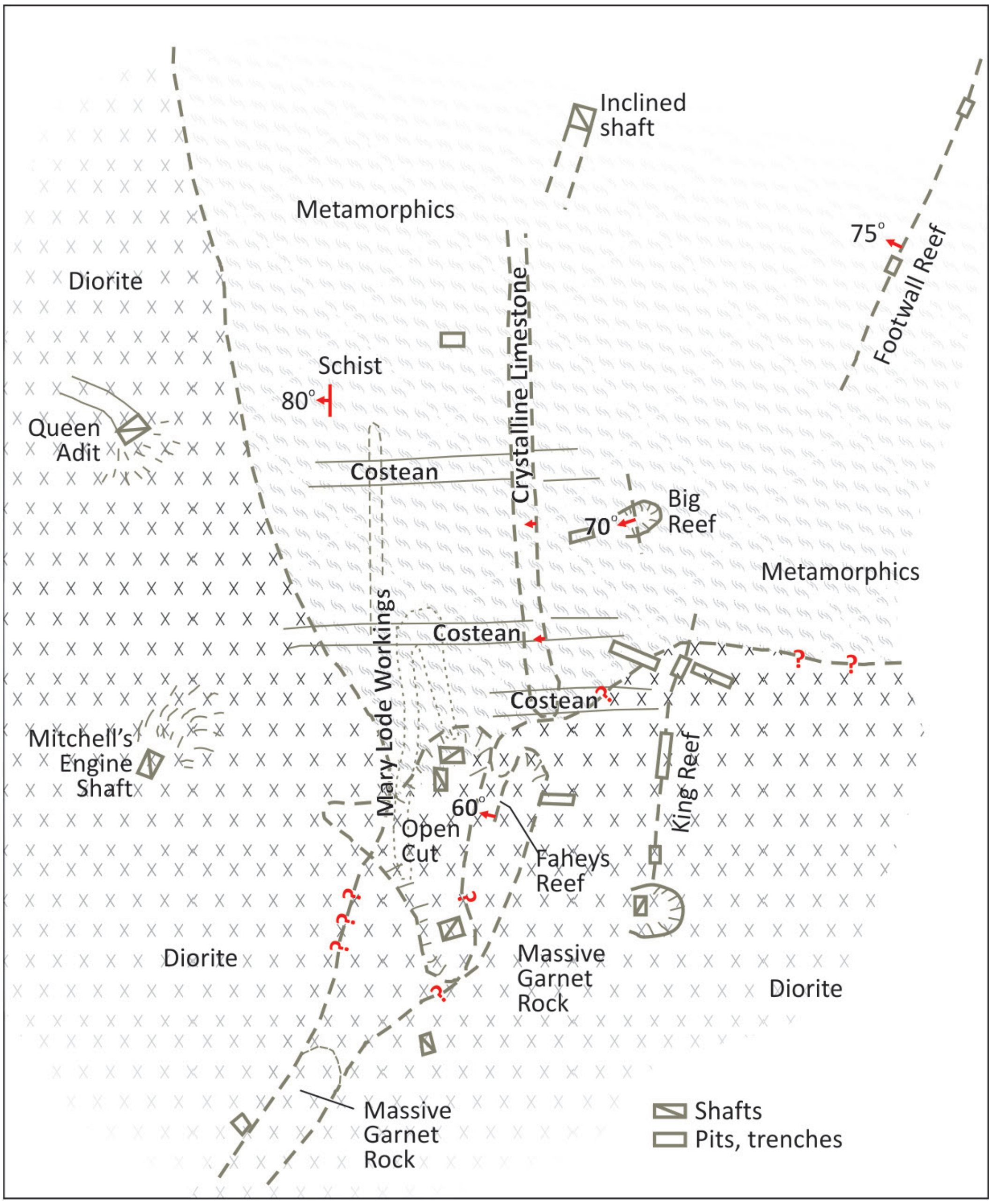


Figure 74. Sketch map of workings at Mount Clifford (from Garrad & Lam, 1993)

Known lode tin deposits hosted by metasediments of the Thomson Orogen are restricted to the Running River Metamorphics (Figure 75). These deposits are part of the tin-rich Kangaroo Hills mineral field (Gunther & others, 1994) which produced 8980t cassiterite and 474t stannite concentrate (Morwood & others 2001). The majority of richer deposits within this field are hosted by sediments of the Broken River Province or Carboniferous intrusions. However, some small deposits, such as in the Lion Group of deposits and members of the Mount Brown Group, are hosted by the Running River Metamorphics.

The Lion Group (**Clinker, Greater Lion and Lion Extended** — Gunther & others, 1994) worked parallel quartz–chlorite veins within mica schist and quartzite of the Running River Metamorphics close to the contact with the Carboniferous Macauley

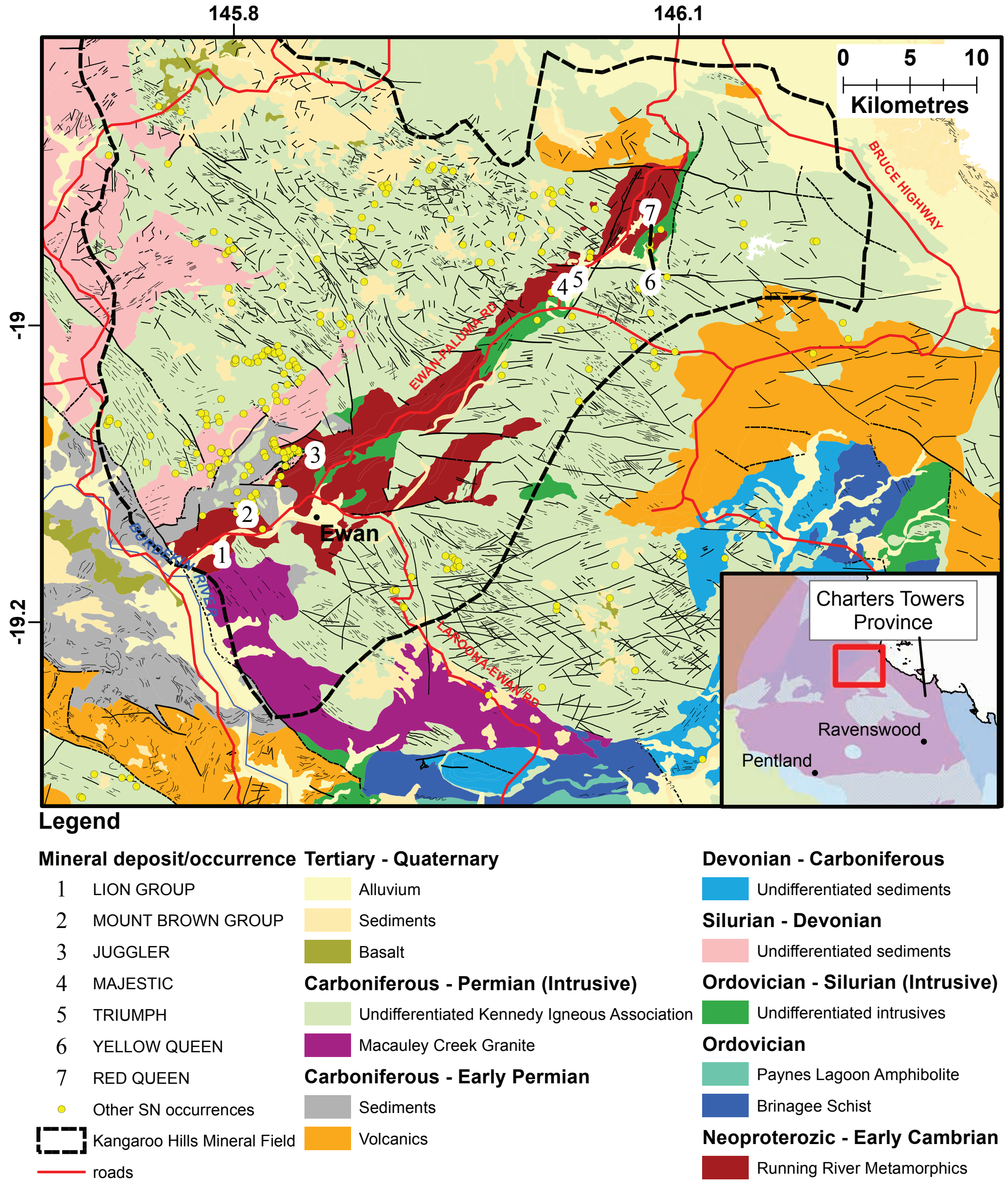


Figure 75. Distribution of alluvial and lode tin occurrences in the Kangaroo Hills Mineral Field (Running River Metamorphics)

Creek Granite. Mineralisation comprises fine- to medium-grained cassiterite which is associated with quartz–chlorite veins. This formed during the middle part of a complex paragenic sequence which includes brecciation of an early quartz phase. Veins are near-vertical and strike at ~120°. Ore zones are pod-like in geometry and comprise numerous quartz–chlorite–cassiterite veins. Wallrock alteration includes early silicification and later chloritisation and is intense but not extensive.

Deposits of the Mount Brown Group that are hosted by the Running River Metamorphics (e.g. **Agnes Campbell, Eclipse, Lucky Fall** and **New Chum**) similarly contain tin ore within quartz–chlorite veins with silicified and chloritised wall rocks. Both groups of deposits commonly exhibit limonite cappings above lodes (Gunther & others, 1994).

Other lode tin deposits hosted by the Running River Metamorphics include **Majestic, Juggler** and **Triumph**. Placer tin deposits are also developed above the Running River Metamorphics and include **Red Queen** and **Yellow Queen**.

GEOTHERMAL ENERGY POTENTIAL

The potential for geothermal energy in Australia is widely considered to be significant (e.g. Geoscience Australia & ABARE, 2010). Although the industry is in its infancy, the potential of this emerging energy source to provide base load electricity is considerable. Exploration for geothermal resources is underway in all states of Australia with significant resources identified (see http://www.ga.gov.au/energy/geothermal-energy-resources.html table 1) and several projects in advanced 'proof-of-concept' or pilot plant development stages.

In Queensland, current exploration activities (Figure 76) target hot rock resources for engineered or enhanced geothermal systems (EGS) at depths of ~4–5km, and shallower (<3km) hot sedimentary aquifer (HSA) systems which focus on the Great Artesian (or Australian) Basin (GAB) (Figure 76). To date, the 80kW power plant at Birdsville in south-west Queensland, which sources 98°C water from the GAB, is the only producer of geothermal energy in Australia. Despite great potential, deeper EGS sources in Queensland are yet to be explored to the extent of those in north-east South Australia.

The great potential of deeper heat sources in Queensland is highlighted by OzTemp (Gerner & Holgate, 2010) — an interpretation of temperatures at 5km depth compiled from bottom hole temperatures from drilling and limited heat flow and thermal conductivity data. The resulting OzTemp map (Figure 77) is dominated by a prominent anomaly covering central to south-west Queensland and extending to north-east South Australia with temperatures >235°C predicted at depth. The temperature extrapolations in this area have a greater level of certainty than elsewhere because of the abundance of petroleum drill holes with associated temperature measurements.

In South Australia, Geodynamics Limited's Habanero project near Innamincka occurs within this temperature anomaly. This is the most advanced EGS project in Australia and work here has encouraged a search for similar targets within the Cooper Basin (e.g. Meixner & others, 2012) and throughout the temperature anomaly area.

Elevated temperatures (up to 270°C at 4.5–5km) targeted at Habenero are related to the Big Lake Suite of intrusions (sometimes referred to as the 'Cooper Basin Granites') at ~3–5km depth, and thick insulating cover of the Cooper and Eromanga basins (Figure 78). The intrusions are considered to be high heat producing granites (HHPGs) and are relatively enriched in the heat producing elements (HPEs) potassium, uranium and thorium. Calculated heat production values are as high as 7.5–10$\mu W/m^3$ (Middleton, 1979). The granites intrude the Warburton Basin sequence

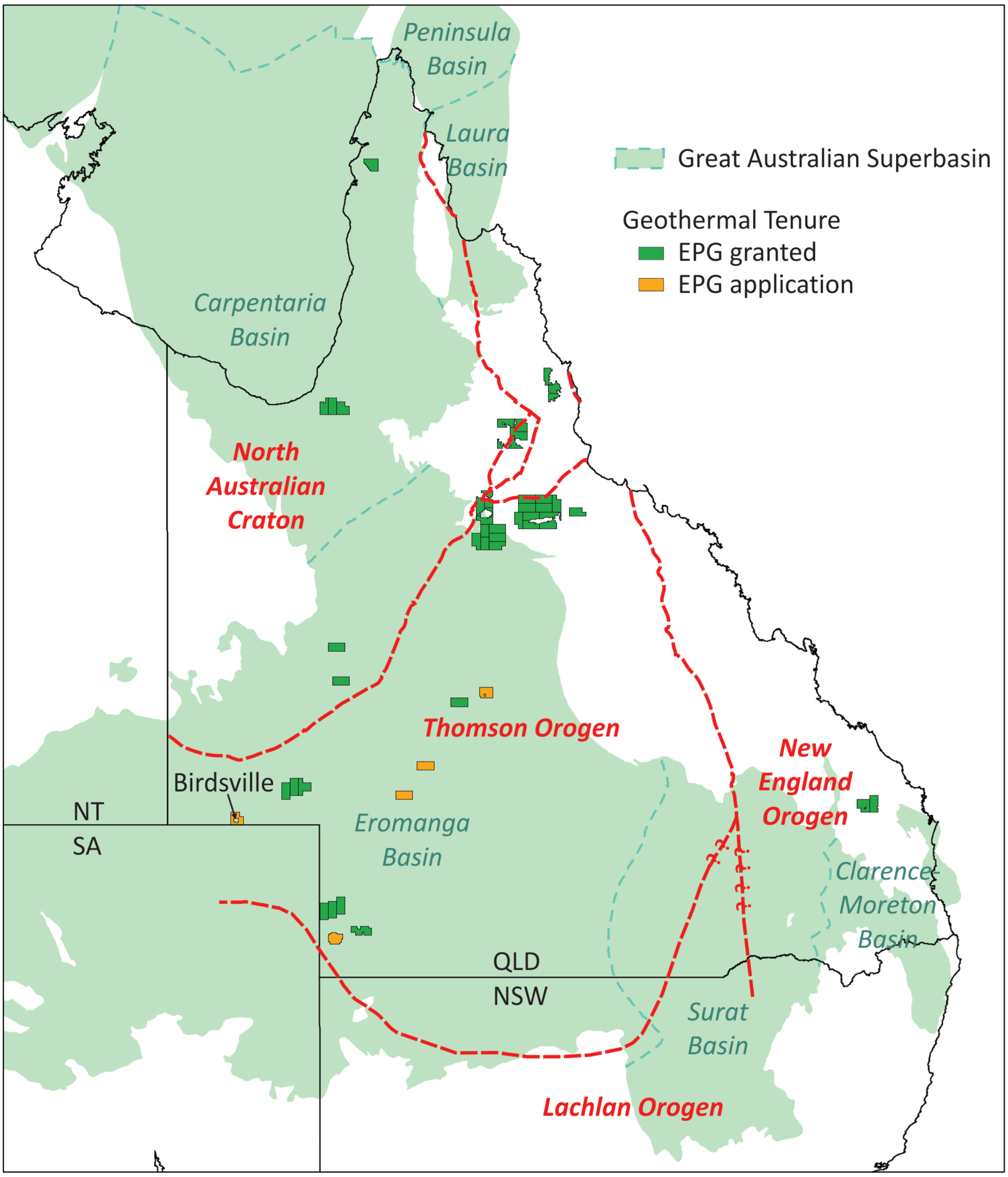


Figure 76. Status of Queensland's geothermal exploration permits (EPGs) at 05/11/2012 relative to the distribution of major crustal elements and the Great Australian Superbasin. Geothermal exploration tenure extracted from Department of Natural Resources and Mines' interactive resource and tenure maps system (http://mines.industry.qld.gov.au/geoscience/interactive-resource-tenure-maps.htm); outline of Great Australian Superbasin from Turner & others (2009).

(possibly originally at ~8km depth — Boucher, 1994) and were uplifted and eroded prior to deposition of the Cooper Basin.

In the Big Lake Suite type locality (drill hole Big Lake 1), granite is described as moderately weathered and coarse-grained with abundant quartz, microcline, orthoclase and sericite (Gatehouse & others, 1995). In a recent comparison with other HHPGs, the 'Cooper Basin Granites' are described as altered, peraluminous, fractionated I-type granites (Marshall & others, 2010). Two U–Pb SHRIMP zircon

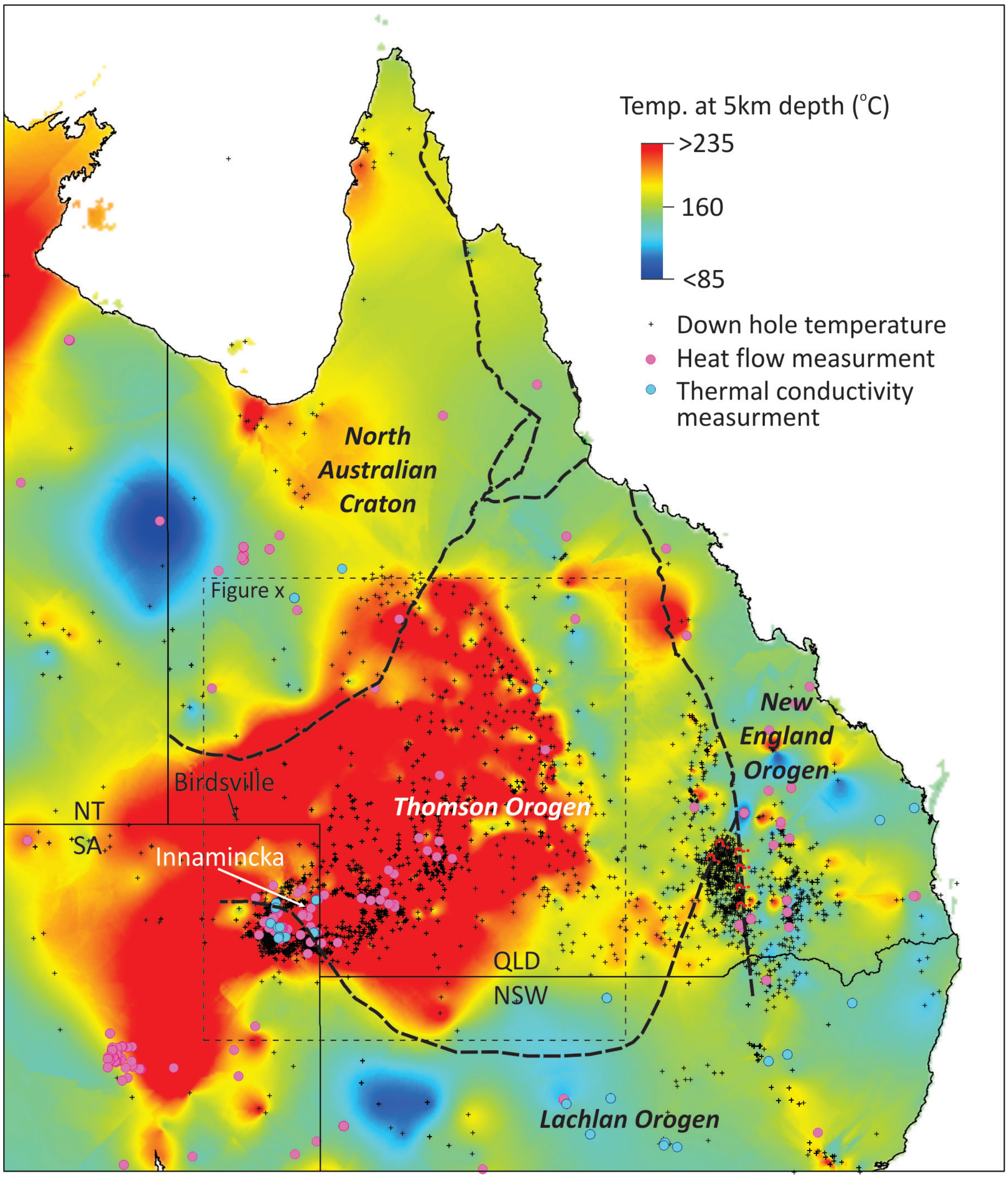


Figure 77. OzTemp map (interpreted temperature at 5km depth) and data sources for thermal modelling. A large temperature anomaly with temperatures >235°C covers central and south-west Queensland and is partly co-incident with the Thomson Orogen. Down hole temperature measurements are abundant in this area, but heat flow and thermal conductivity measurements are scarce. OzTemp data from Gerner & Holgate (2010), heat flow from University of North Dakota (2011), thermal conductivity from Weber & Kirkby (2011), Faulkner & others (2012).

dates from the Big Lake Suite (323 ± 5Ma — Moomba 1, 298 ± 4Ma — McLeod 1, Gatehouse & others, 1995) indicate mid- to late Carboniferous emplacement.

The insulating properties of the Cooper and Eromanga basins overlying the Big Lake Suite are described in thermal modelling works (Beardsmore, 2004; Meixner & others, 2012) and other compilations (Webber & Kirkby, 2011; Gallagher, 1987). Thermal conductivity data for the basement, Big Lake Suite, Cooper Basin and Eromanga Basin in South Australia exhibit a wide range (Figure 79), highlighting the effects of many variables such as water content. In comparison, thermal conductivity

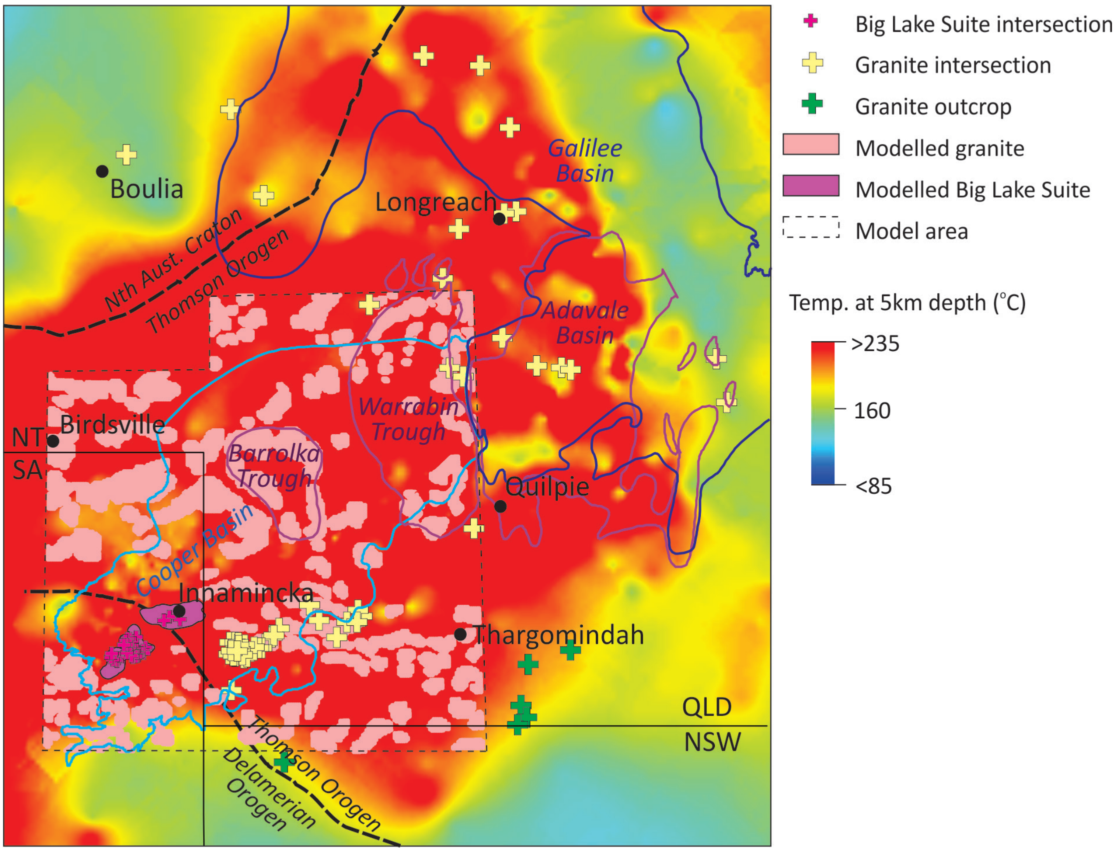


Figure 78. Distribution of subsurface granites (from drill hole intersections and modelling results) in north-eastern South Australia, and central to south-western Queensland relative to the OzTemp map (Gerner & Holgate, 2010) and major basins. Outcropping Eulo granites and Tibooburra Suite also shown. Modelled Big Lake Suite and other granites from Meixner & others (2012).

measurements are scant in Queensland (Figure 77). The only data from basins that overlie the Thomson Orogen in Queensland are from the Eromanga Basin section in GSQ Longreach 2 (Brown & others, 2012). Given the range of current measured values, uncertainties involved with calculation of thermal conductivity from lithological information (e.g. Beardsmore, 2004), and extrapolation of widely dispersed data, it is clear that many more thermal conductivity measurements are required from the Queensland basins that overlie the temperature anomaly (i.e. Adavale Basin, Warrabin Trough, Barrolka Trough, Cooper Basin, Galilee Basin and Eromanga Basin) (Figure 78).

In Queensland, OzTemp data exhibit a bimodal distribution (Figure 80) suggesting two different crustal thermal regimes (geothermal gradients) across the state. The majority of anomalously high temperatures indicated on the OzTemp map coincide with the distribution of the undercover Thomson Orogen (Figure 77). In contrast to the anomaly in South Australia, very little work has been completed in Queensland and the origin of the elevated temperatures remains unclear. Interestingly, initial results of a current research project (Siegel & others, 2012a;b) indicate strong contrasts between the Big Lake Suite in South Australia and basement granites in the Queensland part of the anomaly (Figure 78). The Queensland granites range from syenogranite to monzogranite and from fresh to strongly altered. They are older

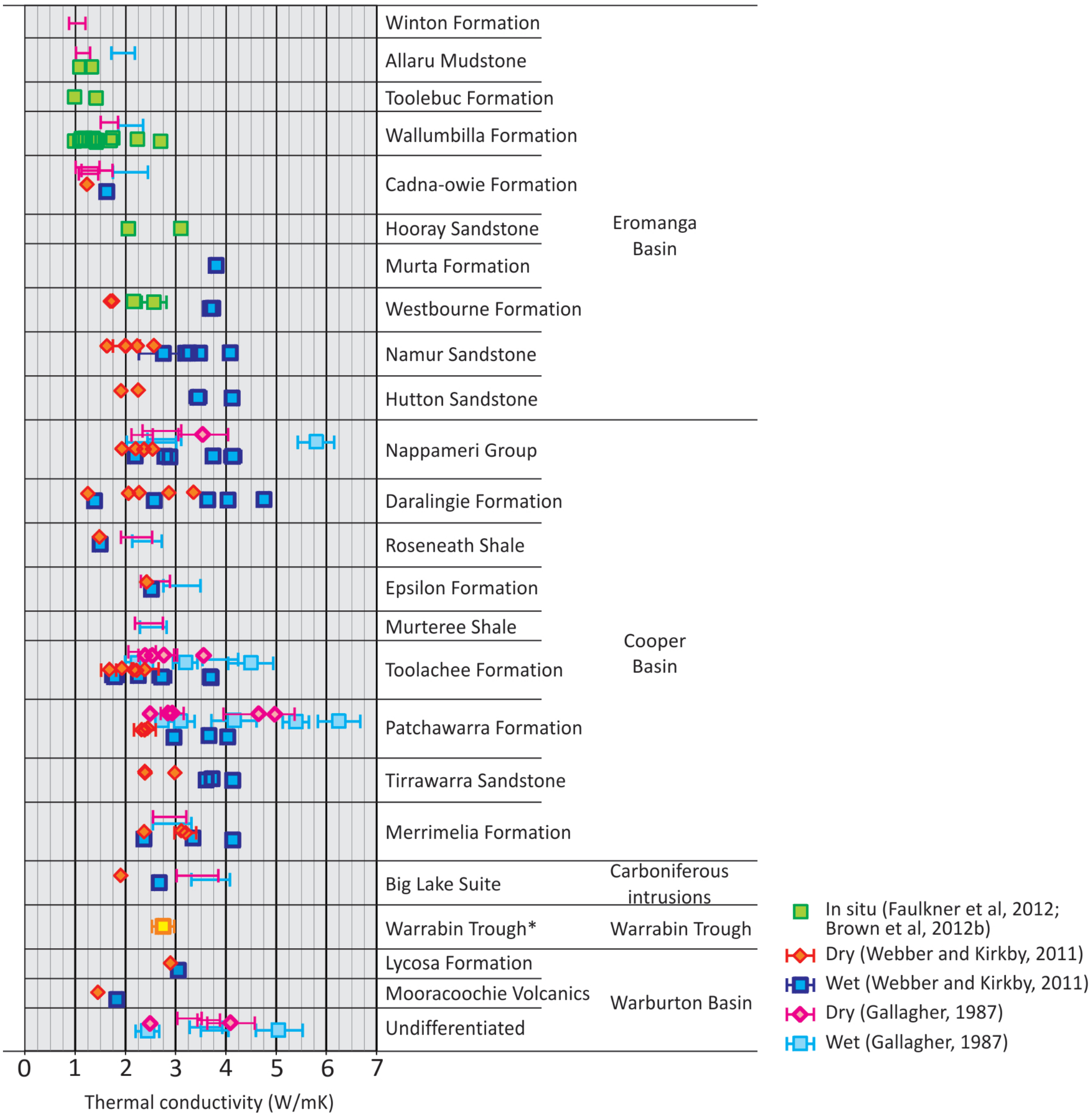


Figure 79. Thermal conductivity data for basement (Warburton Basin), Big Lake Suite intrusions and overlying basins. Note that data is collected under wet, dry or *in situ* moisture conditions. Data for the Warrabin Trough is that used in Meixner & others (2012) and is of uncertain origin. No other data exists for any of the extensive Devonian Basins in Queensland (Adavale Basin, Warrabin Trough, Barrolka Trough).

(~400–860Ma) and have much lower calculated heat production values (~1.5–4µW/m^3) than those of the Big Lake Suite.

The results of basic thermal modelling (Siegel & others, 2012b) show that the combination of these low to moderate heat producing granites with thick, insulative cover can still account for elevated subsurface temperatures. More regional thermal modelling studies (Meixner & others, 2012) also highlight the importance of thick cover, particularly in accounting for a subtle temperature anomaly within the Adavale Basin. This work indicates that more thermal conductivity measurements and more heat flow determinations are required for better modelling results. Other hypotheses to account for elevated subsurface temperatures in south-west and central Queensland include combinations of: 1) the presence of HHPGs at greater depth (Siegel & others, 2012b); 2) higher basement heat production (Meixner & others, 2012); and 3) mantle input (Italliano & others, 2012). Modelling work (Meixner & others, 2012) suggests that modelled heat flow and temperature in the Cooper Basin region are most sensitive to changes in basement heat production, basal heat flow (mantle and lower crust), and thermal conductivity of overlying basins (Figure 81).

Thermal modelling in south-west Queensland by Geoscience Australia is ongoing. Other Queensland-based research is investigating the role of tectonic setting and crustal heritage, magmatic processes and alteration/remobilisation on the distribution and concentration of HPEs in granites (e.g. Marshall & others, 2011; 2012; Siegel & others, 2011; 2012a;b; Middleton & others, 2011).

Regardless of the enormous potential resource outlined by the OzTemp temperature anomaly, EGS development in Queensland faces many challenges. These relate to permeability and other engineering problems associated with deep drilling and deep reservoirs as well as the relative isolation of this potential resource relative to existing consumers and infrastructure.

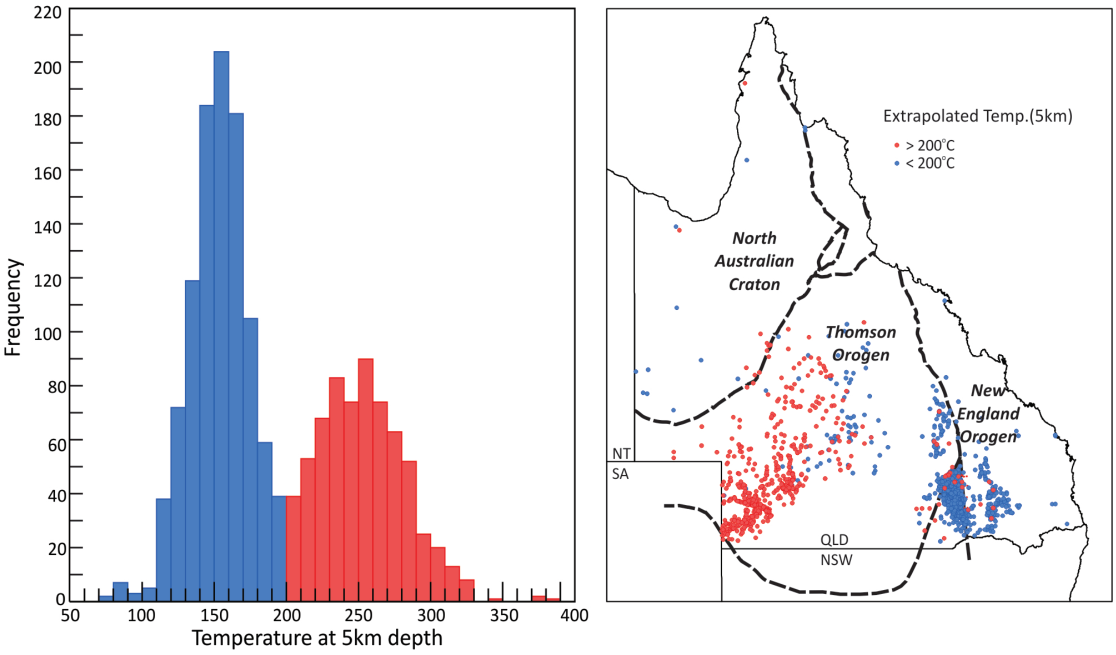


Figure 80. Histogram of interpreted temperature at 5km depth showing bimodal distribution. Lower temperature population roughly corresponds to a typical geothermal gradient of ~25°C/km, higher temperature population corresponds to an elevated gradient of ~50°C/km. Data is calculated from OzTemp (Gerner & Holgate, 2010), and is restricted to temperature at depths >1000m in Queensland.

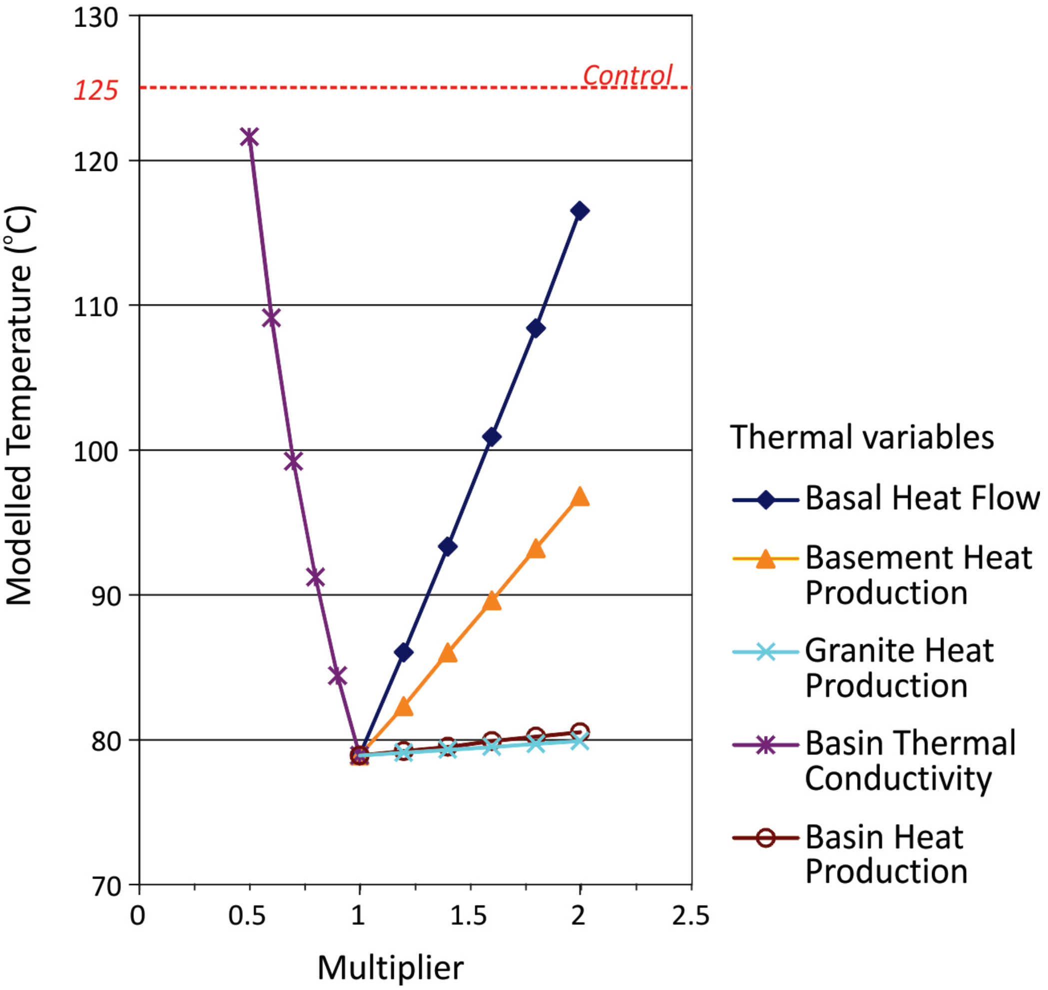


Figure 81. Geothermal modelling — effects of thermal property variation on modelled temperatures in the Cooper Basin 3D thermal modelling of Meixner & others (2012). Initial modelling results (78.9°C) are significantly lower than the control temperature of 125°C. Increases in basal heat flow (mantle and lower crust) and basement heat production, and decreases in the thermal conductivity of overlying basins, have the greatest impact on modelled temperatures. Data from Meixner & others (2012), table 10.

TECTONIC EVOLUTION

Despite the enormous extent of the Thomson Orogen (~1 000 000km^2), it is rarely considered in any detail in models for the tectonic development of Australia. In some large-scale reviews it is mentioned as ‘enigmatic’ or remains undescribed and even misspelt (e.g. Betts & others, 2002; Vos & others, 2007). Models focussing on aspects of the post-Rodinia development of eastern Australia (i.e. the Tasmanides) (e.g. Glen, 2005) attempt to place the Thomson Orogen in context but are hampered by the vast area of deeply covered and unknown geology.

Studies specifically focussed on the Thomson Orogen have been almost entirely based on the outcropping region and have provided valuable detrital zircon age spectra, geochemistry, and structural data (e.g. Fergusson & others, 2007a; 2009; Henderson & others, 2011). Models based on these studies attempt to define events that parallel those described in more thoroughly investigated regions to the south, such as rifting in the late Neoproterozoic, and deformation events that correlate with the Delamerian

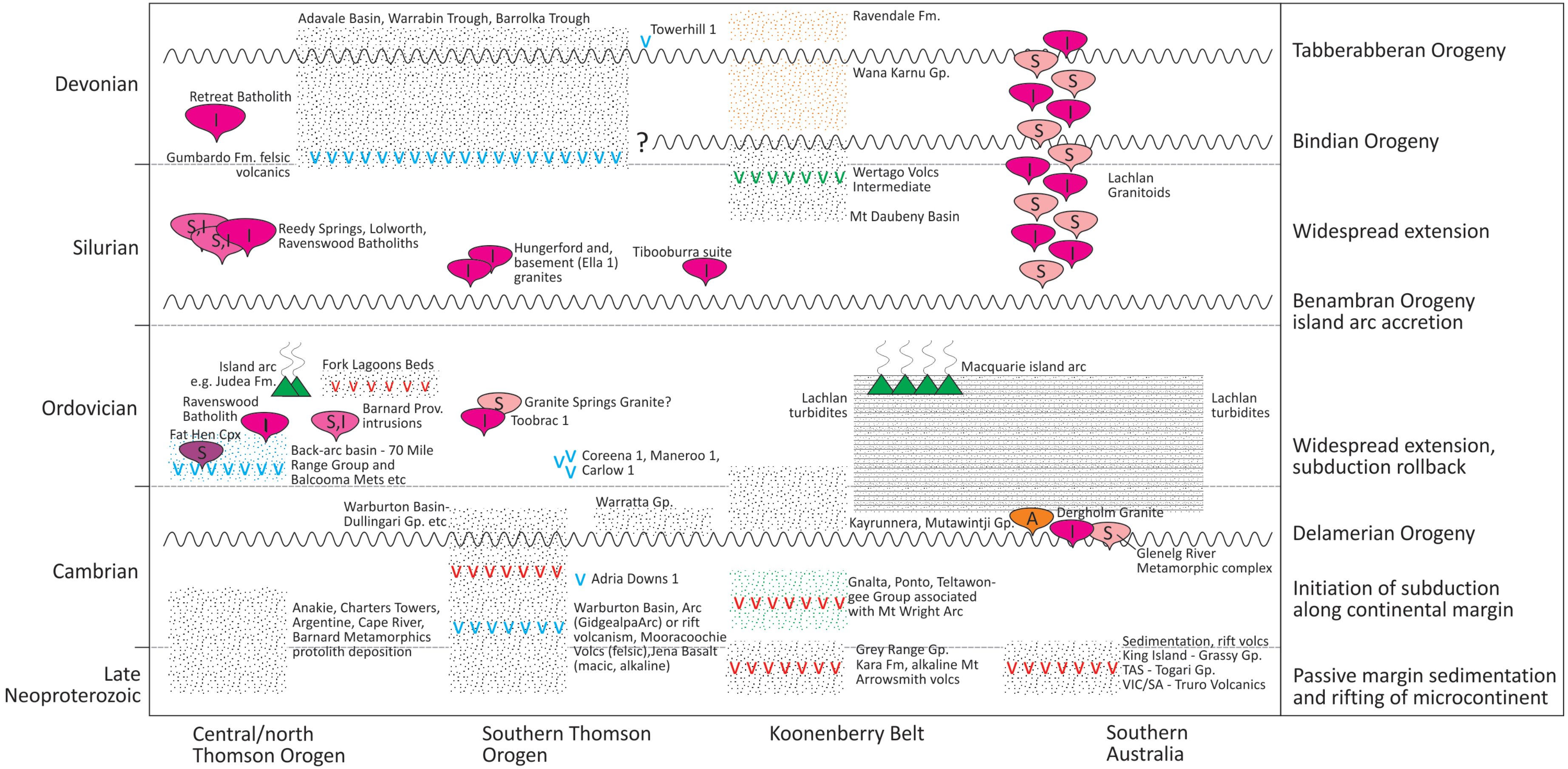


Figure 82. Generalised time–space (north–south) plot of major deposits and events in eastern Australia from the late Neoproterozoic to Devonian

and Benambran Orogenies. However, definite links between the Thomson Orogen and the Delamerian Orogen and Lachlan Orogen to the south are yet to be confirmed, and any straightforward links may be vastly oversimplified considering the uncertainty of the undercover region. Additionally, these models emanate from a restricted authorship group, and are yet to be subjected to the same kind of vigorous debate as models for south-eastern Australia and even Antarctica. Nonetheless, they present the prevailing hypothesis and are used to interpret events and terrane distributions observed in recent seismic and magnetotelluric data (Henson, 2009; Korsch & others, 2012).

Here we describe current hypotheses for the tectonic development of the Thomson Orogen through to the Middle Devonian and place these within the context of models for adjacent regions (e.g. Koonenberry Belt) (Figure 82) and the broader-scale development of the eastern Gondwana Margin.

LATE NEOPROTEROZOIC RIFTED MARGIN

The configuration of the Proterozoic supercontinent Rodinia and the timing and dynamics of its breakup are complex, much debated issues. The most common reconstructions (Figure 83) place Australia adjacent to different parts of Laurentia (SWEAT e.g. Moores, 1991; AUSWUS e.g. Burrett & Berry, 2000; AUSMEX e.g. Wingate & others, 2002), or separated from Laurentia by either Siberia (Sears & Price, 2000; 2003) or South China (Li & others, 2008). Break-up of Rodinia is considered episodic between ~850 and ~750Ma and possibly associated with a superplume (see Li & others, 2008).

While the timing of initial break-up of Rodinia is debated, a second rifting event and development of a passive margin along East Gondwana in the late Neoproterozoic (~600Ma) is commonly invoked (Figure 84a) (Direen & Crawford, 2003a;b; Fergusson & others, 2009; Greenfield & others, 2011). Based on limited detrital age spectra (indicating maximum depositional ages of ~600Ma), and structural and stratigraphic relationships, rocks of this age in the Thomson Orogen comprise the Bathampton Metamorphics (Anakie Metamorphic Group), Charters Towers Metamorphics, Cape River Metamorphics, Oasis Metamorphics, Halls Reward Metamorphics, and Argentine Metamorphics. These are the oldest rocks currently known in the Thomson Orogen and are interpreted to represent a magma-poor rifted margin setting (Fergusson & others, 2009). This is based on 1) the geochemistry of mafic schists in the Bathampton Metamorphics (Anakie Metamorphic Group) and equivalents in the Cape River and Argentine Metamorphics, and 2) the relatively low abundance of these mafic rocks relative to associated pelitic, psammitic, siliceous and calcareous metasediments (Fergusson & others, 2009). Mafic schists of the Bathampton Metamorphics include an alkaline suite and a tholeiitic suite (Withnall & others, 1995; Fergusson & others, 2009). The later exhibit MORB-like geochemical signatures but have chondrite normalised REE patterns (particularly LREE depletion) and low incompatible trace element contents more characteristic of attenuated crustal margin settings. Their age is constrained by detrital zircon age spectra from associated psammitic rocks (Fergusson & others, 2001; 2007a). Both the Cape River Metamorphics and Argentine Metamorphics also include amphibolites with tholeiitic

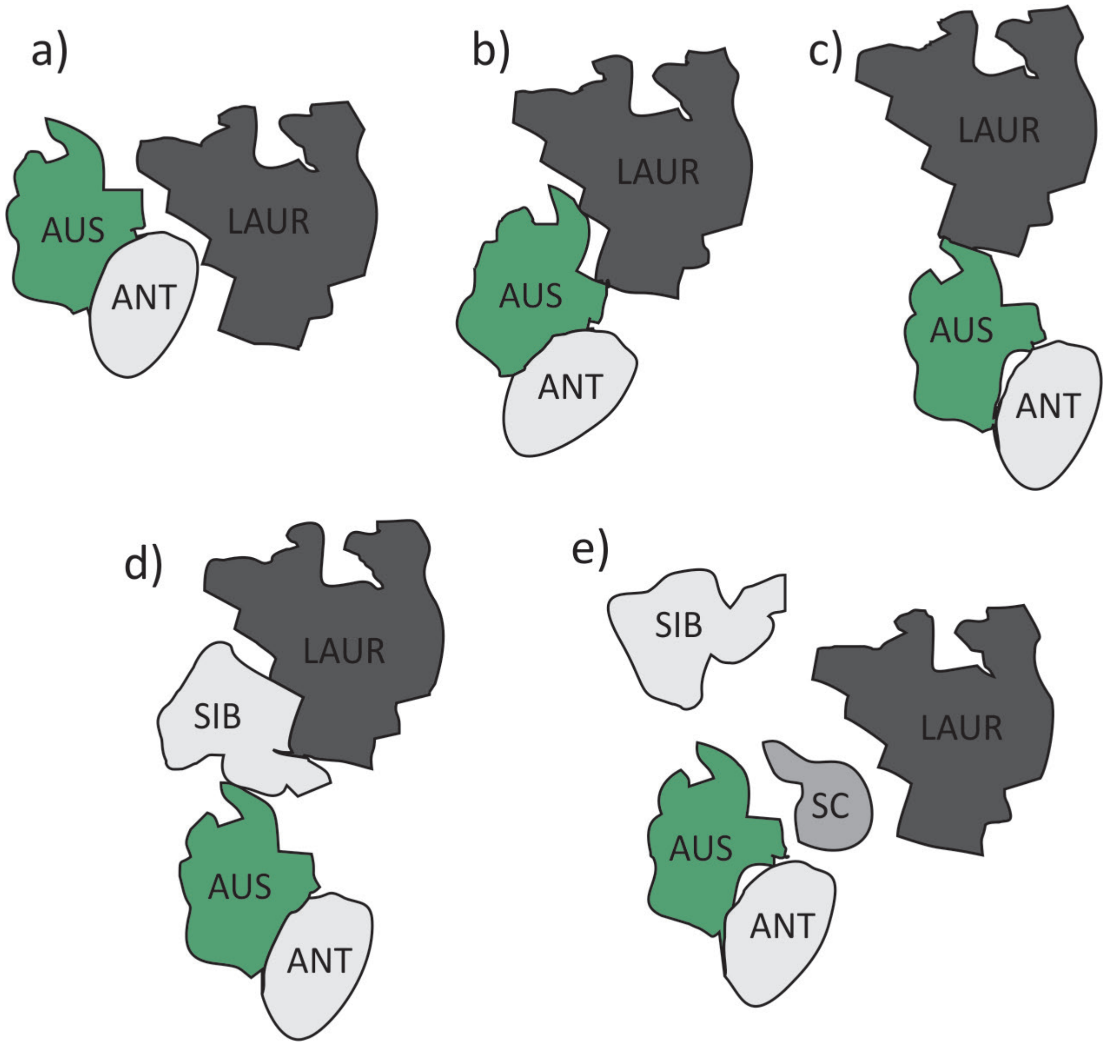


Figure 83. Reconstructions of Australia and Laurentia in the supercontinent Rodinia (modified from Greene, 2010 (after Wingate & others 2002); Sears & Price, 2003; and Li & others, 2008): a) SWEAT (South-west United States – East Antarctica) with connection between Australia and Canada; b) AUSWUS connection between Australia and the western United States of America; c) AUSMEX connection between Australia and Mexico; d) Australia and Laurentia separated by Siberia; and e) Australia and Laurentia separated by South China.

and alkaline affinities although these are less well studied (Fergusson & others, 2013b).

The renewed rifting event at ~600Ma is interpreted to represent breakoff of a microcontinent. This occurred along a rift inboard of an earlier Rodinian fragmentation margin, thereby removing evidence for earlier rifting events (Fergusson & others, 2001; 2009). Vos & others (2007) suggested that the Barnard Province, Anakie Inlier, Charters Towers Province and Argentine Metamorphics may also represent continental fragments rifted at 560–530Ma that were later accreted back onto the continental margin. The abundance of late Mesoproterozoic ('Grenvillian-aged') detrital zircons, particularly relative to North Australia Craton-derived material (1550–1660Ma) within the passive margin sediments, is used to suggest: 1) no significant uplift of the rift shoulder during passive margin formation, and 2) a late Mesoproterozoic orogen (an extension of the Musgrave Complex of central Australia) extended through western and central Queensland forming basement to

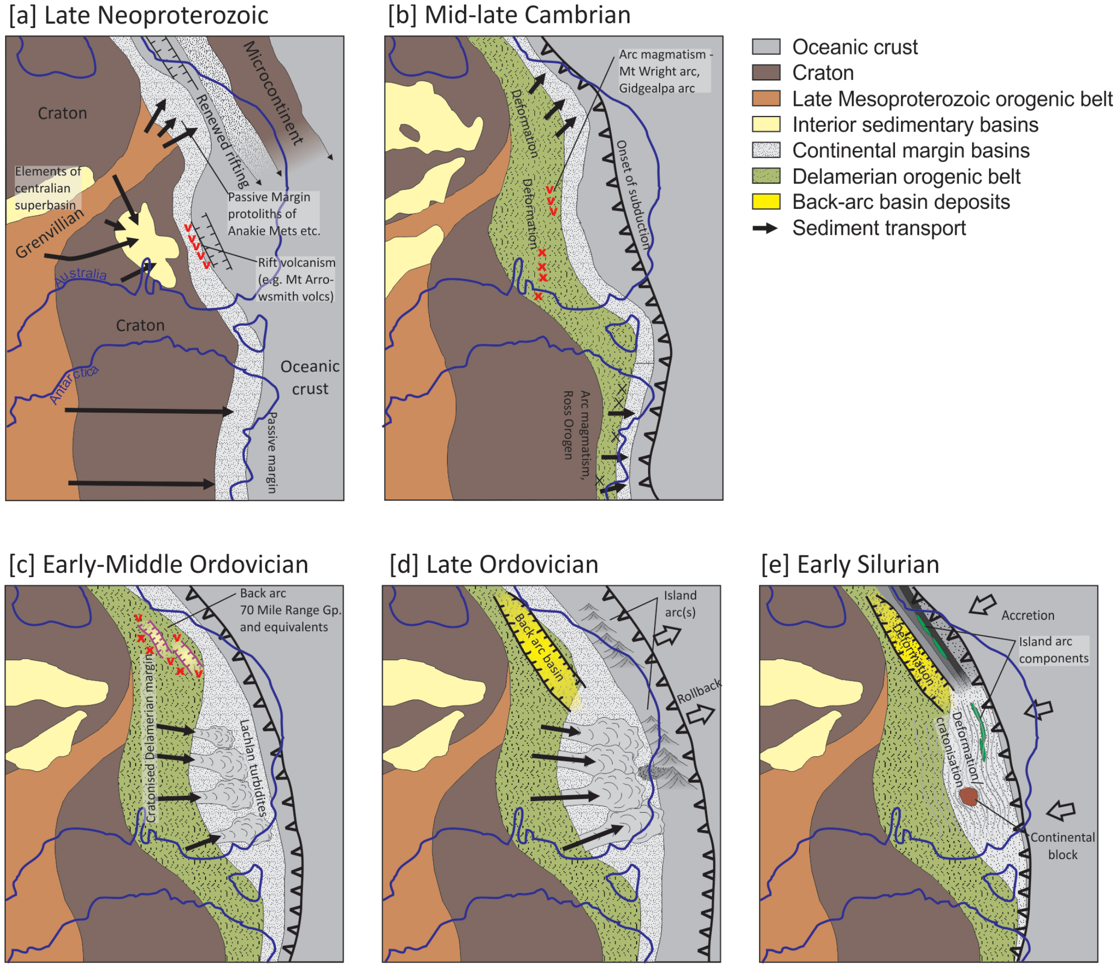


Figure 84. Generalised tectonic model for the eastern Gondwana margin focussed on the Thomson Orogen. Modified from Fergusson & others (2007a) to include aspects of Fergusson & others (2009), Henderson & others (2011), and Greenfield & others (2011): a) Late Neoproterozoic passive margin developed after a secondary rifting event. A Grenvillian-aged source provided the dominant detritus to a magma-poor passive margin setting in the Thomson Orogen; b) mid- to late Cambrian deformation (Delamerian Orogeny) associated with onset of subduction along the margin. Passive margin sediments are deformed and some areas have arc volcanism; c) widespread Early to Middle Ordovician extension. Back arc volcanism and sedimentation begin in the Thomson Orogen, Delamerian Orogen sheds detritus (turbidites) to the Lachlan Orogen; d) Late Ordovician subduction rollback and initiation of island arc magmatism just off margin. Back arc extension in the Thomson Orogen and continued turbidite sedimentation in the Lachlan Orogen; e) Early Silurian deformation (Benambran Orogeny) associated with accretion of island arcs to the continental margin. Back arc basin sediments in the Thomson Orogen and Lachlan Turbidites are deformed.

the passive margin sediments (Fergusson & others, 2007a). The Agwamin Seismic Province, identified by Korsch & others (2012), is tentatively suggested to represent this late Mesoproterozoic, lower crustal domain (Figure 85). Extension of old (Proterozoic) crust eastward of the Tasman Line may also be supported by surface wave tomography (Kennett & others, 2004).

The *magma-poor* rifted margin setting interpreted for the north-eastern Thomson Orogen contrasts with areas further south where a *volcanic* passive margin setting is proposed for rocks in western Tasmania, King Island, western Victoria, and western

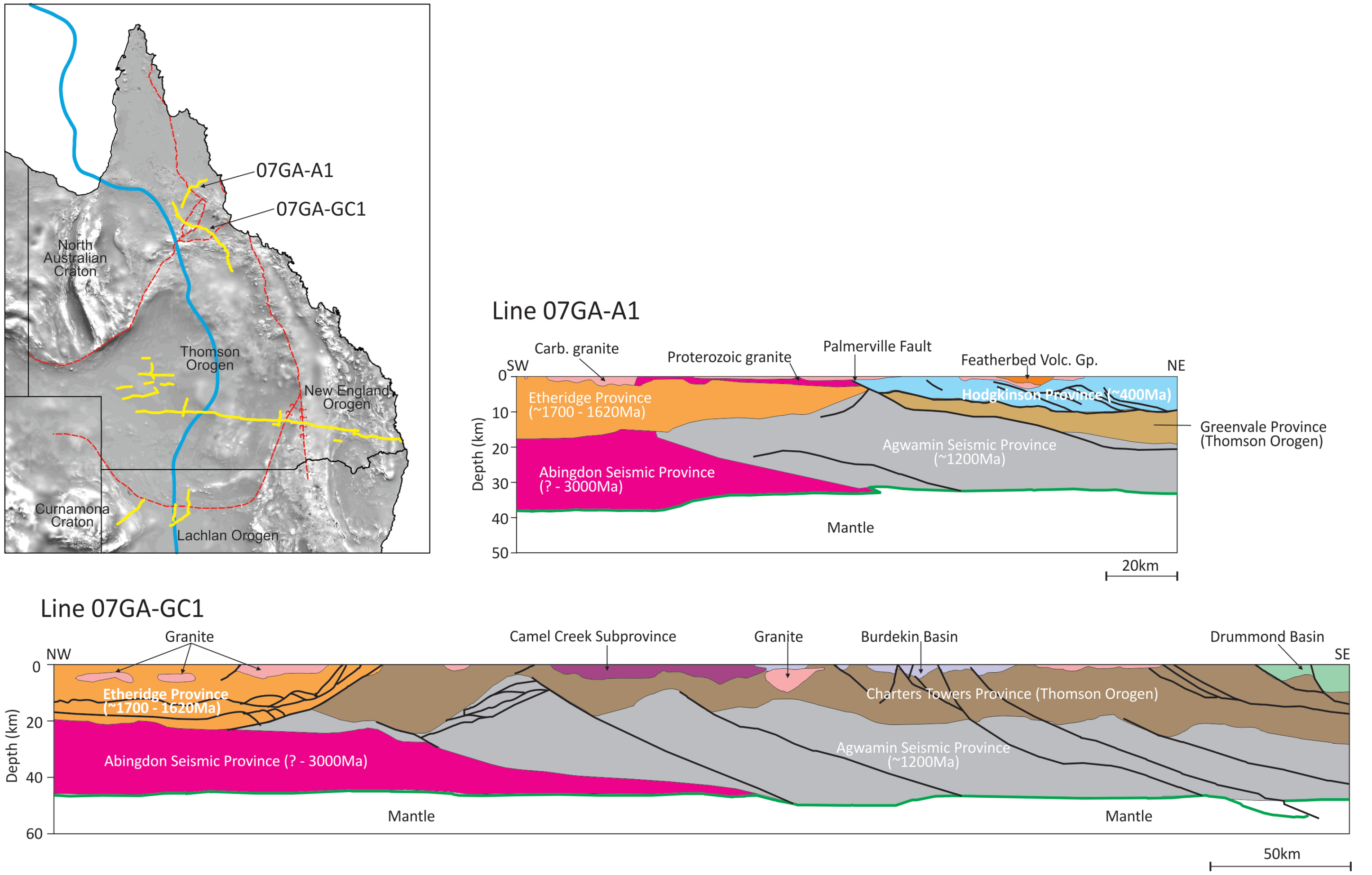


Figure 85. Distribution of the hypothesised Grenvillian-aged Agwamin Seismic Province from deep crustal seismic and geophysical modelling (Korsch & others, 2012). Also note continuation of the Greenvale Province eastward below the Hodgkinson Province. Blue line on inset shows neutral line in perturbation of shear-wave speed (relative to the ak135 reference model) at 125km (Kennett & others, 2004) suggesting extension of old crust significantly eastward of the Thomson – North Australian Craton boundary.

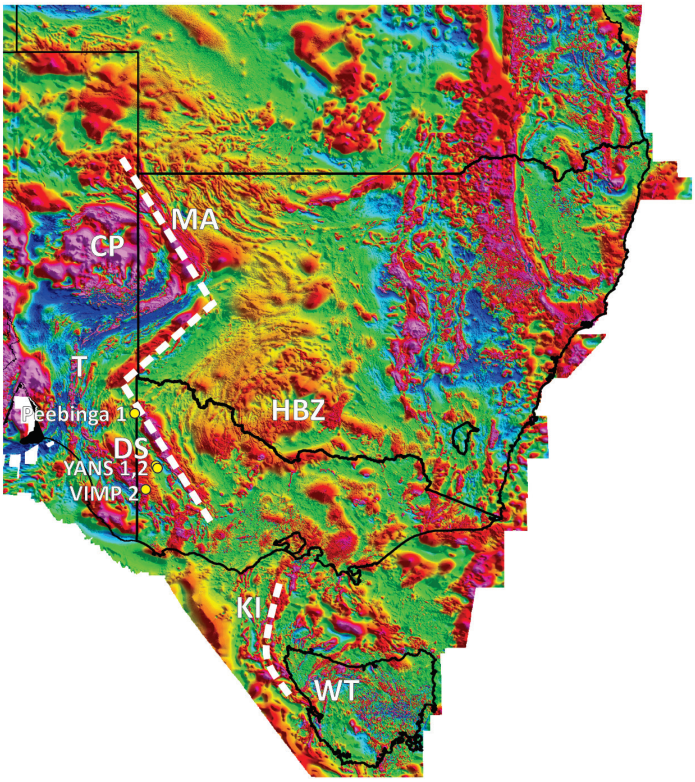


Figure 86. Distribution of magnetic anomalies (TMI) interpreted as Neoproterozoic rift volcanics (Direen & Crawford, 2003a; b); MA – Mount Arrowsmith, CP – Curnamona Province, T – Truro, Adelaide Fold Belt, DS – Dimboola Subzone, KI – King Island, WT – Western Tasmania, HBZ – Hay–Booligal Zone

New South Wales. These are highlighted as elongate magnetic anomalies (Direen & Crawford, 2003a; b) (Figure 86) interpreted as widespread mafic volcanic sequences.

In mainland Tasmania and King Island, rift-related deposits comprise picrites, tholeiitic basaltic lavas and dykes interbedded with sedimentary sequences that include dolostone, diamictite, turbiditic sandstones, and shales (e.g. Skipworth Subgroup of the Grassy Group – King Island, Togari Group – Smithton Trough, north-west Tasmania, and Crimson Creek Formation, western Tasmania, Waldron & Brown, 1993; Crawford & Berry, 1992; Calver & Walter, 2000; Direen & Crawford, 2003b; Meffre & others, 2004; Direen & others, 2009). The Grassy Group on King Island is considered late Neoproterozoic based on correlation with similar rocks in South Australia, a Nd–Sm isochron age of 579 ± 16Ma, and a U–Pb SHRIMP zircon date from the Grimes Intrusive suite of 574.7 ± 3.0Ma (see Meffre & others ,2004; Calver & others, 2004). Rift-related deposits in western Tasmania are constrained in age by stratigraphic relationships, chemostratigraphic correlations (indicating ~650–580Ma, Calver, 1998), K–Ar dates of dykes (584 ± 8Ma, 588 ± 8Ma, 600 ± 8Ma, Adams & others, 1985), and a U–Pb SHRIMP zircon date of a rhyodacite flow (582.1 ± 4.1Ma) in the Kanunnah Subgroup of the Togari Group (Calver & others, 2004).

In the north-western Glenelg Zone of western Victoria, strongly altered submarine rift sequences correlated with the Truro Volcanics are interpreted from drilling (Figure 86). These include strongly altered picritic basalt lava and cumulate metagabbro (Yans 1 and Yans 2), basalt, pyritic limestone and black shale (Peebinga–1), and coarse leucogabbro with MORB composition (VIMP 2) (see VandenBerg & others, 2000). These types of deposits extend into eastern South Australia where they are interpreted to mark early Cambrian intracratonic rifting. In Victoria, they are transitional between within-plate and MORB and are suggested to represent initial ocean floor magmas erupted through extending continental crust (VandenBerg & others, 2000). The only age constraints are from a gabbro in drill hole VIMP 2 (524 ± 9Ma, U–Pb zircon – Maher & others, 1997), but other workers infer a latest Neoproterozoic age based on similarity to rocks of the Grassy Group and Togari Group (Direen & Crawford, 2003a). Geophysical modelling (Direen & Crawford, 2003b) indicates that these volcanics form a component of the major north-west trending magnetic anomaly in western Victoria and South Australia. Other sequences of turbidites, black shale, volcaniclastic deposits and carbonate-bearing rocks deposited in western Victoria during this time are considered equivalent to rocks of the Stansbury Basin (South Australia). They are grouped into the Moralana Supergroup and represent protoliths of the Glenelg River Metamorphic Complex. A maximum depositional age is given by ~590Ma zircons in a biotite gneiss (see VandenBerg & others, 2000).

In the Koonenberry Belt of western New South Wales, the Grey Range Group (Figure 36) which comprises shallow marine sediments (Kara Formation) and intercalated submarine alkaline, volcanics (Mount Arrowsmith Volcanics) are also interpreted as Neoproterozoic rift deposits and considered equivalent to the Farnell Group of the Curnamona Province. The Kara Formation comprises slates (dominant), quartzite, dolomitic limestone, black shale, pyritic siltstone and exhalative units, while the Mount Arrowsmith Volcanics comprise low-grade metamorphosed alkali basalt, trachybasalt and trachyte submarine and subaerial lavas, pyroclastic deposits and intrusions (Gillmore & others, 2007). These volcanics are geochemically distinct from the nearby and younger Mount Wright Volcanics and form a high-Nb, transitional alkali basalt–trachybasalt–trachyte–alkali rhyolite suite with characteristics of modern rift volcanics (Crawford & others, 1997; Greenfield & others, 2011). An alkalic felsic unit from the Mount Arrowsmith Volcanics has been dated at 586 ± 7Ma (Crawford & others, 1997) and 585.5 ± 3.2Ma (Greenfield & others, 2011). Geophysical modelling (Direen & Crawford, 2003b) suggests that much of the north-west-trending magnetic anomaly in western New South Wales adjacent to the Curnamona Province may represent buried equivalents of the rift volcanics. With recent seismic data however, some of the magnetic anomaly is now attributed to younger volcanism (see Greenfield & others, 2011). It is suggested that the volcanics wrap around the Curnamona Province, forming a south-west trending belt and reappearing as the Truro Volcanics in South Australia (Direen & Crawford, 2003b) (Figure 86). Some drill holes within the south-west-trending Loch Lilly – Kars Belt have intersected basalt with similar geochemical characteristics to the Mount Arrowsmith Volcanics (Greenfield & others, 2011).

Recent geochronology from the far southern extent of the Thomson Orogen in New South Wales (Glen & others, 2010) has tentatively identified more Neoproterozoic mafic deposits (Warraweena Volcanics, Getty Gabbro). These form part of the curved gravity and magnetic trends characteristic of the southernmost Thomson Orogen. The Warraweena Volcanics include rocks of both calc-alkaline and within-plate geochemical affinities. They are interpreted as forming part of a continental margin arc (Glen & others, 2010), or (prior to dating) were correlated with the Macquarie Arc in the Lachlan Orogen (Burton & others, 2008; Burton, 2010).

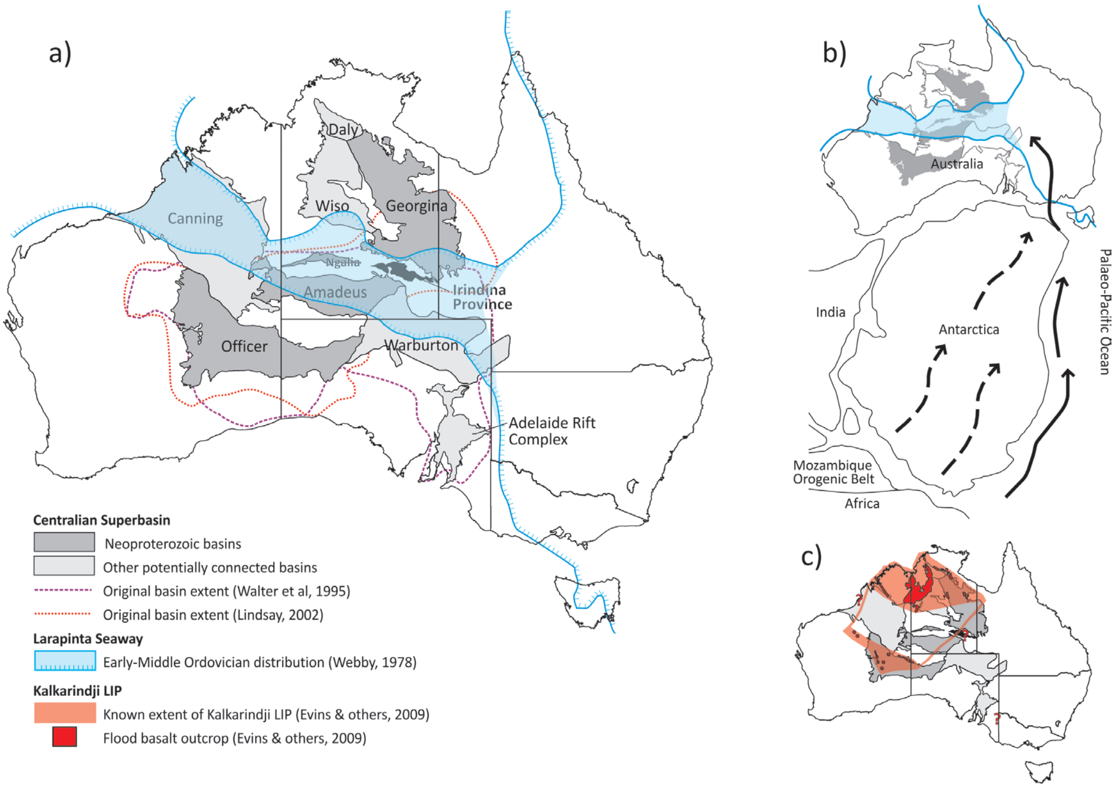


Figure 87. Extent of the intracratonic Centralian Superbasin and Larapinta Seaway; a) Neoproterozoic components of the Centralian Superbasin comprise the Georgina, Ngalia, Amadeus and Officer Basins, now separated by uplifted basement domains. Dotted outlines show hypotheses for original basin extents. The Canning and Warburton Basins were linked with parts of the Centralian Superbasin in the Ordovician during incursion of the Larapinta Sea. b) Suggested transport paths (arrows) for detritus to account for 'Pacific Margin' detrital zircon signatures in Late Cambrian – Ordovician sediments of central Australian basins (from Maidment & others, 2007); c) Extent of the Cambrian (505–510Ma) Kalkarindji LIP (from Evins & others, 2009)

A passive margin succession is also preserved in the Transantarctic Mountains and southern Victoria Land Antarctica (Goodge & others, 2002; 2004; Myrow & others, 2002), indicating that it extended several thousand kilometres along the eastern Gondwana margin. Passive margin shoreline and shallow marine sediments are represented by the Beardsmore Group. These deposits also include interlayered pillow basalts and associated gabbro (in the Goldie Formation) dated at 668 ± 1Ma (Goodge & others, 2002), somewhat older than the mafic magmatism recorded in the eastern Australia portion of the passive margin. Rhyolite clasts in metaconglomerates of the Skelton Group dated at ~650Ma are also interpreted to represent initial rifting of Rodinia along the Antarctic margin (Cooper & others, 2011). It is suggested that the ~580–515Ma period in this area involved both a continuation of platform sedimentation (e.g. Shackelton Limestone) and (possibly distal) continental margin arc magmatism (Goodge & others, 2004).

A late Neoproterozoic rifting event in Australia may also be supported by the depositional history of several intracratonic basins that form the Centralian Superbasin (Figure 87) (Lindsay, 1987; Walter & others, 1995; Lindsay, 2002). In central Australia, these include the Officer, Amadeus, Ngalia and Georgina basins, which to some extent share a common sedimentary history (Walter & others, 1995). These basins also record an influx of 1000–1200Ma detrital zircons related to north–south shortening and uplift of the Musgrave Block during the Petermann Orogeny between 560 and 520Ma (Maidment & others, 2007). Despite massive inferred exhumation (30–40km), this event appears localised (Hand & Sandiford, 1999) and is not yet observed in eastern Australian rocks.

DELAMERIAN–TYENNAN – ROSS OROGEN

An active continental margin is widely interpreted to have replaced the passive margin setting for eastern Gondwana in the middle to late Cambrian (Figure 84b). This resulted in deformation of the passive margin deposits in what is known as the Ross (Antarctica), Delamerian (mainland Australia) and Tyennan (Tasmania/Selwyn Block) Orogeny. In the Thomson Orogen, this event is also attributed to the onset of subduction, and is represented by deformation and metamorphism dated at ~500Ma in the Anakie Metamorphic Group (Withnall & others, 1996), and ~500–510Ma in the Halls Reward Metamorphics (Nishiya & others, 2003). Sedimentation continued during this time with deposition of the upper Anakie Metamorphic Group (e.g. Wynyard Metamorphics) and upper Argentine Metamorphics. These have a 500–600Ma detrital zircon population, which distinguishes them from the older passive margin deposits, and may derive from continued episodic rifting and/or back-arc volcanism (Fergusson & others, 2007a).

Thomson Orogen rocks interpreted to exhibit Delamerian deformation are commonly suggested to continue southward from the Anakie Inlier in the subsurface, forming the Nebine Ridge. Basement metasediments intersected in drill holes along this basement high are multiply deformed (Murray, 1994) but have relatively young K–Ar (biotite) and Ar-Ar (muscovite) ages of 416 ± 2Ma (Murray, 1986) and 412.9 ± 1.3Ma (Wood, 2006) respectively (drillhole Alba 1).

Rocks and deformation associated with the Delamerian Orogeny in *southern* mainland Australia, the Tyennan Orogen in Tasmania, and the Ross Orogen in Antarctica are well documented. In Australia, orogenesis began at 514 ± 3Ma affecting rocks in the Adelaide Fold Belt (South Australia), the Glenelg Complex (western Victoria), the Selwyn Block (central Victoria), the Wonaminta Block (western New South Wales), and Proterozoic and Cambrian sequences in Tasmania, and was terminated at 490±3Ma (Foden & others, 2006). Orogenesis involved several phases of dominantly east–west compressional deformation and extension. The deformation is attributed to events including arc–continent collision, accretion of mafic/ultramafic and sedimentary blocks, emplacement of syntectonic S- and I-type intrusions, post-collisional rift magmatism, calc-alkaline volcanism, marine sedimentation, and offshore volcanic arc development (for reviews, see VandenBerg & others, 2000; Glen, 2005; Champion & others, 2009). The complexity of the Delamerian Orogen in south-eastern Australia is reflected by disagreement concerning the polarity of subduction during this time, various interpretations of the eastern boundary of the orogen in Victoria, and contrasting interpretations of calc-alkaline volcanics beneath the Melbourne Zone.

Convergence (possibly as early as ~580Ma — see Goodge & others, 2004) and orogenesis (beginning at ~540Ma — Myrow & others, 2002; Goodge, 1997; Goodge & Dallmeyer, 1996; Stump & others, 2007) in Antarctica began much earlier and may have provided detritus to basins in Australia (Kanmantoo Basin) (Foden & others, 2006). While calc-alkaline plutons associated with the Ross Orogen may be as old as 546 ± 10Ma (Cottle & Cooper, 2006); voluminous calc-alkaline continental arc magmatism defining a magmatic arc occurred much later, (i.e. after ~530Ma), but may have varied through space (see Encarnación & Grunow, 1996; Allibone & Wysoczanski, 2002). Major changes in sedimentation and sediment provenance in the Ross Orogen at ~515Ma (Myrow & others, 2002; Goodge & others, 2004) highlight a significant tectonic event, which parallels initiation of the Delamerian Orogeny, and may additionally relate to accretion of island arc rocks to the margin or a change from oblique to orogen-normal convergence (see Boger & Miller, 2004, figure 3, page 39).

Directly adjacent to the undercover Thomson Orogen, Delamerian rocks are well described in the Koonenberry Belt of western New South Wales following a major mapping project by the Geological Survey of New South Wales (Greenfield & others, 2010a). According to Greenfield & others (2011), a continental volcanic arc assemblage (Mount Wright Arc) associated with south-west dipping subduction, overlies the Neoproterozoic passive margin deposits (e.g. Mount Arrowsmith Volcanics) in this area and originally extended south-eastward into the palaeo-Pacific Ocean. An alternative hypothesis (Crawford & others, 1997) suggests that the Mount Wright Volcanics and associated sediments formed in an immature continental rift.

In the continental volcanic arc model (Figure 88) (Greenfield & others, 2011) back-arc deposits are intersected in drill holes (andesitic–dacitic volcanics in Bancannia South No. 1 — 506.2 ± 2.8Ma) and modelled below the Bancannia Trough. Volcanic arc deposits comprise the early to late Cambrian Gnalta Group which includes calc-alkaline and tholeiitic volcanics and intrusions ranging from basalt to rhyolite in composition (Mount Wright Volcanics), intercalated with shallow marine limestone, siltstone, mudstone and pyroclastic deposits with U–Pb SHRIMP zircon dates of 510.3 ± 3.2Ma, 510.5 ± 2.9Ma, and 510.1 ± 2.3Ma (compiled in Greenfield & others, 2011). Fore-arc basin deposits are represented by the Ponto Group, which comprises laterally extensive marine mudstone and siltstone with intercalated air-fall deposits (508.6 ± 3.2Ma, 512.0 ± 3.1Ma and 511.7 ± 3.5Ma — compiled in Greenfield & others, 2011) that have calc-alkaline chemistry and are correlated with volcanism in the Mount Wright Arc. The Ponto Group also includes mafic volcanics (Bittles Tank Volcanics) with affinities to both ocean island tholeiites and MORB. Deformation of the Mount Wright Arc during later stages of Delamerian orogenesis culminated in oroclinal folding around the Curnamona Province to form a north-east trending belt (Loch Lilly – Kars Belt) and thrusting of parts of the fore-arc over arc volcanics. This may be associated with arrival of a microcontinent (Hay – Booligal Zone) at the subduction zone (Musgrave & Rawlinson, 2010, figure 6; Greenfield & others, 2011, figure 11).

Aeromagnetic lineaments associated with the Koonenberry Belt in western New South Wales continue north-west to the Warburton Basin in the north-east corner of South Australia. The Gidgealpa Volcanic Arc (Gatehouse, 1986) was tentatively

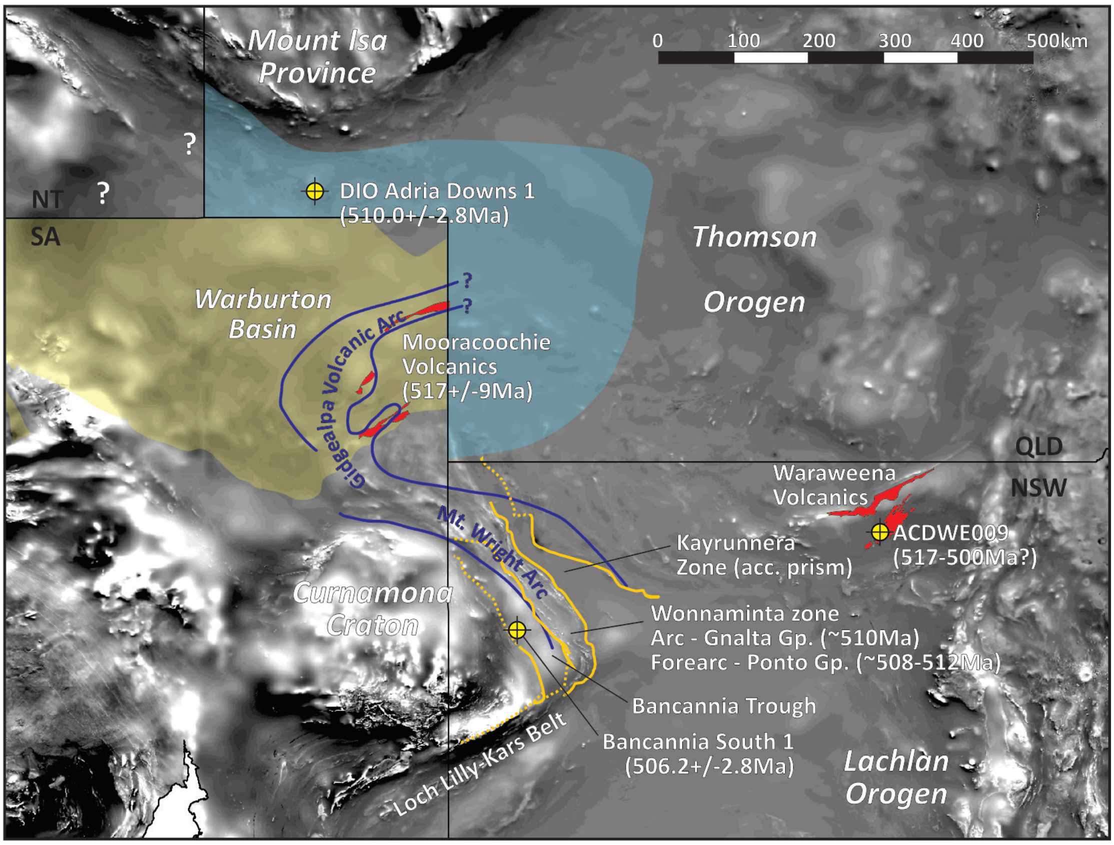


Figure 88. Location and division of Cambrian rocks variably interpreted as components of volcanic arc systems. Extension of any arc components into Queensland is very uncertain. Conflict between the distribution of the Warburton Basin in South Australia (yellow) and Queensland (blue) also shown.

proposed in this area as a continuation of the Mount Wright Arc and is displayed as a curved belt (Figure 88) which swings from just south of the New South Wales – South Australia – Queensland corner, through the Warburton Basin back into Queensland where its distribution is unknown. The location of the arc is based on the distribution of the Mooracoochie Volcanics (Gatehouse, 1986), which are dated at 517 ± 9Ma (U–Pb Zircon — Armstrong, 1995, cited in Sun & Gravestock, 2001). A similar age of 510.0 ± 2.8Ma for felsic volcanics in DIO Adria Downs 1 (Figure 88) (Draper, 2006) suggests possible continuation of these rocks into Queensland. A back-arc rift basin setting has also been proposed (Roberts & others, 1990).

The most recent work (Sun, 1996), using geochemistry and volcano-sedimentary facies analysis, defined two phases of volcanism in the Warburton Basin. Both are associated with rifting and are not arc-related. The first phase, represented by the early Cambrian Mooracoochie Volcanics, comprises rhyolitic–rhyodacitic lavas, ignimbrite and other volcaniclastic deposits, continental red-bed sediments and late-stage basalt. These are widespread and attributed to multiple silicic vents, including a caldera, and a cryptodome. Continental depositional environments were succeeded by marine incursion. Second phase volcanics (Jena Basalt) are middle to early Late Cambrian and comprise alkaline basaltic lava facies that have within-plate geochemical affinity. These are interbedded with deep marine carbonates and mudstone and are interpreted to reflect renewed intra-plate rifting (or plume) (Boucher, 1991; Sun, 1996).

Delamerian deformation in the Warburton Basin may be recorded by unconformities and breccias (Figure 32). Some of these are correlated with events in the Koonenberry Belt of New South Wales and termed the Mootwingee Movement (Boucher, 1991; Gravestock & Gatehouse, 1995), although the lateral extent of these events is poorly constrained and may be variable.

Despite clearly expressed uncertainty (Gatehouse, 1986), and subsequent hypotheses suggesting rifting (Boucher, 1991; Sun, 1996), the concept of a Gidgealpa Arc in the Warburton Basin continues to pervade the literature (Scheibner & Veevers, 2000; Radke, 2009). The assignment of volcanics in the Warburton Basin to either rift or arc environments is of major significance and demands a fresh look at the geochemistry of these rocks, particularly in comparison to new data and interpretations for the adjacent Mount Arrowsmith Volcanics and Mount Wright Volcanics in New South Wales (Greenfield & others, 2011). Additionally, the distribution of rift or arc sequences in Queensland and the potential offset of such rocks between the Warburton Basin or Koonenberry Belt and the Anakie Inlier require explanation. Consideration should also be given to the effects of the Kalkarindji large igneous province (LIP) which was active druing the 505–510Ma period (see Evins & others, 2009). Known occurences of volcanics associated with the Kalkarindji LIP are very widespread, but the eastern distribution is poorly defined and largely unknown (Figure 87c).

POST-DELAMERIAN EXTENSION

A long period of significant extension was widespread along the eastern Gondwana margin following the Ross–Tyennan–Delamerian Orogeny (Figure 84c,d). In the outcropping Thomson Orogen, the Seventy Mile Range Group and northern equivalents (e.g. Balcooma Metavolcanic Group) were deposited during this phase in the late Cambrian to Early Ordovician. These are inferred to overlie the deformed Neoproterozoic to Cambrian passive margin sediments and represent a period of dominantly silicic, calc-alkaline volcanism. At mid-crustal levels, the passive margin deposits (Argentine, Cape River and Charters Towers Metamorphics) were deformed (D2), resulting in development of a prominent sub-horizontal foliation (Fergusson & others, 2005; 2007c), and metamorphosed, locally to high grade, with migmatite development and associated granitoid emplacement (e.g. Fat Hen Creek Complex — Hutton, 2004). In contrast, similar sub-horizontal foliation associated with D2 in the Anakie Metamorphic Group has been associated with contraction during the Delamerian Orogeny rather than later extension (Offler & others, 2011). Older components of the Ravenswood and Lolworth Batholiths (e.g. Sunburst Granodiorite, Schreibers Granodiorite) were also emplaced during this time. These typically comprise I-type, calc-alkaline granite, granodiorite and quartz monzonite (Hutton & others, 1994). The majority of the Ravenswood Batholith was emplaced slightly later during the Middle Ordovician.

The post-Delamerian assemblage in the outcropping Thomson Orogen area, including silicic volcanism (Seventy Mile Range Group), deformation, metamorphism and granitoid emplacement has typically been attributed to a continental back-arc setting associated with a magmatic arc to the east (Henderson, 1986; Stolz, 1995; Fergusson & others, 2007a,b). In contrast, Hutton (2004) suggested a continental extensional setting, but contested the presence of a subduction zone, citing: 1) the lack of a late Cambrian – Early Ordovician volcanic arc or subduction complex; 2) the widespread distribution of metamorphic/migmatite complexes; 3) the lack of any linear distribution of I-type intrusions; and 4) the presence of similar rocks in cratonic regions (Arunta Inlier) suggesting a continental-scale extensional event. This final point may be supported by limited age data from the undercover Thomson Orogen, which suggest that Early Ordovician silicic magmatism (associated with extension) was widespread (Draper, 2006).

In central Australia, Early Ordovician extension is known as the Larapinta Event. This event is recorded in the Harts Range Group (or Irindina Supracrustal Assemblage), and produced a regional, sub-horizontal foliation and metamorphism up to granulite facies with peak conditions (800°C and 10.5kbar) developed at ~470Ma (Mawby & others, 1999; Buick & others, 2001). Protoliths of these high-grade metamorphics were deposited in the Cambrian at ~520–500Ma and form part of the Centralian Superbasin (Irindina Province — Figure 87) (Buick & others, 2001; 2005; Maidment, 2007). Deposition within this basin continued at least until the Devonian and the locus of Early Ordovician metamorphism appears to correlate with a significant depocentre (Mawby & others, 1999; Maidment, 2007).

Contemporaneous with extension, and paralleling events to the south (Macquarie Arc — see below), Fergusson & others (2007b) and Henderson & others (2011) invoked oceanic island arc development to the east, proximal to the continental margin as a result of slab rollback (Figure 84d). According to this model, subduction was west-dipping. Early Ordovician deep marine sediments and incipient arc volcanics (Judea Formation) were deposited on oceanic crust (Gray Creek Complex), which was also intruded by plutonic equivalents of the incipient arc (Saddington and Netherwood Tonalites). More mature oceanic island arc assemblages are apparently represented by the Late Ordovician Carriers Well Formation, Everett Creek Volcanics and Wairuna Formation volcanics. Henderson & others (2011) also suggested that the Late Ordovician active margin was more broadly developed, citing the Fork Lagoons beds to the south (faulted against the Anakie Metamorphic Group) and thin, fault bounded units on the western margin of the Hodgkinson Province to the north (Van Dyke Litharenite, Mulgrave Formation and Mountain Creek Conglomerate).

Termination of Delamerian deformation, and associated uplift, erosion and onset of extension, began elsewhere along the eastern Gondwana margin abruptly at the end of the Cambrian. Termination of deformation was diachronous and bracketing of deformed and non-deformed plutonic rocks indicates final deformation at ~503–490Ma (Foden & others, 2006). In contrast to synkinematic I- and S-type intrusions, postkinematic magmatism was bimodal, and comprised high-level, mantle derived suites including layered gabbro and A-type volcanics and granites (Turner & others, 1996; Foden & others, 2002; 2006).

Buoyancy-driven exhumation of the thickened Delamerian crust is dated by Ar–Ar (biotite, muscovite and hornblende) cooling ages of 490–485Ma (Turner & others, 1996). Similar Ar–Ar ages from detrital muscovite in lower Lachlan Orogen turbidites indicates that 1) the turbidites were derived from the uplifted Delamerian Orogen, and

2) uplift, erosion and redeposition were rapid (Turner & others, 1996, Foden & others, 2006).

Most workers suggest that the termination of deformation and onset of extension is a result of slab rollback, although causes are rarely given. Foden & others (2006) suggested that rollback resulted from a loss of negative buoyancy in the subducting slab as it reached the middle mantle transition zone at ~650km. Turner & others (1996) suggested that termination of convergent deformation, exhumation and erosion resulted from convective removal of lithospheric mantle following lithospheric thickening during orogenesis. Alternatively, Delamerian orogenesis may have been terminated by accretion of an exotic microcontinent (VanDieland — including the Selwyn Block and Tasmania) to the Delamerian continental margin (Cayley, 2011). Rollback and associated trenchward migration of the magmatic axis in the Antarctic part of the margin is revealed by progressive younging of intrusions toward the (present) east (see Goodge & others, 2004 — figure 13d).

Marine incursion during this time is suggested by many workers (Webby, 1978; Maidment & others, 2007) to have culminated in linking of central Australian basins (Amadeus, Canning, Warburton) and possible expansion into eastern Gondwana to form an extensive epicratonic sea (Larapinta Seaway — Figure 87). This is recorded by major changes in sedimentation of the central Australian basins, and reflected by a dominance of detrital zircon spectra with a ‘Pacific Gondwana margin’ signature defined by major peaks at ~500–600Ma and 1000–1200Ma (e.g. Maidment & others, 2007, figure 11). This signature is also recorded in the outcropping Thomson Orogen (Fergusson & others, 2001) and Koonenberry Belt (Greenfield & others, 2010a) and has led to the suggestion that sediment was transported several thousand kilometres along the margin from east Antarctica or the Mozambique Belt of the East African Orogen (Figure 87) (Maidment & others, 2007). In central Australia, the peak of marine incursion and a major depocentre correlate with the locus of high-grade extensional metamorphism (Larapinta Event — above) (Mawby & others, 1999; Maidment & others, 2007).

In the Koonenberry belt of northern New South Wales, incursion of the Larapinta Seaway resulted in a widespread unconformity followed by deposition of the Kayrunnera (shallow marine), Mutawintji (fluvial to deltaic) and Warratta (shallow to deep marine) groups (Mills, 2010b). Termination of deformation in the Koonenberry belt is dated by trilobites in the Kayrunnera Group (Mindyallan Stage ~502–499Ma), by an intrusion that cuts the Delamerian fabric (496.3 ± 3.1Ma), and by deposits above the unconformity, including a felsic tuff in the Waratta Group (497 ± 2.6Ma) (see Greenfield & others, 2011). Rocks of the Waratta Group (Easter Monday, Jeffreys Flat and Yancannia Formations) crop out north-east of the Olepoloko Fault. They are considered part of the Thomson Orogen in northern New South Wales and correlate in age and partly lithologically with the Dullingari Group of the Warburton Basin (Greenfield, 2010a).

In the Warburton Basin during the middle to late Cambrian, shallow marine shelf to basin carbonates of the Kalladeina Formation were deposited unconformably on the Mooracoochie Volcanics, and turbidite units of the Dullingari Group were deposited as lateral equivalents in a deeper water environment (Sun, 1996; Meixner & others, 1999). This was followed by deposition of glauconitic sandstone and siltstone of the marginal to shallow marine Pando Formation and red sandstone/siltstone of the Innamincka Formation (‘Innamincka Red Beds’) in a prograding delta system (Sun, 1996; Meixner & others, 1999).

As noted above, sediment eroded from the uplifted Delamerian region was deposited eastward in turbidite successions of the Lachlan Orogen. The quartz-rich turbidites were deposited in a deep marine setting on oceanic crust basement. They are extremely extensive, often being described as turbidite (mega) fan(s), comparable to the Bengal Fan (e.g. Fergusson & Coney, 1992). Although widespread, variations in the sediments are noted (e.g. VandenBerg & others, 2000), including chert and black shale that indicate areas or times of sediment starvation and deposition of condensed sequences, and shallow marine sequences above a submarine continental plateau (Selwyn Block). Black shales are abundant in the Late Ordovician part of the marine sedimentary succession. Similar thick turbidite successions were deposited outboard of the Antarctic Ross Orogen margin (see Boger, 2011).

Marine sedimentation and the turbidite mega fan represent one of two defining features of the Lachlan Orogen. The other comprises several structural belts of calc-alkaline volcanic, intrusive, volcaniclastic, and carbonate rocks interpreted as an oceanic island arc (the Macquarie Arc). This developed 100s or possibly >1000km outboard of the former eastern Gondwana margin in the palaeo-Pacific Ocean during the earliest Ordovician and accreted to the eastern Gondwana margin in the early Silurian (Glen & others, 1998; Glen, 2005; Glen & others, 2007).

The Macquarie Arc has been the focus of detailed studies (Crawford & others, 2007 and references in Australian Journal of Earth Sciences Special Issue — volume 54, issue 2,3, 2007), because it hosts numerous alkalic porphyry gold–copper deposits (e.g. Northparkes, Cadia) (Cooke & others, 2007). Division of the Macquarie Arc into four structural belts (Glen & others, 1998) and development of the Macquarie Arc through four phases (Crawford & others, 2007; Percival & Glen, 2007) is reasonably well accepted. However, other factors such as the original configuration of the structural belts, the relationship between the turbidite succession and the arc, the polarity of any oceanic subduction zone(s), and processes involved in the incorporation of the arc to the eastern Gondwana margin are debated, leading to a variety of sometimes complex models (e.g. Gray & Foster, 2004; Fergusson & others, 2009; Meffre & others, 2007; Glen, 2005; Glen & others, 2007). It should also be noted here, that in something of a paradigm shift, the most recent work (Quinn & others, 2012) suggests that these rocks are related to localised rifting within an established marginal or back-arc basin rather than accretion. Details of this new interpretation are yet to be fully published.

BENAMBRAN OROGENY

A second major compressional deformation event known as the Benambran Orogeny affected the eastern Gondwana margin in the Late Ordovician to early Silurian. In the outcropping Thomson Orogen this has been related to accretion of the Ordovician island arc to the continental margin (Fergusson & others, 2007c; Henderson & others, 2011), again paralleling events interpreted to the south (Figure 84e). Docking is recorded by submarine mass flow deposits dated at ~435Ma (Crooked Creek Conglomerate in the Broken River Province) indicating tectonic relief (Henderson & others, 2011). The model is complicated however, by a need for either a jump in the plate boundary (to the western side of the island arc) or a reversal (flipping) of subduction direction before collision. It is suggested that the thinned backarc crust facilitated a jump in subduction location and that most of the back-arc basin was subducted (Henderson & others, 2011).

Following accretion, an accretionary wedge and fore-arc basin developed in the late Silurian, and arc magmatism (presumably now continental) occurred to the west in the Georgetown Inlier (White Springs and Dido supersuites) (Henderson & others, 2011). An alternative hypothesis (Vos & others, 2007) suggests that deformation at this time was caused by lock-up of subduction as a continental fragment (the Barnard Terrane/ Province, represented by the Barnard Metamorphics) was accreted to the continental margin.

The early Silurian contractional deformation caused uplift and erosion of the Greenvale Province, and resulted in steepening of foliations in former back-arc basin deposits of the Balcooma Metavolcanic Group and Lucky Creek Metamorphic Group (Fergusson & others, 2007c). The main age constraint is from the syn-deformation Dido Tonalite (~431 ± 7Ma) which exhibits locally strong, steeply dipping foliation with a north-east trend (Bain & others, 1997). Further south in the Charters Towers Province, contractional deformation is north–south and constrained to the early Silurian by deformed Middle Ordovician and undeformed middle Silurian to Early Devonian granites of the Ravenswood Batholith (Berry & others, 1992; Hutton & others, 1997a; Fergusson & others, 2005). Deformation is locally strong in the Seventy Mile Range Group and reflected by east–west trending upright cleavage and folding (Berry & others, 1992; Fergusson & others, 2005). Older metasedimentary units were also deformed during this event generating D_3 in the Cape River Metamorphics and further foliations in the Argentine and Charters Towers Metamorphics (Fergusson & others, 2005).

Deformation during the early Silurian may also be responsible for the strong, broadly north-trending cleavage in the Les Jumelles beds (Figure 10) and foliation of the Early Ordovician Coquelicot Tonalite (Purdy & Withnall, in preparation). It is also attributed to strong deformation of the Fork Lagoons beds and upright folds (F_3) and associated cleavage in the Anakie Metamorphic Group (Fergusson & others, 2005; Green & others, 1998).

In the south-west Thomson Orogen, low-grade metamorphism, deformation and uplift of the Warburton Basin succession may be broadly co-incident with Benambran orogenesis. The timing of deformation is poorly constrained, but must have occurred after deposition of the Innamincka Formation (poorly constrained to Middle – Late Ordovician — Sun, 1996), and possibly prior to middle Silurian intrusion of granite intersected in DIO Ella 1 at 428 ± 5Ma (Draper, 2006).

In the far southern Thomson Orogen in northern New South Wales, strong north-west-trending penetrative cleavage, concertina-style folds and steep reverse faults with easterly vergence were developed in the Waratta Group (Greenfield, 2010b). Age constraints include pre-orogenic fossils (Darriwillian Stage, ~468–461Ma), K–Ar and Ar–Ar dates (~460–420Ma) of syn-orogenic foliation phases, and a 427.7 ± 2.3Ma post-orogenic granodiorite (Tibooburra Suite) (see Greenfield, 2010b, page 355). More broadly within the Koonenberry Belt, deformation during this time (D_2) is described (Greenfield, 2010b) as north-east – south-west shortening and broadly coeval with the Benambran Orogeny. It is suggested that deformation is more closely related to closure of the Larapintine Seaway and deformation in the Thomson Orogen (Greenfield, 2010b), or collision of the Thomson Orogen with the Delamerian highlands (Greenfield & Reid, 2006), than accretion of the Macquarie Arc in the Lachlan Orogen.

Elsewhere along the eastern Gondwana margin, the Benambran Orogeny is generally attributed to accretion of the Macquarie Arc to the continental margin and is considered a major cratonisation event. Complex factors such as the number and location of subduction zones, and the possible presence of Precambrian continental blocks involved with this event, are subject to debate and a detailed discussion of these is beyond the scope of our document. The reader is instead referred to review papers (e.g. VandenBerg & others, 2000; Fergusson, 2003; Gray & Foster, 2004; Glen, 2005; Glen & others, 2007). Some key points however are:

- accretion may have been associated with lock-up of subduction
- compression was generally east–west and caused locally intense deformation, metamorphism and thrusting onto the adjacent Delamerian Orogen
- deformation appears partitioned into the extensive quartz-rich turbidite pile
- several phases of deformation are recognised beginning as early as ~455Ma and terminating as late as ~425Ma
- sediments above the Melbourne Zone (Selwyn Block) were undeformed and sedimentation continued in this area.

In central Australia, this period broadly corresponds to the start of episodic north–south to north-east – south-west shortening known as the Alice Springs Orogeny. Initial phases of this event at ~450Ma caused exhumation of the Harts Range Group and sedimentation changes in the Amadeus and Georgina basins (Mawby & others, 1999).

POST-BENAMBRAN EXTENSION AND COMPRESSION

Following the Benambran Orogeny most workers consider the Thomson Orogen, and more broadly the Tasmanides, to have developed through extensional and compressional phases in a ‘back-arc’ environment (e.g. Glen, 2005). However, the setting of sedimentation in areas adjacent to the outcropping Thomson Orogen (e.g. Hodgkinson Province and Broken River Province of the Mossman Orogen) and the setting of Pama Province (i.e. Silurian–Devonian) intrusions remains unclear with fore-arc, back-arc and continental rift settings suggested and debated (see Kositcin

& others, 2009; Henderson, 1987; Bultitude & others, 1990; Withnall & Lang, 1993; Vos & others, 2007). An important point for consideration here is the presence of older metasediments and intrusions to the east in the Barnard Province, which may be considered part of the Thomson Orogen (Korsch & others, 2012) and may underlie the Mossman Orogen (Korsch & others, 2012).

In contrast to south-eastern Australia, deformation events after the Benambran Orogeny were mild and/or of limited extent in the Thomson Orogen. Major events such as the late Silurian to Early Devonian Bindian/Bowning Orogeny are not clearly identified, and in the undercover area volcanics as old as ~480Ma are apparently undeformed (Draper, 2006).

Sedimentation appears to have been absent in the Thomson Orogen from the Benambran Orogeny until the Early Devonian (below). The only rocks emplaced during this time were intrusive suites. These are voluminous in the outcropping Thomson Orogen and form parts of the Ravenswood, Lolworth and Reedy Springs Batholiths (Figure 12). Emplacement occurred during an extensional period, with the earliest 'post tectonic' granites dated at ~426Ma (Hutton, 2004). The batholiths exhibit different geochemical, isotopic, and inherited zircon signatures and different depths of emplacement indicating variation in the crustal architecture across this region (Hutton & others, 1997a). An intriguing aspect is the east–west trend formed by these extensive batholiths (Figure 12), contrasting strongly with the dominantly north-north-east trends in eastern Queensland. The Reedy Springs Batholith in the west exhibits a transition to a northerly trend concordant with enclosing metasedimentary units.

Granites were also emplaced in the undercover Thomson Orogen region during this period, although few are dated. DIO Ella 1 in the far south-west of Queensland intersected a medium-grained, biotite–muscovite granite dated at 428.3 ± 5.2Ma (SHRIMP, U–Pb zircon — Draper, 2006). Granitoids are intersected in several adjacent drill holes and it is likely that this area forms an extensive batholith (Brown & others, 2012). However, the origin of magmatism so far away from any plate boundary during this time is enigmatic (Murray, 1994).

The Silurian date from Ella 1 broadly corresponds to emplacement of the Tibooburra Suite intrusions in the far southern Thomson Orogen in northern New South Wales. This comprises three named plutons (Tibooburra Granodiorite, Dynamite Tank Granodiorite, Creswells Tank Granodiorite) interpreted to be part of a larger body at depth, and unnamed gabbroic to aplitic (and pegmatite) dykes. The suite was emplaced from 427.7 ± 2.3Ma to 420.2 ± 3.3Ma (Black, 2006; 2007) into late Cambrian metasediments. On tectonic discrimination diagrams, the intrusions plot in within-plate or volcanic arc granite fields and are interpreted as metaluminous I-types, with some similarities to contemporaneous Lachlan Orogen granitoids (Vickery, 2010).

Brittle deformation features in the Tibooburra Suite are assigned to D_3 (Greenfield, 2010b), which elsewhere may correspond to the Bindian Orogeny. In the southern

Thomson Orogen, this deformation is interpreted to occur following, or as a late 'lock-up' stage of, the Benambran Orogeny and is more clearly expressed in metasediments of the Tibooburra Inlier and Waratta Inlier to the south. Deformation is related to stress directed from the north-north-east against the craton margin and is characterised by reactivation of major faults and refolding and penetrative deformation of Benambran fabrics (Greenfield, 2010b).

Elsewhere in the Koonenberry Belt during this time, the subsurface Allambie Woolshed Granite was emplaced (423.1 ± 2.4Ma — SHRIMP U–Pb zircon, Black, 2006), and the Mount Daubeny Basin developed as a pull-apart basin associated with dextral transpression on the Koonenberry Fault with deposition between ~425 and 414Ma (Mills, 2010b). The timing of D_3 is constrained by the emplacement of the pre- or syn-deformation Tibooburra Suite (maximum age of 420–427Ma), mica Ar–Ar ages (417.3 ± 3.3Ma) associated with fluid infiltration and brittle joints and faults, andesitic volcanics (Wertago Volcanics, 425.0 ± 7Ma) at the base of the Mount Daubeny Basin, and late Silurian to Early Devonian plant and trace fossils throughout the basin (see Greenfield, 2010b).

In the Thomson Orogen, renewed extension during the Early Devonian produced the terrestrial to shallow marine Devonian basin array (Barrolka Tough, Warrabin Trough, Adavale Basin, and possibly Belyando Basin). These are the first of an extensive series of basins that overlie the Thomson Orogen (Figures 2 and 3) and are considered cover. Initiation of extension is recorded by felsic volcanics in the basal Gumbardo Formation of the Adavale Basin dated at 401.8 ± 2.1Ma and 408.3 ± 2.4Ma (Draper, 2006).

Areas to the south in the Lachlan Orogen similarly record widespread extension and magmatism interspersed with deformation periods with many tectonic scenarios suggested including multiple subduction zones, delamination, mantle plumes and back-arc extension (see Glen, 2005; Champion & others, 2009; VandenBerg & others, 2000; Foster & Gray, 2000; Gray & Foster, 2004). Extension and deep to shallow marine sedimentation occurred above the Ordovician turbidite pile and remnants of the Macquarie Arc, and was accompanied by S- and I-type, often bimodal magmatism. This is commonly related to subduction roll back following the Benambran Orogeny. Extension was terminated and basins were inverted during the poorly understood 420 to 410Ma Bindian Orogeny. The effects of this event appear to differ across the Lachlan Orogen and may have involved transpression and substantial strike-slip movement (see VandenBerg & others, 2000). Extension recommenced, again accompanied by widespread magmatism, in the Early Devonian, particularly in the central and eastern Lachlan Orogen.

The next major compressional event, known as the Tabberabberan Orogeny, is interpreted to have affected the entire Lachlan orogen, including sediments deposited above the Selwyn Block (Melbourne Zone), and eastern Tasmania (Glen, 2005, Champion & others, 2009; VandenBerg & others, 2000). The effects of this event are spatially variable, but range up to isoclinal folding, development of slaty cleavage and low grade metamorphism (VandenBerg & others, 2000). Compression was dominantly east–west but also included a minor north–south component, and although short-lived (e.g. 395–385Ma in Victoria, VandenBerg & others, 2000), it is interpreted to have cratonised the Lachlan Orogen.

Effects of the Tabberabberan Orogeny are different in the Kooneberry Region, which is interpreted to have already been cratonised by this time. The Tabberabberan Orogeny here is associated with open folding, brittle faulting and reactivation of major faults (Greenfield, 2010b) resulting from east-north-east – west-south-west compression. Sets of shears interpreted from deep seismic and associated with this event are suggested to continue through the thickness of the crust with one (Koonenberry Shear Zone) appearing to correlate with a displacement in the Moho (Mills, 2010b).

In the Thomson Orogen area, Tabberabberan deformation, if present, is difficult to distinguish from other events, and division of eastern Australia versus central Australia (e.g. Alice Springs Orogeny) deformation events becomes unclear. Deformation of this age may be recorded by a Middle Devonian unconformity within the Adavale Basin sequence (McKillop & others, 2005) and as angular unconformities in areas adjacent to the Thomson Orogen (Broken River Province — Withnall & Lang, 1993).

Other Devonian sediments and volcanics are observed in outcropping regions overlying the Anakie Metamorphic Group, and overlain by the Late Devonian to Carboniferous Drummond Basin (e.g. Ukalunda beds, Douglas Creek Limestone, Theresa Creek Volcanics). Felsic volcanics intersected in drill core in the eastern part of the undercover Thomson Orogen (adjacent to the Drummond Basin) may occupy a similar stratigraphic position and are dated at 385.0 ± 4.6Ma (AAE Towerhill 1, Draper, 2006). Similar or slightly younger ages are recorded in inherited zircons from the Drummond Basin (Henderson & others, 1998) and Campwyn Volcanics (Bryan & others, 2004) suggesting widespread magmatism. The Retreat Batholith which is dominated by I-type intrusions ranging from diorite to granite was also emplaced during this time, although dates differ considerably (~366–385Ma, see Crouch & others, 1995a). The only U–Pb (SHRIMP) age from the batholith (392.4 ± 10.2Ma) is from the foliated Mount Newsome Granodiorite (Wood & Lister, 2013). Analyses of the Retreat Batholith generally plot in ‘volcanic arc granites’ fields (Crouch & others, 1995b) but the setting of this magmatism is ultimately unknown. Withnall & others (1995) suggest that a direct subduction-related origin is unlikely and instead propose an origin more akin to the Basin and Range Province of south-west USA.

During this time, the New England Orogen was developing to the east, and (regardless of interpretations for the early development of the New England Orogen) this probably had some influence over the Thomson and Lachlan Orogens.

RELATIONSHIP BETWEEN THE THOMSON, LACHLAN AND DELAMERIAN OROGENS

One of the great unknowns in eastern Australia’s tectonic development is the relationship between the Thomson Orogen and the Delamerian and Lachlan Orogens

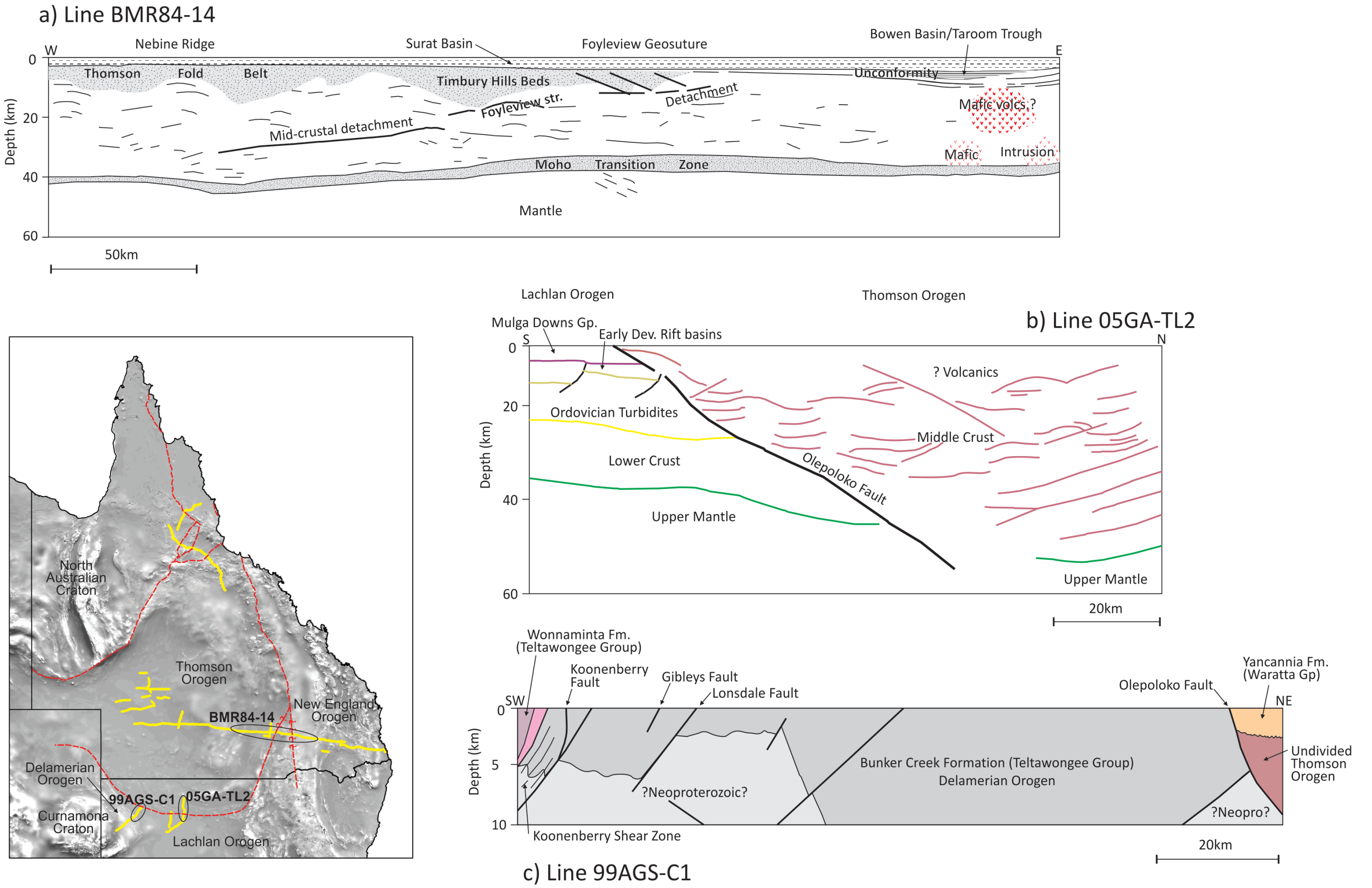


Figure 89. Location and interpretation of deep crustal seismic lines that cross the boundary between the Thomson Orogen and adjacent basement tectonic elements: a) Interpretation of part of the Brisbane–Eromanga Geoscience Transect (from Finlayson & others, 1990) showing location of the Foyleview Geosuture and a vague transition from the Thomson Orogen to eastern tectonic elements; b) preliminary Thomson–Lachlan interpretation (Glen & others, 2007) showing the Olepoloko Fault as a north-dipping structure that offsets the Moho; c) interpretation of the Koonenberry line from Greenfield & others (2011) showing the north-east dipping Olepoloko Fault and Thomson Orogen rocks in the north-east. An alternative hypothesis (Mills & David, 2004) has the Olepoloko Fault dipping to the south-west and not extending to the surface along the section.

to the south. The interface between these elements exceeds 1000km in length and is crossed (potentially at multiple locations) by deep crustal seismic lines (Figure 89). Despite this, models for the relationships between these tectonic elements differ widely, and this highlights our lack of understanding of the undercover Thomson Orogen in particular. In general terms, models can be divided into: 1) those that suggest or imply a shared history whereby the Thomson Orogen was continuous with, and has elements of, both the Delamerian Orogen and Lachlan Orogen (e.g. Henderson, 1986; Fergusson & others, 2007a,b; Burton, 2010); and 2) those that suggest a partially separate history and development (e.g. Murray & Kirkegaard, 1978; Gray & Foster, 2004; Glen, 2005; Draper, 2006; Glen & others, 2010). Both models have positive and negative aspects.

A major problem with the 'shared history' model lies in the geochronology reported by Draper (2006) which shows that metasediments in one Thomson Orogen drill hole are overlain by (and must be considerably older than) essentially undeformed Early Ordovician (~473Ma) volcanics. Additionally, we see the connection made by some authors (and required by this model) between the Delamerian Orogen of northern New South Wales, the Gidgealpa Arc of the Warburton Basin in South Australia and the Anakie Inlier of central Queensland (or the Nebine Ridge if a southern extension is accepted) as a major unresolved issue with this model. Many reconstructions (e.g. Fergusson & others, 2007a, figure 8; Foden & others, 2006, figure 1a) portray this connection as a broadly curved line/belt or equate the late Neoproterozoic to Cambrian margin to the Tasman Line (see Direen & Crawford, 2003a), ignoring the Anakie Inlier and Nebine Ridge. In reality, such a connection would need to be far more convoluted and would describe an unusual morphology for the late Neoproterozoic to Ordovician continental margin. Large-scale geophysical images (Figure 1) show no evidence for this connection, implying a far more complex scenario.

The 'shared history' model must also explain the origin of prominent 'east–west' gravity and magnetic features commonly used to define the Thomson/Lachlan boundary. Burton (2010) is the only worker to investigate this issue and uses rudimentary analogue modelling to suggest that these features represent a zone of crustal thickening associated with the effects of a continental promontory (i.e. the Curnamona Craton) during east-north-east – west-south-west Benambran contraction, and further suggests that some magnetic highs may be slivers of oceanic crust. Other workers have investigated the effects of continental promontories and embayments (e.g. Curnamona Province — Williams & others, 2009; Greenfield & others, 2011), and the effects of indenters such as rigid crustal blocks as they separate from and/or collide with the continental margin (e.g. Selwyn Block and Hay–Booligal Zone — Greenfield & others, 2011; Musgrave & Rawlinson, 2010; Cayley & others, 2002; Cayley, 2011). These are important factors interpreted for the Delamerian and Lachlan Orogens in south-east Australia that may need to be considered in interpretations of the Thomson Orogen.

An important aspect of the alternative 'separate history' model is that it requires the Thomson/Lachlan Orogen boundary to be a major crustal suture, commonly recognised as the Olepoloko Fault (Figure 1) (Stevens, 1991; Glen, 2005; Glen &

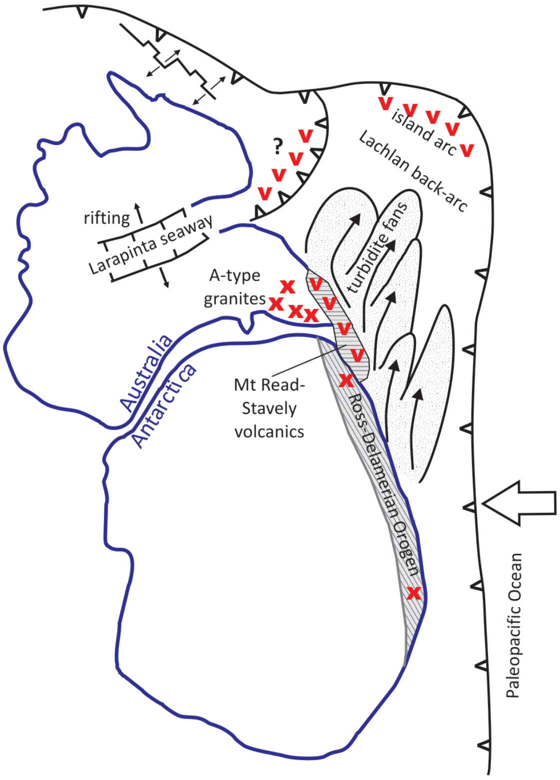


Figure 90. Tectonic model for eastern Australia during the Early Ordovician (modified from Gray & Foster, 2004). This model shows the Thomson–Lachlan Orogen interface as a north-dipping subduction zone implying a different origin and history for the Thomson and Lachlan Orogens.

others, 2007). Based on deep crustal seismic, the Olepoloko Fault is interpreted to be a planar fault dipping at ~45° to the north offsetting the Moho and separating thinner (32km) but more reflective lower crust of the Lachlan Orogen from thicker crust of the Thomson Orogen (~48km) (Figure 89) (Glen & others, 2007). It should be noted however, that alternative views question both the location and significance of this feature (Adams, 2011; Burton, 2010).

Many workers interpret the Thomson/Lachlan contact to be an east–west subduction zone during the Cambrian and Ordovician (Figure 90) (e.g. Gray & Foster, 2004; Glen, 2005; Glen & others, 2007) thus invoking a complex tectonic arrangement in eastern Australia. Eventual thrusting of the Thomson Orogen over the Lachlan Orogen along the Olepoloko Fault is interpreted to have occurred prior to the Devonian (VandenBerg & others, 2000; Glen & others 2007). Gray & Foster (2004) further linked the east–west subduction interface between the Thomson and Lachlan Orogens with an interconnected shear zone array to the west in the Arunta Complex.

Despite these different models, most workers suggest that the Thomson Orogen is underlain by extended Proterozoic continental crust (see references in Finlayson, 1990), whereas the Lachlan Orogen is developed on oceanic crust (as outlined in Glen, 2005). However, the extent of thinned continental crust below the Thomson Orogen is unclear and may not extend to its eastern boundary (see Fergusson & others, 2007a; Kennett & others, 2004).

In Queensland, an approximately east–west deep crustal seismic line crosses the boundary between the Thomson Orogen and possible Lachlan Orogen where it is orientated north–south (Figure 89). Here, a crustal domain referred to as the 'crust below the Taroom Trough' separates the Thomson and New England Orogens (Finlayson & others, 1990) and may represent a northern extension of the Lachlan Orogen (e.g. Glen 2005, figure 2). This interface is named the Foyleview Geosuture, and is described as a shallow-dipping structure characterised by progressively deepening, prominent, upwardly convex reflectors that separate major crustal provinces (Finlayson & others, 1990). The structure corresponds to a gravity boundary west of Roma (Wellman, 1990), and is speculated to have formed during the early–middle Carboniferous (Finlayson & others, 1990).

Interestingly, this geophysical work also shows that: 1) the Moho is deepest under the Nebine Ridge (44km); 2) upwardly convex reflectors over the Nebine Ridge coincide with increased velocity and may represent mafic melt fractions associated with Carboniferous plutonism; 3) the Nebine Ridge probably represents a zone of reworking on the margin of a major crustal block; 4) despite probable age differences, no boundary is identified between the Timbury Hills Formation (Roma Shelf) and the Thomson Orogen; and 5) the Thomson Orogen can be divided near Quilpie into north-west and south-east domains of differing gravity, magnetic and seismic character and differing crustal thickness (Finlayson & others, 1990; Wellman, 1990).

FUTURE WORK

The Thomson Orogen remains the most poorly understood element of eastern Australia geology. This is despite an enormous spatial extent and important location (in time and space) between the North Australian Craton and accretionary orogens to the east. The lack of knowledge primarily relates to the concealment of vast areas by younger sedimentary basins. Learning more about the geology of the undercover area is therefore an obvious focus for future investigations, but there are also many unresolved issues in the outcropping region. Some key areas or topics for future work identified by our review are outlined below.

In terms of mineralisation, a key focus should be to assess the prospectivity of the undercover Thomson Orogen. Outcropping areas in both Queensland and New South Wales are relatively rich in mineralisation, and a wide variety of styles are represented, yet little exploration to date has extended to areas below cover. Several mineralisation styles (e.g. VHMS, lateritic nickel, podiform chromite) are clearly associated with specific stratigraphic intervals while other styles (e.g. orogenic gold) are more widely distributed. An assessment of the undercover area must involve:

1. generation of a detailed depth to basement surface for areas of relatively shallow cover such as the Eulo Ridge area and areas directly adjacent to mineralised outcrop
2. detailed knowledge of the styles/settings/ages of mineralisation in the outcropping area (including New South Wales), followed up with extra geochronology etc where data gaps exist
3. a geological interpretation (based on geophysics, drilling etc) of areas of relatively shallow cover.

Future investigations could also involve identification of potential mineralisation targets undercover and testing with a shallow drilling program.

The potential geothermal energy resource co-incident with the Thomson Orogen in Queensland is clearly outlined by Geoscience Australia's OzTemp work (see Geothermal Energy Potential section). However, current research suggests that unlike the well-known Big Lake Suite at Innamincka, granitoids in the undercover Thomson Orogen are not high heat producing. Thus the question remains — what is the origin of high subsurface temperatures in south-west Queensland? More thorough and widespread thermal modelling work is needed to resolve this issue and would require major improvements to existing datasets including:

1. accurate (preferably *in situ*) thermal conductivity measurements for the Thomson Orogen (basement), and all basins that overlie the Thomson Orogen surface (data are particularly lacking for the Devonian basins)
2. heat production values for basement rocks
3. expansion of the heat flow measurement database
4. a better understanding of the basement geology
5. an understanding of the crustal structure, including depth to the MOHO and the distribution and composition of crustal domains to assess basal heat input.

The last two points above also relate more broadly to improving our knowledge of the tectonics of the Thomson Orogen and may be achieved by obtaining new geophysics data and/or re-interpreting existing data. The existing seismic database may provide valuable information in this regard. Data along the Eromanga–Brisbane Geoscience Transect, for example, intersects several important boundaries and features, but these are only vaguely defined in accompanying interpretations. A fresh look at these data may be useful, particularly in light of interpretations of recently acquired deep seismic data in New South Wales.

The undercover area of the Thomson Orogen is clearly a 'missing piece' in the Tasmanides of eastern Australia. An understanding of the geology of this area is fundamental to placing the Thomson Orogen into the context of the Tasmanides and the development of the eastern Gondwana margin following Rodinia Break-up. Some key unknowns and questions regarding the geology and tectonics of the Thomson Orogen highlighted by our review include:

1. Does the Lachlan Orogen (including the mineralised Macquarie Arc) extend into Queensland? If so, what is its distribution?
2. What is the relationship between the Thomson Orogen and Roma Shelf?
3. What age are the Roma Shelf basement rocks? What is the origin of the Roma Granites? Can multiple units/ages be defined amongst the metasediments (Timbury Hills Formation)?
4. What is the provenance of the Thomson Orogen and Timbury Hills Formation (Roma Shelf) metasediments?
5. Is the undercover Thomson Orogen comparable to the outcropping Thomson Orogen terms of ages, lithology, geochemistry, provenance etc?

6. Can metasediments of the vast covered region of the Thomson Orogen be correlated with the Warburton Basin/Centralian Superbasin?
7. What is the nature of the contact between the Thomson Orogen and North Australian Craton? Does the North Australian Craton continue below the Thomson Orogen? If so, what is its distribution?
8. What is the age and tectonic setting of intrusive and volcanic rocks in the Thomson Orogen?
9. Do hypotheses for the Thomson/Lachlan Orogen relationship stand up in Queensland?
10. Does the Thomson Orogen in Queensland include a Cambrian magmatic arc as hypothesised in New South Wales (Mount Wright Arc) and South Australia (Gidgealpa Arc)?
11. Do deformation events in the Thomson Orogen correlate with those defined to the south in the Tasmanides (e.g. Delamerian, Benambran, Tabberabberan Orogenies) or with central Australian events (e.g. Petermann and Alice Springs Orogenies)?

In the outcropping Thomson Orogen, correlation of the Sefton Metamorphics (Iron Range Province) with the Thomson Orogen needs investigation. In particular, geological mapping and geochronology is required here to determine if units of different age exist and to explore the previously reported Grenvillian maximum depositional age.

Tectonic evolution hypotheses based on the outcropping Thomson Orogen can also be tested by reviewing and/or enhancing the existing geochemistry and geochronology database. Specifically, the existence and location of magmatic arcs during the Cambrian and Ordovician should be investigated.

Many of the questions above can be investigated via basic geological work including compilation of information from existing datasets (e.g. well completion reports, GSQ publications and databases, and published sources), core logging, field mapping/sampling and petrography. It is clear that the undercover area and parts of the outcropping area also suffer from a lack of modern (e.g. U–Pb SHRIMP zircon) geochronology and other advanced geochemical work such as Nd–Sm, Lu–Hf, and O isotopic studies.

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APPENDIX 1

GLOSSARY OF TERMS ASSOCIATED WITH THE THOMSON OROGEN AND SURROUNDS

Alice Springs Orogeny — A Devonian to Carboniferous deformational event localised to central Australia in which significant north–south shortening and exhumation of the Arunta Inlier took place (Betts & others, 2002). Peak metamorphic conditions were 600°C and 500MPa.

Benambran Orogeny — Late Ordovician to early Silurian contractional deformation event affecting much of the eastern Gondwana margin and resulting in widespread backarc inversion within the Lachlan (Foster & Gray, 2000), Thomson (Withnall & others, 1995) and Mossman (Henderson & others, 2011) Orogens.

Bindian/Bowning Orogeny — An Early Devonian orogenic event recorded in western Victoria. It resulted in the development of strike-slip faults, voluminous granite intrusion and significant uplift of early Paleozoic complexes.

Centralian Superbasin — Extensive intracratonic basin developed in the Neoproterozoic with sedimentation continuing sporadically to the Devonian. Remnants of the basin are now separated by uplifted basement domains and include the Georgina, Amadeus, Ngalia and Officer Basins. Also linked to Wiso Basin, Warburton Basin and Adelaide Rift Complex at various times.

Delamerian Orogeny — Multiple, predominantly east–west contractional events occurring between 515–490Ma (Foden & others, 2006) and affecting rocks in the Adelaide Fold Belt (South Australia), the Glenelg Complex (western Victoria), and the Koonenberry Belt/Wonaminta Block (western New South Wales). Thought to have been part of a much wider subduction event known as the Terra Australis Orogen (see below and Cawood, 2005).

Devonian Basin Array — Widespread Devonian basins throughout Queensland. Comprises the Adavale Basin, Warrabin Trough, Barrolka Trough and may include the Belyando Basin. Outcropping equivalents may include the Ukalunda Formation and Theresa Creek Volcanics.

Eulo Ridge — Broad, north-east-trending basement high, extending from northern New South Wales into central southern Queensland. Includes basement outcrops at Eulo, Granite Springs, Currawinya, and on the border at Hungerford.

Foyleview Geosuture — Seismically-defined, crustal-scale, low angle (5–10°), west-dipping suture. Thought to mark the subsurface boundary between the south-eastern Thomson Orogen and the north-eastern Lachlan Orogen (Finlayson & others, 1990).

Gidgealpa Arc — Tentatively proposed as an extension of the Mount Wright Volcanic Arc where it intersects the Warburton Basin. Extent of the arc is defined by the distribution in drill holes of the ~517Ma Mooracoochie Volcanics (see Gatehouse, 1986).

Grenvillian signature — Refers to zircon populations with an age range of 1200–1000Ma, similar to the Grenvillian Orogeny in North America, which has time correlatives in several areas of Australia (see Maidment & others, 2007).

Irindina Supracrustal Assemblage/Association/Province — Neoproterozoic to Cambrian metasedimentary and igneous province which formed a deep depocentre of the Centralian Superbasin and was metamorphosed in the Ordovician Larapinta Event.

Kennedy Igneous Association — Voluminous early Carboniferous – late Permian association of intrusive and extrusive units occurring between the Torres Strait and Bowen.

Koonenberry Belt — Outcropping and subsurface belt of rocks emplaced after the late Proterozoic break-up of Rodinia that wrap around and define the eastern margin of the Curnamona Province in north-west New South Wales. The belt includes parts of the Delamerian and Thomson orogens (see Greenfield & others, 2010).

Lachlan Orogen — A late Cambrian to Ordovician tectonic element predominantly within New South Wales and dominated by thick successions of turbidites variably intruded by igneous rocks.

Larapinta Event – Major Early Ordovician extensional deformation event defined in central Australia. Produced a regional, sub-horizontal foliation and metamorphism up to granulite facies with peak conditions (800°C and 10.5kbar) developed at ~470Ma. Observed in the Harts Range Group (Mawby & others, 1999; Buick & others, 2001).

Larapinta Seaway — Also known as the Larapintine Sea or Larapinta Sea. Extensive west-north-west-trending epicratonic seaway linking the Warburton (east), Amadeus (central) and Canning (west) Basins in the Ordovician. Resulted from progressive marine incursion from the latest Cambrian to Early Ordovician and potentially allowing an influx of sediments with a ‘Pacific Gondwana signature’ to central Australia (Webby, 1978; Maidment & others, 2007).

Macrossan Igneous Association — Late Cambrian to Middle Ordovician intrusive units occurring predominantly in the Charters Towers Province, and in the Barnard and Etheridge provinces and the Anakie Inlier.

Maneroo Platform — Basement high in the northern Galilee Basin area

Mossman Orogen — A Silurian to Devonian tectonic element of northern Queensland encompassing voluminous marine sedimentary and igneous rocks (Withnall & Henderson, 2012; Henderson & others, 2013). The Orogen formed immediately following the Benambran Orogeny and was terminated by the Tabberaberan Orogeny (see below).

Mount Wright Arc — Early to middle Cambrian continental margin volcanic arc associated with west-dipping subduction in the Koonenberry Belt of north-west

New South Wales. Comprises the Gnalta Group (volcanic arc and back-arc deposits), and Ponto Group (fore-arc) (see Greenfield & others, 2011).

Nebine Ridge — Basement high comprising multiply deformed metasedimentary rocks, which extend in the subsurface south from the Anakie Inlier, curving slightly to the west (see Murray, 1994). Interpreted as a southern extension of the Anakie Inlier (Withnall & others, 1995).

New England Orogen — The youngest and easternmost element of the Tasmanides. Commonly interpreted as a collage of convergent margin tectonic elements developed in response to advancing and retreating subduction from the Devonian to the Triassic.

North Australian Craton (NAC) — Discrete crustal block amalgamated with the South Australian and West Australian Craton in the Paleoproterozoic to form the western two thirds of the Australian Continent. The eastern part of the NAC is exposed in Queensland and comprises the Mount Isa Province to the west, and the Etheridge, Croydon, and Savannah provinces in the Georgetown, Dargalong, Yambo and Coen inliers further east.

Olepoloko Fault — Crustal scale, north-dipping fault that separates the southern Thomson Orogen and northern Lachlan Orogen in northern New South Wales. The nature of the fault is contested, but the most widely supported theory suggests that the fault offsets the MOHO and represents a Cambrian–Ordovician subduction zone (e.g. Glen, 2005).

Pacific Gondwana signature — Refers to zircon populations with an age range of 500–600Ma and Grenvillean ages (see above) and has been shown to occur along the eastern margin of Gondwana (see Maidment & others, 2007).

Pama Igneous Association —Widespread association of Silurian–Devonian intrusive units between the Coen Inlier and Charters Towers in northern Queensland.

Petermann Orogeny — North–south shortening event localised to central Australia that exhumed the Musgrave Block by 30–40km at ~560–520Ma. This provided abundant 1000–1200Ma aged detritus to adjacent parts of the Centralian Superbasin (see Maidment & others, 2007).

Roma Granites — Collective term grouping all intrusive rocks in the Roma Shelf area (see Murray, 1994).

Roma Shelf — Basement platform comprising granites and metasediments. Lies immediately east of the Taroom Trough, which is a major depocentre of the Bowen Basin.

Ross Orogen — Multiple, predominantly east–west contractional events that began as early as 544Ma and continued into the Early Ordovician and affected rocks in Antarctica. Thought to have been part of a much wider subduction event known as the Terra Australis Orogen (see above, below and Cawood, 2005) and equivalent to the Delamerian Orogeny in southern Australia.

Tabberabberan Orogeny — A Middle Devonian, dominantly east–west compressional deformation event affecting the Lachlan Orogen in Victoria. Essentially represents the final cratonisation event. Overlaps in time with the Alice Springs Orogeny. In north Queensland, it has been equated with a somewhat later Late Devonian event and therefore may be diachronous (Withnall & Henderson, 2012).

Tasman Line — First suggested by Hill (1951), this line represents the boundary between Precambrian and Phanerozoic basement rocks of Australia. Essentially it marks the boundary between the Tasmanides (Phanerozoic) and the Precambrian North Australian, Central Australian and South Australian cratons.

Tasmanides — Series of late Neoproterozoic to Triassic orogenic belts developed on the eastern Gondwana margin in response to plate convergence. Sometimes referred to as the Tasman Fold Belt.

Terra Australis Orogen — Neoproterozoic to late Paleozoic orogenic belt developed along the Pacific and Iapetus margin of Gondwana from north-east Australia through Tasmania, New Zealand, the Transantarctic Mountains and Antarctic Peninsula to southern Africa and into South America, some 18 000km strike length (Cawood, 2005).

Thomson Orogen — A largely subsurface Neoproterozoic to Ordovician tectonic element occurring throughout Queensland and dominated by marine sediments with minor volcanics. Deposition is thought to have been terminated by the Benambran Orogeny (see below). Igneous rocks intruded the orogen from the Cambrian to the Permian.

Timbury Hills Formation — Broad, informal unit name applied to all metasedimentary rocks in the Roma Shelf (see Murray, 1994). Erroneously applied to metasediments west of the Roma Shelf in some well completion reports.

Tyennan Orogeny — Cambrian deformation event (equivalent to the Ross and Delamerian Orogenies) effecting Tasmania and the Selwyn Block of Victoria.

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