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Natalie Kositcin, David C. Champion and David L. Huston

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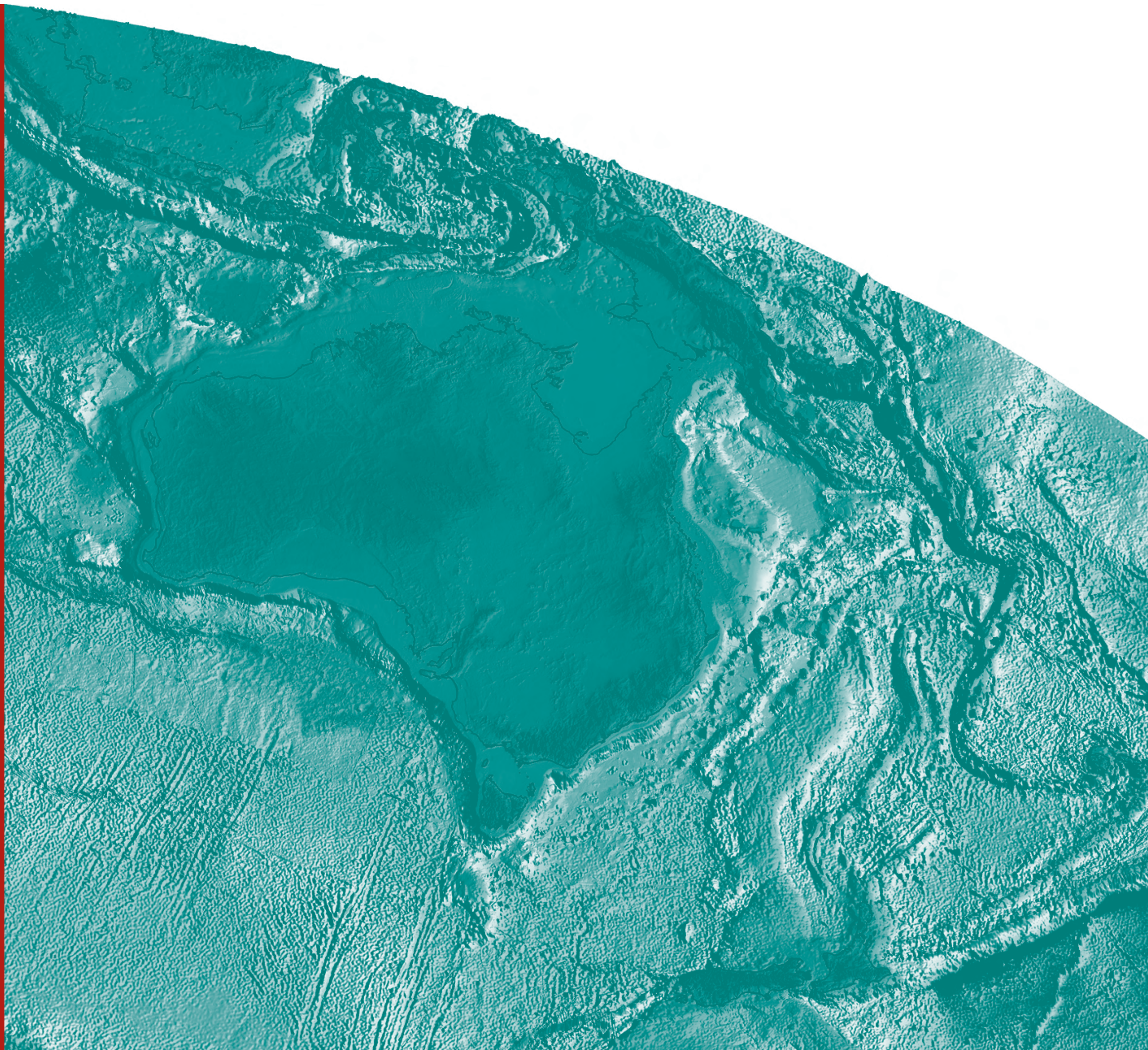

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Geodynamic Synthesis of the North Queensland Region and Implications for Metallogeny

GEOSCIENCE AUSTRALIA
RECORD 2009/30

by

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Introduction

This report presents the results of a geodynamic synthesis of North Queensland. This was undertaken with the dual aims: (1) to better understand the tectonic and geodynamic setting of existing mineral deposits within North Queensland, and (2) to provide a predictive capability, within the synthesised geodynamic framework, not just for extending potential regions of known mineralisation but also for possible new styles and commodities.

The report combines the Mineral Systems approach of Wyborn (1997) with the 'Five Questions' methodology adopted by the Predictive Mineral Discovery CRC (pmd*CRC; http://www.pmdcrc.com.au/RESprograms.html; Barnicoat, 2007, 2008). It is clearly targeted at the first of the 'Five Questions', namely, constraining and understanding the regional and local geodynamic environment as the first step in delineating mineral systems. To achieve this we have synthesised geological data on a regional, largely orogenic, basis. This was undertaken to identify geological events and geodynamic cycles, and to produce regional geological syntheses and accompanying time-space-event plots. These regional syntheses were used to produce an interpreted geological and geodynamic synthesis of North Queensland. This new synthesis provided the geodynamic framework to both constrain known mineralisation and allow a predictive capability for potential new mineralisation. Outputs are delivered in 3 sections. Geological summaries and time-space-event plots are presented in Section 1. Our interpreted geological and geodynamic synthesis is presented in Section 2. Section 3 places metallogenic events into the framework established in Section 2 and uses the relationships between metallogeny and geodynamics to predict mineral potential for the North Queensland region.

This report uses, to some extent, information synthesised as part of Geoscience Australia's Phanerozoic Synthesis Project (Champion et al., 2009), which provided a synthesis and geodynamic framework of the Tasman Orogen of Eastern Australia, including North Queensland, for the Late Neoproterozoic-Early Cambrian to the end of the Hunter-Bowen Orogeny (Triassic). For the current report we are focussing on the one region, and including all geological events, that is, encompassing the geological and geodynamic history of the North Queensland region from the Paleoproterozoic to Recent. The report also differs from the previous project in that less emphasis is placed on orogenic cycles, particularly for the Proterozoic and Mesozoic and younger rocks, where orogenic cycles are less well defined.

The synthesis of North Queensland's provinces and basins is presented as a series of time-space plots, based on information captured within GA's PROVINCES and EVENTS databases. Although largely Province-based, the synthesis, and related figures, discuss the area in terms of geographic regions, e.g., Greenvale region. These regions are for the most part synonymous with the provinces, e.g., Charters Towers region mostly equates with the Charters Towers Province (Figures 2b, 3, 4), though because younger rocks and events (not strictly part of the Province) are also discussed the term 'region' is preferred. Also the large Etheridge Province (Figure 3) has here been subdivided into the Coen and Georgetown regions (Figure 4).

Acknowledgements

The report was greatly assisted by detailed discussions on Queensland geology, geodynamic environments and metallogeny, with I. Withnall, C. Murray, L. Hutton, J. Draper (Geological Survey of Queensland), C. Fergusson (University of Wollongong), R. Henderson, W. Collins, R. Wormald (James Cook University of North Queensland), and R. Blewett, P. Henson, R. Korsch, G. Gibson, L. Wyborn, A. Lambeck, N. Neumann (Geoscience Australia). We thank Terry Mernagh and Anthony Schofield for their contributions. We also thank Russell Korsch and Alan Whitaker who provided detailed internal reviews at Geoscience Australia, and Ian Withnall, Laurie Hutton, Margie Scott and Terry Denaro (Geological Survey of Queensland) are thanked for their reviews of the manuscript.

SECTION 1. GEOLOGICAL SUMMARIES AND TIME-SPACE PLOTS FOR THE NORTH QUEENSLAND REGION

Introduction

The North Queensland region (Figures 1, 2b) consists of Paleoproterozoic to Mesoproterozoic continental basement bounded by the accretionary North Queensland Orogen to the east, and enigmatic Thomson Orogen to the south. The Georgetown and Coen Regions (Figures 3, 4), the main exposed areas of Paleoproterozoic to Mesoproterozoic in eastern North Queensland, represent the remnant eastern margin of the Proterozoic Australian continent after Neoproterozoic Rodinian breakup (e.g., Cawood, 2005). The North Queensland Orogen (terminology of Glen, 2005), and constituent provinces, subprovinces and geographic regions (Figures 2a, b, 3, 4) represent the northern part of the largely Paleozoic Tasman Orogen, which dominates eastern Australia, and is generally thought to have been produced by a long-lived accretionary convergent margin (e.g., Cawood, 2005; Collins and Richards, 2008; Glen, 2005). The Thomson Orogen comprises Neoproterozoic to Middle Palaeozoic rocks best exposed within the Anakie Inlier (Withnall et al., 1995) and the Charters Towers region (e.g., Hutton et al., 1997). The Orogen, however, is poorly exposed, being largely covered by Paleozoic and Mesozoic basins, and is poorly understood. In particular the age, nature and origins of the basement rocks in the orogen are largely unknown, although a variety of models have been proposed (see discussion in Champion et al., 2009). The Charters Towers and Barnard regions, which may be part of either the North Queensland or the Thomson orogens are included within the North Queensland Orogen in this report. As such the Thomson Orogen is not discussed in any detail. Geological province and subprovince nomenclature used in this report follows Geological Survey of Queensland usage, largely as outlined in Bain and Draper (1997), but with the recent modifications of Withnall et al. (2009a; see Figures 2b, 3).

1.1. Paleoproterozoic to Neoproterozoic

Geological and tectonic summary

Rocks of Paleoproterozoic to Neoproterozoic age in North Queensland are best represented in the Georgetown and Coen regions (e.g., Withnall et al., 1988; Bain and Draper, 1997; Black et al., 1998; Blewett et al., 1998). The region is bounded to the east by the Tasman Line, and separated from the Mount Isa Province to the west by the Mesozoic Eromanga-Carpentaria Basin. Most sedimentary successions have poor age constraints although recent dating has provided some maximum depositional ages, particularly in Georgetown area, and important information regarding sediment provenance.

For this geochronological review and construction of the associated Time-Space plots (Figures 5, 6, 10, 17, 20), we have used the regional and stratigraphic subdivisions of Bain and Draper (1997), who divided the area into the Georgetown and Coen Regions (Figure 4). The Georgetown and Coen regions were originally divided into a number of structural units (Withnall et al., 1997) – the Etheridge Province (consisting of the Forsayth Subprovince in Georgetown, and the Yambo Subprovince in Coen), the Savannah Province and the Croydon Province. Subsequent work has resulted in the term Etheridge Province being expanded to include all these original provinces, which are now downgraded to subprovinces (see Withnall et al., 2009a; Figure. 3). The Iron Range Province in the Coen region remains unchanged (Figure 3).

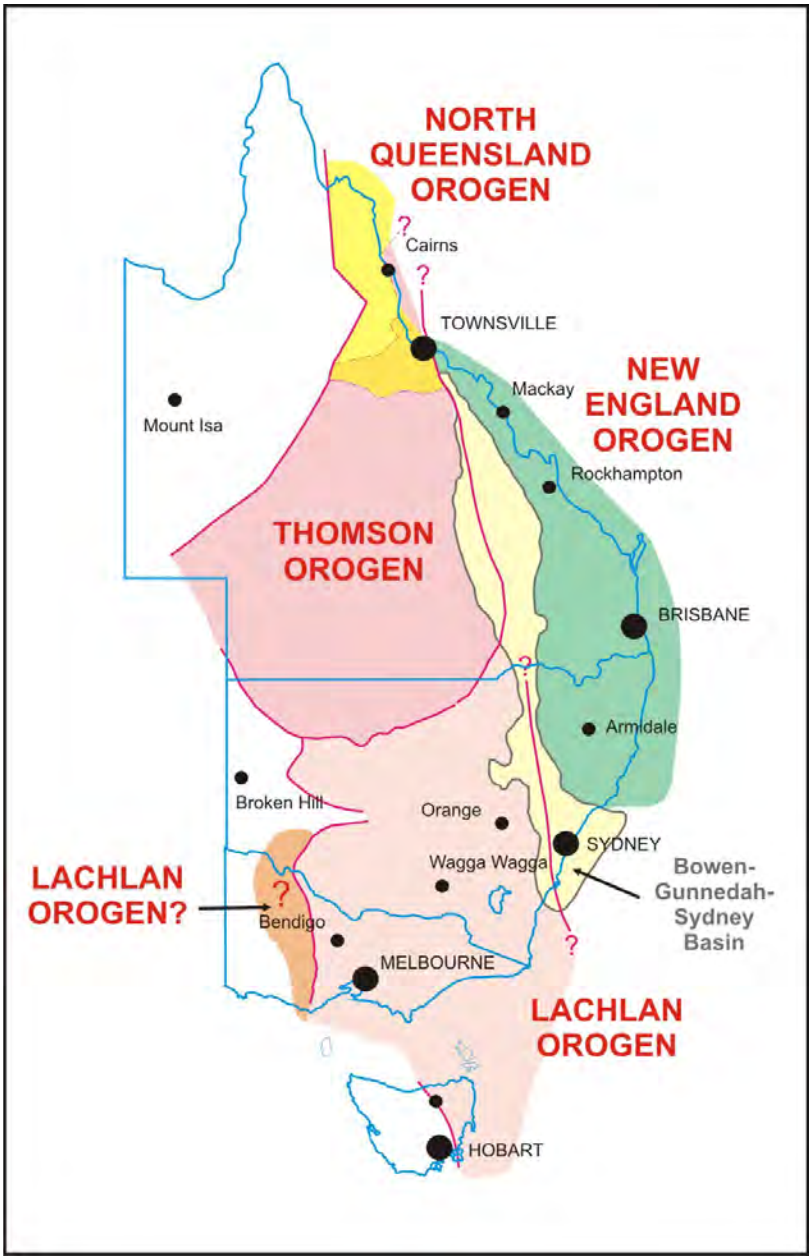

Figure 1 . Location map showing the distribution of Proterozoic Australian Craton and eastern Australian orogens of the Tasman Orogen. Orogen names follow Glen (2005). Orogen boundaries from Glen (2005), VandenBerg et al. (2000), Seymour and Calver (1995), Bain and Draper (1997), and unpublished GA-GSQ Nd isotope data for the eastern Thomson Orogen. The boundary of the Thomson Orogen has been extended to the north to include the Cape River and Barnard provinces (darker yellow and area of pink east of Cairns, respectively) of Bain and Draper (1997). The Cape River Province is included in the North Queensland Orogen, although is of uncertain parentage. The Bowen-Gunnedah-Sydney Basin outline is from Geoscience Australia's 'Basins' national data set.

The Paleoproterozoic to Mesoproterozoic Georgetown Region consists of deformed metasedimentary rocks, together with both volcanic and intrusive igneous rocks. The exposed metasedimentary rocks represent the oldest known rocks in northeast Queensland and include variably metamorphosed sub-aerial to marine sediments, volcaniclastics and mafic and felsic volcanic rocks (Withnall et al., 1988, 1997a, 2009b; Withnall, 1996). Up to 11 km of sediment was deposited, probably in an intracratonic setting, from about 1700 to 1600 Ma (Blewett et al., 1998). Granitoids were intruded locally around 1690 Ma and mafic volcanism and intrusion occurred around 1670 and 1650 Ma (Blewett et al., 1998).

The main tectonothermal event, ca. 1590-1550 Ma (Cihan et al., 2006), involved deformation, metamorphism and magmatism related to clockwise PTt paths (Boger and Hansen, 2004; Cihan et al., 2006). Magmatism appears to relate to the decompression stage, with mostly S-type, and lesser sodic I-type, granites at about 1560-1550 Ma (Bain et al., 1985; Black and McCulloch, 1990). The Proterozoic geology of the Georgetown region has been described in detail by Withnall (1996) and Withnall et al. (1988, 1997a, 2002), and also Withnall et al. (2009b) who describes significant recent revisions to the structural and metamorphic history of the region.

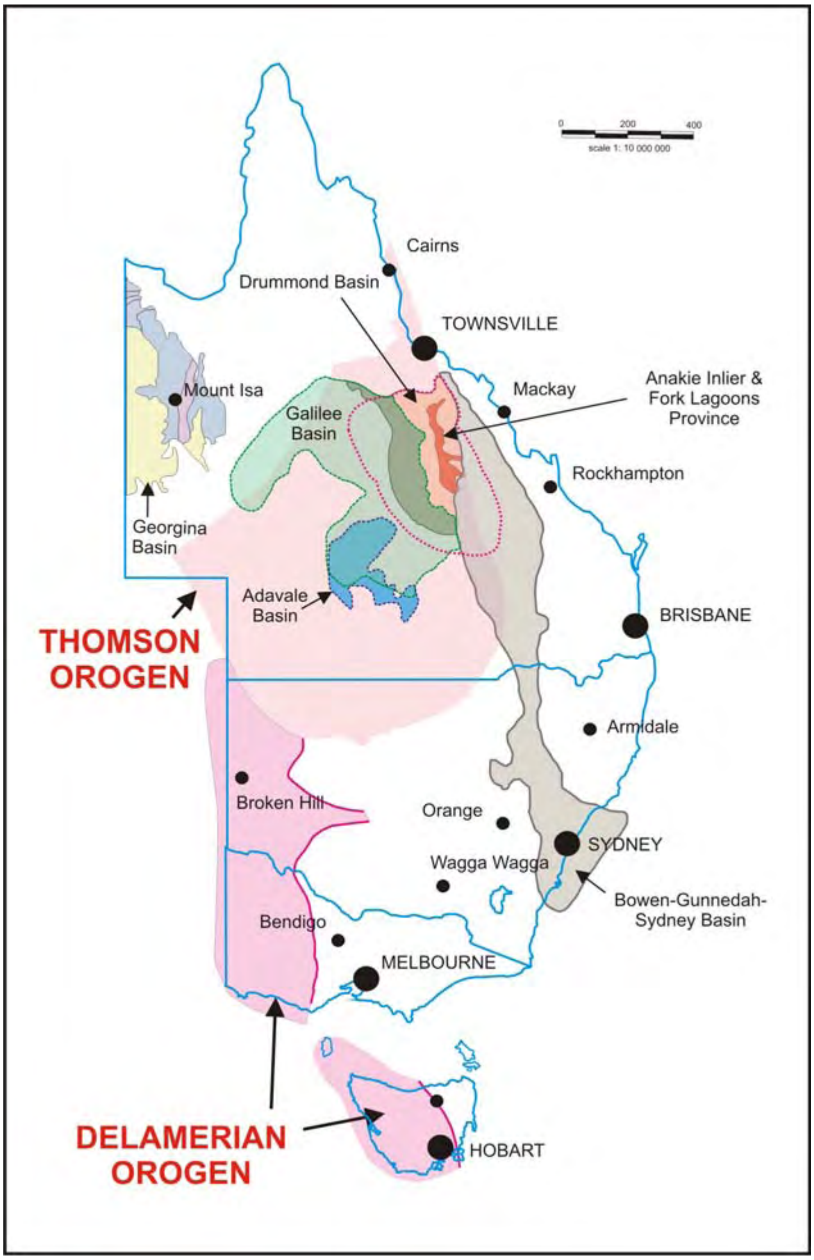

Figure 2a. Location map showing the distribution of eastern Australian orogens, basins and other regions. Orogen names and boundaries are derived from the studies of Glen (2005), Bain and Draper (1997), and unpublished GA-GSQ Nd isotope data for the eastern Thomson Orogen. The boundary of the Thomson Orogen is extended north to include the Cape River and Barnard provinces of Bain and Draper (1997). The Adavale, Galilee, Bowen-Gunnedah-Sydney Basin outlines are from Geoscience Australia's 'Basins' national data set. Drummond Basin, Georgina Basin and Mount Isa and Anakie Inlier boundaries from 'Geology of Queensland' (www.dme.qld.gov.au/mines/projects.cfm). Red dotted line is extent of the Drummond Basin in the subsurface.

Proterozoic to late Paleozoic metamorphic and igneous rocks underlie much of Cape York Peninsula and are exposed in the Coen Region. The Coen Region is dominated by a north-south grain, and was divided into two main Proterozoic provinces by Blewett et al. (1997): the late Paleoproterozoic to Mesoproterozoic Yambo Subprovince and the Mesoproterozoic Savannah Subprovince (Figure 3). We include poorly age-constrained rocks of the Late Mesoproterozoic (to Palaeozoic?) Iron Range Province in the time-space summary for the Coen Region (Figure 5).

The main crustal fabric of the Coen Region is thought to have developed by a series of intracontinental clastic sedimentary episodes, probably following rifting, interspersed with deformational, metamorphic and largely intraplate felsic magmatic episodes (Blewett et al., 1997). Like the Georgetown region, the Coen region also records high pressure metamorphism at ca. 1590 Ma (Ellis, in Blewett et al., 1997). The Proterozoic geology of the Coen Region has been described by Blewett et al. (1997, 1998) and Blewett and Black (1998) (see summary below).

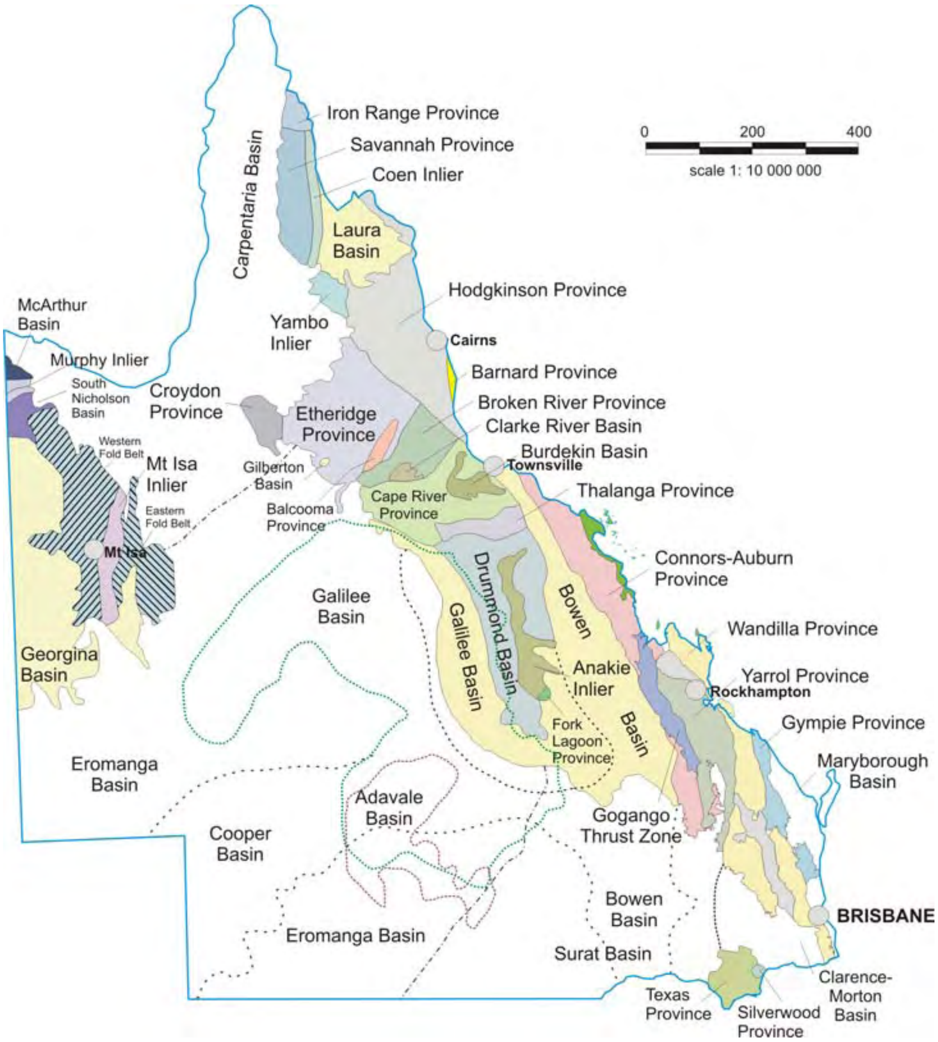

Figure 2b. Geological framework of Queensland showing the distribution of Proterozoic and Phanerozoic provinces and basins (from 'Geology of Queensland' www.dme.qld.gov.au/mines/projects.cfm). Province names have been updated to reflect modified Province nomenclature (Withnall et al., 2009a).

Although not contiguous outcrop (obscured by overlying younger basins), the similarities between the Georgetown and Coen regions are particularly striking and all reconstructions interpret the two regions as belonging to the one province during the Paleoproterozoic (e.g., Bain and Draper, 1997). The relationship between the combined Georgetown-Coen region – now collectively called the Etheridge

Province (see Withnall et al., 2009a) – and the Mount Isa Province to the west (Figure 2b) is more speculative. Despite considerable uncertainty, most models for the Paleoproterozoic evolution of the Australian continent (Laing, 1996; Betts et al., 2002; Giles et al., 2004), consider Georgetown to be a part of the North Australian Craton (NAC). For example, Betts et al. (2002) inferred that the eastern margin of the North Australian Craton was ocean-facing prior to Mesoproterozoic (ca. 1600-1500 Ma) orogenesis, which they postulated was related to a west-dipping subduction zone and ultimately continental collision due to docking of the North American Craton at ca. 1540 Ma during the formation of Rodinia. The area has, therefore, been considered important in determining possible configurations of Rodinia (e.g., SWEAT versus AUSWUS versus AUSMEX: Dalziel, 1991; Moores, 1991; Karlstrom et al., 2001; Burrett and Berry, 2000; Wingate et al., 2002). Possible links between North Queensland (east Australia) and North America (Laurentia) in the Rodinian Supercontinent (SWEAT) have been discussed by Blewett et al. (1998), who favoured North Queensland as a source area for the Mesoproterozoic Belt Supergroup in North America. Recent work by Wingate et al. (2002) favours AUSMEX reconstructions where late Mesoproterozoic provinces in northeast Australia, such as the Charters Towers Province southeast of the Georgetown region, aligns with similar aged Grenville rocks in southernmost Laurentia.

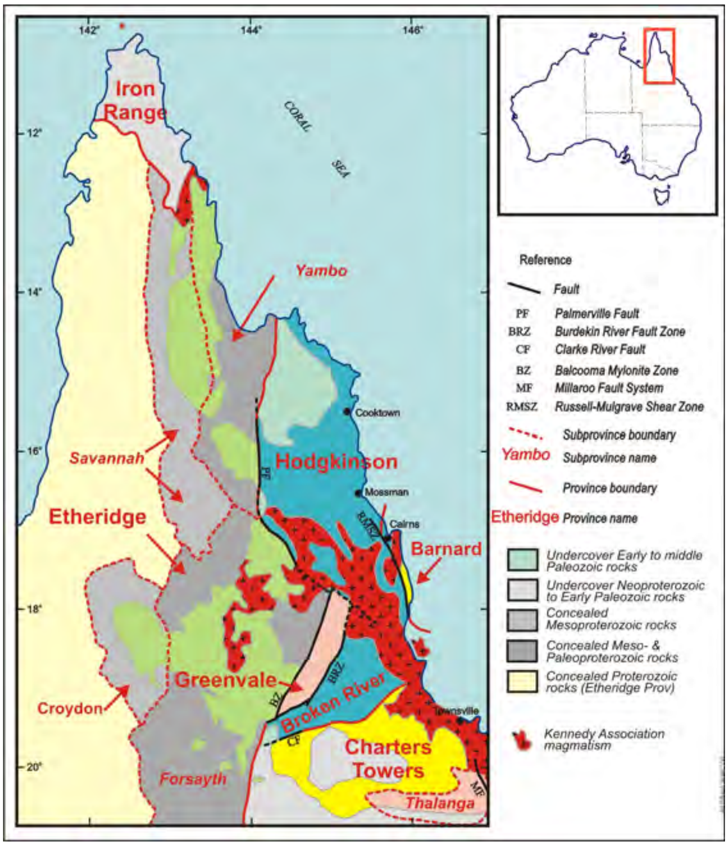

Figure 3. Distribution of geological provinces in North Queensland. Province names and boundaries as defined by Bain and Draper (1997), with modifications from Withnall et al. (2009a), namely merging of Etheridge, Savannah and Croydon Provinces into the Etheridge Province, and Cape River, and Thalanga Provinces into Charters Towers Province. The magmatic Macrossan (Cambrian-Ordovician), and Pama (Silurian-Devonian) Associations are not shown. In the Time-Space plots for northern Queensland, Provinces are grouped into regions (see Figure 10).

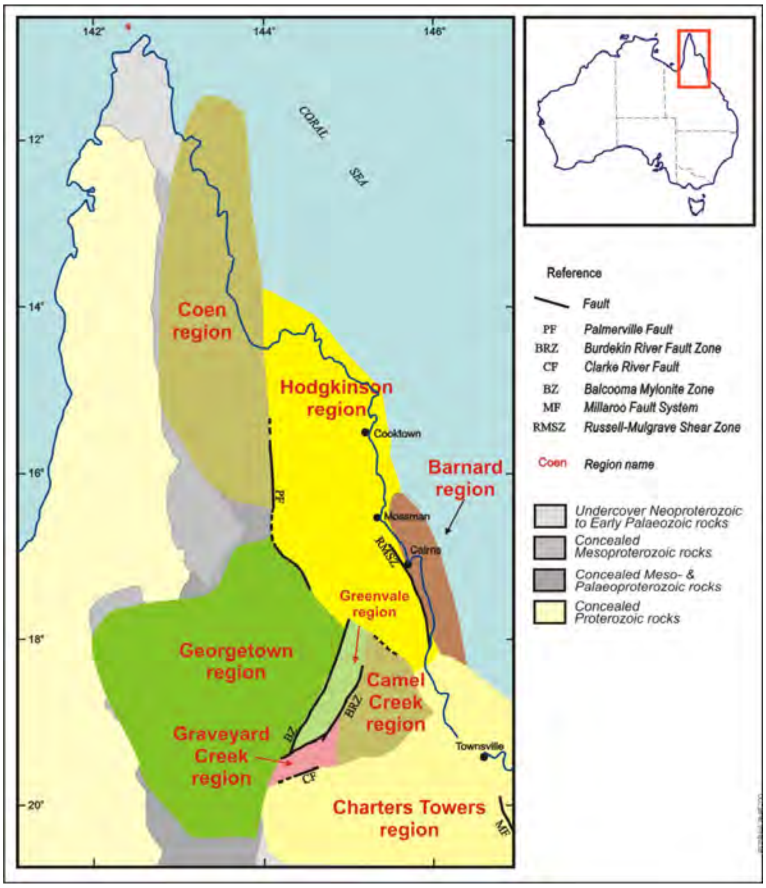

Figure 4. Distribution of geological regions as used for the North Queensland Time-Space Plot (Figure 10). Geological regions are largely based on the geographic subdivisions used in Bain and Draper (1997). Regions have been used here for areas which include more than one geological province. This approach was largely required because of the large and widespread magmatic Macrossan (Cambrian-Ordovician magmatism), Pama (Silurian-Devonian magmatism) and Kennedy (Carboniferous-Permian magmatism) Associations which occur across north Queensland and within all of the sedimentary-metamorphic provinces shown in Figure 3.

Most models for the North Australian Craton imply a similar (and connected) evolution for the Georgetown and Mt Isa regions based on, for example, similarities in the timing of deformation and synorogenic metamorphism (Page and Sun, 1998; Perkins and Wyborn, 1998; Giles and Nutman, 2002), lithostratigraphic similarities between Proterozoic successions (Black et al., 1998; Blewett and Black, 1998; Page and Sun, 1998; Betts et al., 2002; Giles et al., 2002), anomalously high heat flow expressed as magmatism and low-pressure – high-temperature metamorphism (Giles et al., 2002), and similar ages and kinematics of deformation (O'Dea et al., 1997; Betts et al., 2000; Blewett and Black, 1998; Blewett et al., 1998). Nevertheless, Boger and Hansen (2004) recently speculated that the Georgetown region was accreted to the North Australian Craton during the construction of Rodinia, as opposed to always having been part of it. These authors based their reasoning on a number of apparent differences between the two regions, including: the polyphase metamorphic evolution of the Georgetown region; its distinct structural evolution and structural grain (i.e. east-west versus north-south; O'Dea et al., 1997); differences in the crust and/or crustal evolution based on S-type versus I- and A-type magmatism at ~1550 Ma (Black and McCulloch, 1990; Wyborn et al., 1992); and a normal versus high geothermal gradient during peak metamorphism (Rubenach, 1992; Boger and Hansen, 2004).

More recent geochronological, geochemical and seismic data support the notion that there are substantial differences in the geological make up of the Georgetown and Mt Isa regions. Detrital zircon studies have shown that the provenance age spectra of the lower and upper Etheridge Group at Georgetown differ, with a voluminous influx from a young provenance (ca. 1650 Ma) recorded in the Upper Etheridge Group (N.L. Neumann, unpublished data, in Withnall et al., 2009b), matched also by a change in Nd isotopic signature (Lambeck et al., unpublished data). Similar provenance and isotopic changes have been recorded within Paleoproterozoic assemblages in the Curnamona Province and perhaps the Mount Isa region (Barovich and Hand, 2008). Barovich and Hand (2008) suggested that the provenance changes and switch to less radiogenic Nd signatures may be explicable by sourcing from southwest Laurentia, which in AUSMEX and AUSWUS models, is considered proximal to eastern Australia.

As pointed out by Withnall et al. (2009b), the source area for the lower Etheridge Group was also different to that for the Mt Isa Province. The latter clearly records a dominant source from young rocks (ca. 1750-1900 Ma) that is not the source for the lower Etheridge Group. The provenance for the upper Etheridge Group has more similarities with that observed at Mount Isa (Withnall et al., 2009b), although it is not identical. It is not entirely clear, however, what constraints this places on tectonic reconstructions regarding the relative positions of Mount Isa and Georgetown. Withnall et al. (2009b) suggested that the switch from different provenance to broadly similar provenance may indicate that an east-west event occurred between ~1660 Ma and ~1640 Ma to bring these two terranes together (Withnall et al., 2009b). Although a possible deformation is recorded at this time in both regions, it appears to reflect north-south contraction (e.g., Betts et al., 2006).

The suggestion of accretion between Mt Isa and Georgetown is, however, compatible with interpretations from the recent seismic reflection survey from Mt Isa across to Georgetown (Korsch et al., 2009c, d), which suggest two possible suture zones between the two regions. A major discontinuity in western Georgetown is mapped by the seismic data, which corresponds to a step in the Moho and the presence of a west-dipping reflector in the mantle. In the eastern Mt Isa area, the seismic and magnetotelluric (MT) data also map a major discontinuity, associated with a change in seismic character, a step in the mantle and electrical contrast in conductance. These two 'structures' are tentatively assigned as a fossil subduction zone and suture between three crustal blocks, respectively (Korsch et al., 2009c). These data also point to a potentially unidentified province between Mount Isa and Georgetown – the Numil Seismic Province (Korsch et al., 2009c and refer to Section 2). Even if the interpreted sutures are correct and do represent terrane accretion events, there are few available age constraints, making estimates for the timing of such events at best speculative. The best estimates for the eastern Mt Isa suture are accretion at or before ca. 1860 Ma, for example, accretion may relate to ocean closure after the suggested ca. 2.0-1.97 Ga arc of McDonald et al. (1997). Similarly, the only constraint on the Georgetown subduction zone is that, based on the current interpretation, it predates deposition of the Etheridge Group, that is, pre ca. 1710 Ma (Withnall et al., 2009b). What is apparent on the seismic section is that the seismic character of the crust is very similar on either side of the interpreted fossil subduction zone, which led Korsch et al. (2009d) to suggest the two blocks were originally one prior to rifting and subsequent collision. There are no age constraints on this postulated rifting, although it was probably pre-1710 Ma, or even pre-1860 Ma, as there is no significant deformation recorded in Mt Isa between ~1860 Ma and 1640 Ma.

Geological history and Time-Space plot explanation

***Georgetown region** (includes Etheridge and Croydon regions)*

- Predominantly shallow-water, clastic, metasedimentary rocks, together with minor basaltic lavas and related doleritic intrusions (Black et al., 1998; 2005) of the Etheridge Group (Figure 5). This metasedimentary succession was deposited in an intracratonic rift setting between 1710 Ma and at least 1650 Ma, based on the dating of mafic bodies (1675-1655 Ma) and granitic gneisses (1684-1696 Ma) associated with this Group and the Einasleigh Metamorphics (e.g., see Black et al., 1998). These ages provide a younger limit for the depositional age of the local succession (Black et al., 1998).
- Detrital zircon geochronology has been used to determine that the lower Etheridge Group was deposited between ~1700 Ma and ~1660 Ma and is dominated by Archean-earliest Paleoproterozoic detrital ages (Figure 6). The upper Etheridge Group was deposited after ~1655 Ma and is dominated by Proterozoic detrital ages (Withnall et al., 2009b). The provenance age spectra of the lower and upper Etheridge Groups differs markedly and implies a change at ~1650 Ma (approximately equivalent to the Lane Creek Formation) (Withnall et al., 2009b). This change is further recorded in Nd isotopes, with the lower Etheridge Group having a more evolved signature compared to samples from the upper Etheridge Group (Lambeck et al., unpublished data).
- Biotite gneiss and calc-silicate gneiss of the Einasleigh Metamorphics may be stratigraphically lower than the Etheridge Group (Withnall et al., 1997) or, alternatively, may, at least partly, be

equivalent to the Bernecker Creek and Daniel Creek Formations of the Etheridge Group. However, the metamorphic rocks contain leucogneiss, which has not been identified in low-grade equivalents (Withnall et al., 1997). Sedimentary precursors of the Einasleigh Metamorphics began to be deposited on unknown basement before ca. 1700 Ma. Their precise age is bracketed between 1696 ± 2 Ma by an intruding granite (Black et al., 1998) and 1706 ± 6 Ma by interbedded leucogneiss (Black et al., 2005; Figures 5, 6). Additional age constraints from felsic leucogneisses from the Einasleigh Metamorphics (e.g., Black et al., 2005), suggest deposition of the Einasleigh Metamorphics from ~1700 Ma to ~1655 Ma.

- An amphibolite within the Einasleigh Metamorphics has a U-Pb zircon SHRIMP crystallisation age of 1675 ± 3 Ma and, based on stratigraphic correlations, suggests that mafic rocks within the lower Etheridge Group also crystallised at that time (Black et al., 1998). This age, coupled with a U-Pb zircon SHRIMP crystallisation age of 1656 ± 2 Ma for a leucogabbro sill which intruded the Lane Creek Formation (Cobbold Metadolerite), suggest two periods of mafic magmatism associated with the lower Etheridge Group (Black et al., 1998).
- The Paleoproterozoic Yambo Subprovince is represented by the Dargalong Metamorphic Group. The Dargalong Metamorphic Group consists of banded migmatitic gneiss, augen gneiss, amphibolite, with schist, quartzite and minor calc-silicate gneiss, and are suggested to be deposited after 1640 Ma (Withnall et al., 1997a). Two mylonitised granodioritic to tonalitic gneisses from the Dargalong Metamorphics, analysed for U-Pb zircon SHRIMP geochronology (Blewett et al., 1998; 1586 ± 5 Ma and 1580 ± 4 Ma), are interpreted to record the crystallisation of the igneous precursor of these gneisses (Blewett et al., 1998).
- The McDevitt Metamorphics consist of laminated to thin-bedded metapelite and subordinate metaarenite, quartzite and mafic sills (Withnall et al., 1997). There are no geochronological age constraints for the McDevitt Metamorphics, but they are suggested to correlate with either the Etheridge or Dargalong Metamorphics Groups.
- Mica schists of the Juntala Metamorphics are lithologically similar to the higher-grade parts of the Corbett Formation of the Etheridge Group, and these two units may be correlative (Withnall et al., 1997). The Cassidy Creek Metamorphics consist of mica schists and quartzite similar to the Juntala Metamorphics. They occur spatially separate from, and are lower metamorphic grade than, the Einasleigh Metamorphics (I. Withnall, written comm., 2009).
- Regional metamorphism and deformation in the Georgetown region was essentially confined to the Etheridge Group (Figure 5). A poorly constrained (ca. 1650-1600 Ma) north-south contractional deformation (D1) with east-west folds, predated the Langlovale Group, and significantly deformed the Etheridge Group (Withnall et al., 2009b). This was overprinted by slightly younger (ca. 1600-1550 Ma) D2 (east-west) and D3 (northwest-southeast) contractional deformation and metamorphism (e.g., Withnall et al., 2009b). Metamorphic grades during D2-M2 varied from lower greenschist facies in the west to amphibolite facies in the east (Bell and Rubenach, 1983; Reinhardt and Rubenach, 1989; Withnall, 1996). Igneous and metamorphic crystallisation of zircon occurred at about 1584 Ma in North Queensland (i.e. Arkara Gneiss, 1586 ± 5 Ma and 1580 ± 4 Ma; Blewett et al., 1998), an age favoured by Black et al. (2005) as the age of D2-M2. Cihan et al. (2006) record a similar monazite age for deformation and metamorphism. Murgulov et al. (2007) also record a major zircon peak at ca. 1580 Ma, consistent with felsic magmatism at that time. Deformation related to D2 is best expressed in the southern and western parts of the Etheridge Group (where later structural overprinting is not as strong). Structures vary from east-west in the south to more northerly in the north (Boger and Hansen, 2004). Boger and Hansen (2004) indicate that D2-M2 was high-pressure, moderate-temperature, and Cihan et al. (2006) indicate clockwise PTt paths for D2-M2.
- The Mesoproterozoic, fluvial to marine, Langlovale Group (Withnall et al., 1997a; Black et al., 2005) in the western Etheridge Province unconformably overlies the Etheridge Group (Figure 5). The Langlovale Group includes the Malacura Sandstone, which is interpreted to be deposited in a fluviatile environment, and Yarman Formation, which is suggested to represent turbiditic facies associated with a prodeltaic system (Withnall et al., 1997a). The Langlovale Group was deposited after ~1625 Ma and is dominated by Proterozoic detrital ages (Withnall et al., 2009b; Figure 6). This group is thought to postdate D2 in the Etheridge Group and pre-

dates both D3 and the Croydon Volcanic Group. As such it may have been deposited at about 1560-1550 Ma (Black and McCulloch, 1990; Withnall, 1996; Withnall et al., 1997a, 2009b).

- The Etheridge Group and Einasleigh Metamorphics were deformed (northwest-southeast contraction) and metamorphosed by a third event (D3-M3) between ~1560-1550 Ma (Black and Withnall, 1993; Black et al., 2005; Withnall et al., 2009b). Zircon growth at ~1553 Ma accompanied upper amphibolite to granulite metamorphism during D3-M3 (Black et al., 1998). The peak of D3-M3 was accompanied by migmatisation and extensive felsic, largely S-type, magmatism at ca. 1555-1550 Ma (Black and McCulloch, 1990; Black and Withnall, 1993; Black et al., 1998, 2005; Murgulov et al., 2007; Figures 5, 6, 7). Boger and Hansen (2004) indicate that D3-M3 was low-pressure, high-temperature. Cihan et al. (2006) indicate decompression and exhumation for D3-M3, and record ages of ca. 1542 Ma for this event. The intensity of this event is strongest in the east (with tight to isoclinal folding), whereas in the west the contemporaneous but undeformed Croydon Volcanic Group overlies low-grade Etheridge Group affected by D2-M2. Detailed microstructural studies by Davis (1995), of the Robertson River Metamorphics, suggests that D3 (and perhaps D2) structures are composite and may include additional events; he equated his D4 with the regional D2. As indicated by Davis (1995), however, variable strain partitioning makes structural correlation between regions difficult.
- Based on U-Pb zircon studies, peraluminous S-type granites of the Forsayth Supersuite were intruded at ~1560-1550 Ma (Black and McCulloch, 1990; Black, OZCHRON; Murgulov et al., 2007; Figures 5, 6, 7). Along the eastern margin of the Forsayth Supersuite, biotite-muscovite leucogranites of the Lighthouse Supersuite were intruded in the same interval (e.g., 1561 ± 10 Ma; L.P. Black, cited in Withnall et al., 1997a), although they are geochemically distinct from the Forsayth Supersuite with geochemical signatures showing closer affinities to I-type Silurian granites in the region (Champion, 1991). The Forest Home Trondhjemite may have been intruded at ~1650 ± 17 Ma (Black and Withnall, 1993) which is an older age limit for emplacement. This age, however, may be inherited, as it could be based on xenocrystic or inherited zircons. Rb-Sr dating (e.g., Black and McCulloch, 1990) suggest ages of ca. 1550 Ma (but with large errors). A recent SHRIMP U-Pb date of 1567 ± 10 Ma is interpreted as the crystallisation age of the Forest Home Trondhjemite (N. Kositcin, unpublished data).
- The Lyndbrook Complex consists of a complex mix of probable Mesoproterozoic, two-mica and biotite granites, and high grade gneiss, quartzite, amphibolite and migmatite, probably related to the Einasleigh Metamorphics (Withnall et al., 2002). Withnall et al. (2002) suggested the granites, migmatisation and metamorphism relate to the regional D3-M3 deformation and metamorphism observed in the Einasleigh Metamorphics elsewhere. The granites are thought to relate to the S-type Forsayth Supersuite. SHRIMP data on gneissic granite (M. Fanning, unpublished) suggest ages of 1560-1570 Ma with inherited zircon populations at ~1595 Ma and 1620 Ma (I. Withnall, pers. comm. 2009).
- A number of additional deformational events have been documented for the Etheridge Group (e.g., Withnall et al., 1997). The timing of D4 (D3 of Withnall et al., 1997), which produced generally open, east-west structures, is poorly constrained. Rb-Sr dating by Black et al. (1979) suggests this event occurred at ca. 970 Ma, although it could also be either Mesoproterozoic or Early Palaeozoic in age (e.g., Withnall et al., 1997).

Croydon Area

- The Mesoproterozoic S-type Croydon Volcanic Group and related granites of the Esmeralda Supersuite crystallised at ~1550 Ma (Idalia Rhyolite 1552 ± 2 Ma, Black and McCulloch, 1990; 1548 ± 18 Ma, Black and Withnall, 1993), and probably postdates D3 in the Etheridge Group (Figures 5, 6, 7). The group unconformably overlies the Langlovale Group.
- The Esmeralda Supersuite (Champion, 1991; Figures 5, 6), characterised by coarse-grained, S-type biotite granite, crops out in the westernmost part of the Georgetown region and intruded the Croydon Volcanic Group and the upper Etheridge and Langlovale Groups (Withnall et al., 1997; Figures 5, 6). A sample from the supersuite has a U-Pb zircon multi-grain TIMS age of 1558 ± 4 Ma (Black and McCulloch, 1990).

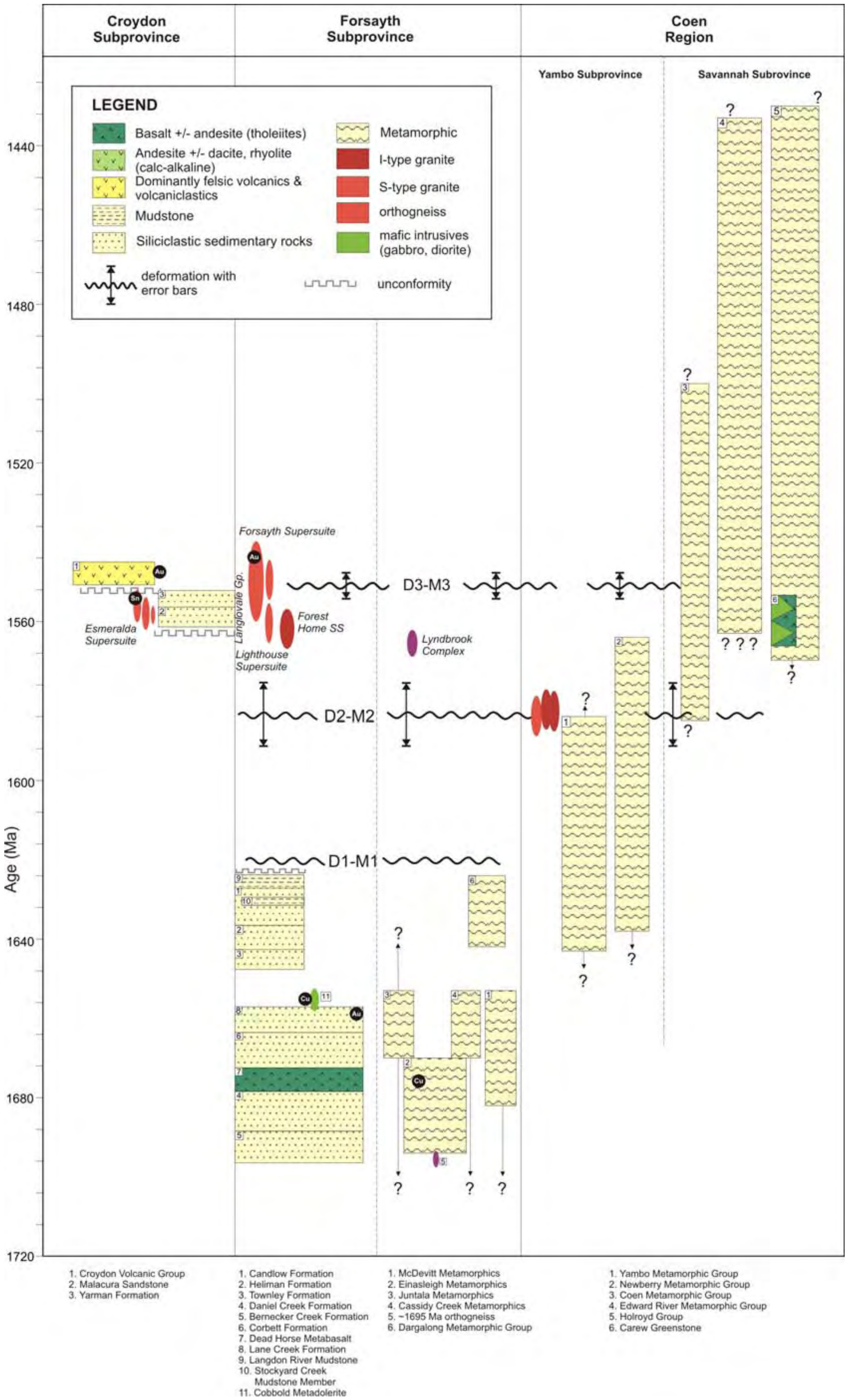

Figure 5. Time-space event plot for Proterozoic Georgetown (Croydon and Forsayth subprovinces) and Coen regions.

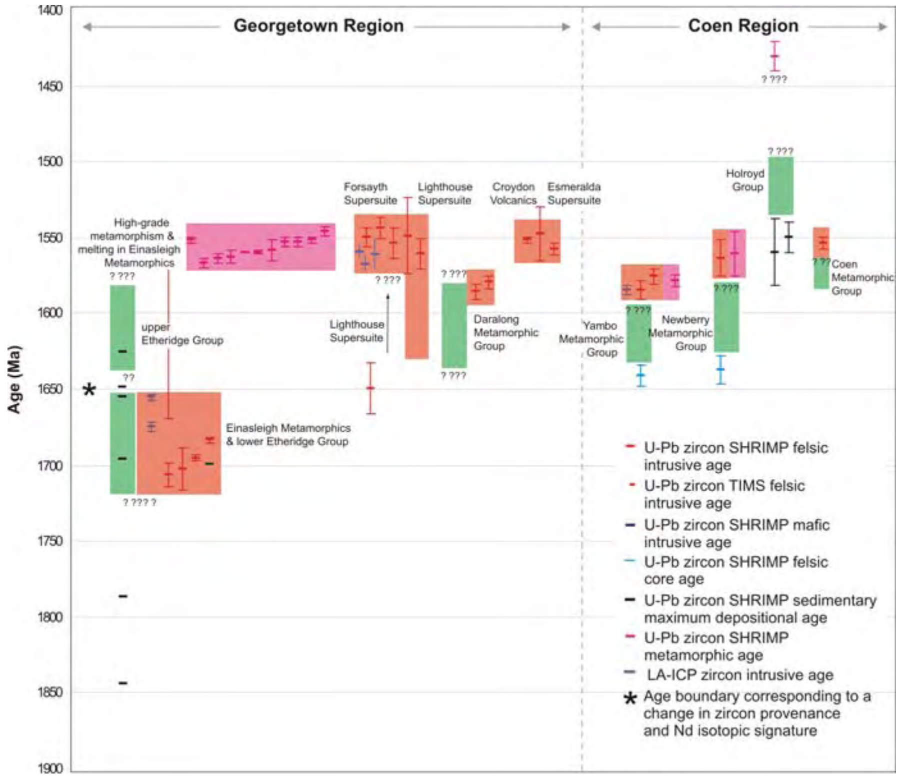

Figure 6. Geochronological data and summary time-space-event plot of the Georgetown and Coen regions for the period 1900-1400 Ma. Modified from Neumann (2007) with more recent data from the Etheridge Group from N. Neumann (unpublished data), and age data from Murgulov et al. (2007).

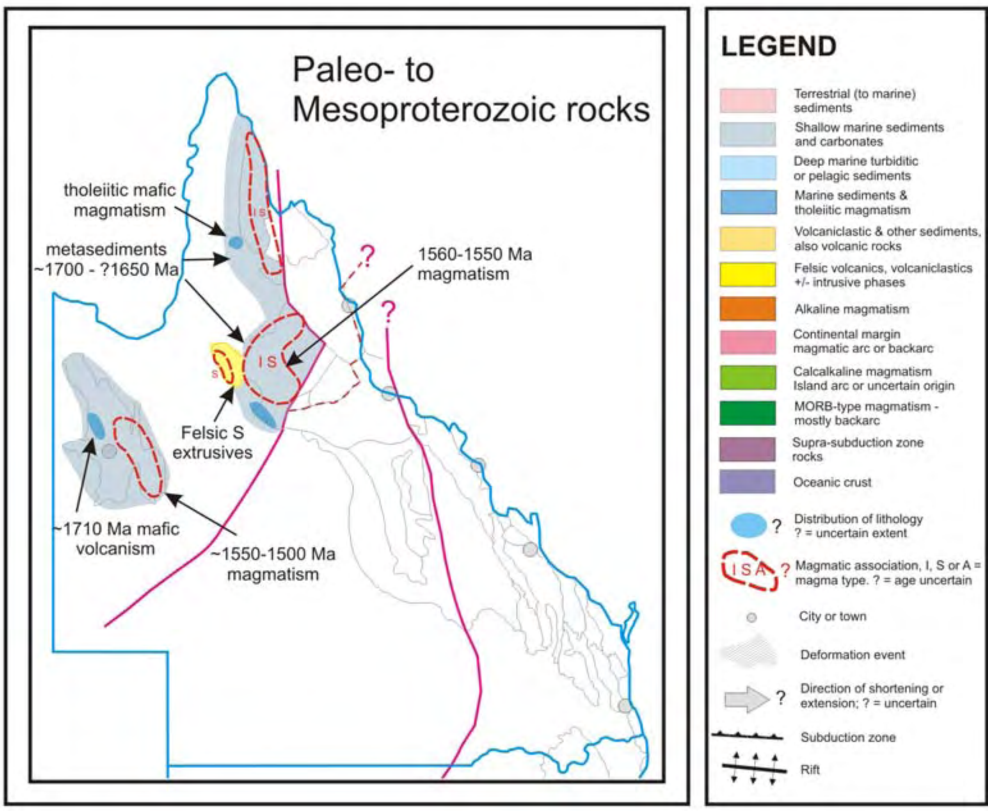

Figure 7. General distribution of Paleoproterozoic and Mesoproterozoic rocks in North Queensland. Refer to text for discussion. Solid pink lines define the boundary of the Thomson Orogen, with the Mesoproterozoic Australia craton to the left and the New England orogen to the right. The broken pink line highlights the possible northern margin of the Thomson Craton (approximate surface limit of Neoproterozoic).

Coen Region

- High-grade metasedimentary and meta-igneous rocks of the Yambo and Newberry Metamorphic Groups (Figure 5), together form the Yambo Subprovince of the Etheridge Province. Sedimentary protoliths are interpreted to have been shallow-marine sediments which accumulated in an intracontinental basin setting after ~1640 Ma (Blewett et al., 1997), possibly correlating with the upper parts of the Etheridge Group based on detrital zircon ages for the latter in the Forsayth subprovince (Withnall et al., 2009b). Similar, although slightly younger, rocks make up the Newberry Metamorphic Group, of uncertain protolith.
- Intrusion of I-type granodiorite and orthogneiss plus minor mafic rocks, and S-type granites at ~1580 and 1566 Ma (Blewett and Black, 1998; Blewett et al., 1998; Figure 7), interpreted to be coincident with amphibolite- to granulite-facies metamorphism and deformation (Blewett and Black, 1998). Ellis (cited in Blewett et al., 1997) reported PT conditions up to 770˚ and 8.75 kb for this metamorphism. PT conditions and the age closely match that reported for D2-M2 in the Georgetown region (Boger and Hansen, 2004; Cihan et al., 2006).
- Deposition of clastic sedimentary rocks of the Holroyd Group in a shallow marine, intracontinental or foreland basin setting (Blewett et al., 1997; Figures 5, 6), intruded by small volumes of mafic magmas at the base of the succession. The latter, the Carew Greenstone, is a metadolerite with MORB-like tholeiitic chemistry (Blewett et al., 1997; Figure 7). The group is constrained between a maximum age of ~1560 Ma (maximum depositional zircon age for the Astrea Formation; Black, OZCHRON) and 1410 ± 10 Ma, the interpreted crystallisation age of granitic gneiss within the group (L. Black, OZCHRON). The Edward River Metamorphic Group is considered to have been deposited in a similar setting and similar time interval (<1563 and >1433 Ma; Blewett et al., 1997). Although multiply-deformed, the Holroyd Group is not as structurally complex as the older Yambo and Newberry Metamorphic Groups (Blewett et al., 1997).
- Schist, gneiss and lesser quartzite of the Coen Metamorphic Group is structurally and metamorphically correlated with the Holroyd Group (Blewett et al., 1997; Figures 5, 6). Detrital zircons provide a maximum age of ca. 1585, while one paragneiss has a recorded age of 1544 ± 4 Ma, which may represent in situ partial melting (Blewett et al., 1997).
- Metaconglomerate from the Sefton Metamorphics has a maximum depositional age of ~1200 Ma (U-Pb detrital zircon data; Blewett et al., 1998), although little is known about the environment or tectonic setting of deposition.

1.2. Late Neoproterozoic to Early Cambrian

Rodinian breakup (pre-Delamerian): ca. 600 Ma to 515 Ma

Geological and tectonic summary

Rocks of Late Neoproterozoic to Early Cambrian age in North Queensland are best represented in the Greenvale and Charters Towers regions, but also occur in the Georgetown and Coen regions and in the Barnard Province (Figures 8, 10). Most sedimentary successions have poor age constraints. The tectonic environment for this period is typically interpreted as a passive margin, related to (post-dating) Rodinian breakup. Fergusson et al. (2007a, 2007b, 2009) suggested the presence of Late Neoproterozoic rifting (ca. 600 Ma) in the region, based on the presence of common 600-500 Ma detrital zircons and on correlation with other regions, for example, in the Thomson Orogen. The recent results of Fergusson et al. (2007a, 2009) also indicate that the Tasman Line, as previously defined, along the western margin of the Greenvale Province, does not represent Rodinia breakup, but rather younger (possibly Benambran?) west-directed thrusting of younger rocks over Mesoproterozoic basement.

Geological history and Time-Space plot explanation

Greenvale region

- Metasedimentary-dominated Halls Reward Metamorphics (Withnall et al., 1997a). Age uncertain, but has Cambrian metamorphic ages (ca. 520-510 Ma) and Neoproterozoic detrital zircon ages (Nishiya et al., 2003; Figures 8, 10)
- Mafic to ultramafic magmatic rocks of the Boiler Gully and Gray Creek Complexes, intimately associated with the Halls Reward Metamorphics. Uncertain origin – may be tectonically emplaced and/or intrusive. Withnall et al. (1997a) suggested it was intrusive, at least in part. Ages are poorly constrained and could even postdate the Delamerian Orogeny, though as noted by I. Withnall (written comm., 2009) has undergone amphibolite-facies metamorphism similar to that in the enclosing Halls Reward Metamorphics.
- Late Neoproterozoic-Early Paleozoic sedimentation (dolomitic carbonate and quartzofeldspathic sediments) of the Oasis Metamorphics (Figures 8, 10). Most probably shallow-marine environment formed as part of the passive Gondwana margin (Withnall et al., 1997a; Fergusson et al., 2007a). The Oasis Metamorphics include tholeiitic mafic igneous rocks (intrusive/extrusive; e.g., Withnall et al., 1997a). Age constrained to between 540-520 Ma (youngest detrital zircon population) and ca. 485 Ma (overprinting metamorphism; Fergusson et al., 2007a).

Georgetown region

- Terrestrial sedimentary rocks of the Inorunie Group (Withnall et al., 1997a; Figures 8, 10). Ages are poorly constrained, and the group may be as old as Mesoproterozoic – the preferred age of Withnall et al. (1997a). Unconformably overlie the Croydon Volcanics (ca. 1550 Ma).

Barnard region

- Barnard Metamorphics (metasedimentary rocks, amphibolite, metavolcanics) and the intrusive(?) Babalangee Amphibolite (Bultitude et al., 1997; Figures 8, 10). Ages are poorly constrained but must be older than Early Ordovician (ca. 490 Ma), the age of cross-cutting granites (Bultitude et al., 1997).

Coen region

- Sefton Metamorphics – poorly age-constrained metasedimentary rocks (Blewett et al., 1997; Figure 10) and mafic magmatic rocks. Detrital zircons indicate the succession is younger than ca. 1200 Ma (Blewett et al., 1997).

Charters Towers region

- Widespread remnants of largely marine metasedimentary rocks (Charters Towers Metamorphics, Argentine Metamorphics, Running River Metamorphics, Cape River Metamorphics; Hutton et al., 1997; Figures 8, 10). Also includes mafic magmatic rocks, which appear to include both alkaline and tholeiitic compositions (Fergusson et al., 2007b). Ages are not well constrained, except for the Argentine Metamorphics which Fergusson et al. (2007b) dated at ca. 500 Ma (certainly older than 480 Ma). The Cape River Metamorphics give similar minimum ages, based on intrusive contacts (> ca. 490 Ma; Hutton et al., 1997).

Georgina Basin

- During the Neoproterozoic breakup of the Rodinia supercontinent, a northwest-trending transcontinental rift system developed (Dunster et al., 2003). Fluvial, lacustrine and marine Neoproterozoic sedimentary rocks of the Centralian Superbasin (Georgina, Amadeus, Ngalia, and Officer Basins) (Lindsay et al., 2005), were deposited in extensional basins initiated at ca. 850 Ma (Walter et al., 1992; 1995), thought to have developed in response to mantle activity (i.e., Gairdner Large Igneous Province; Zhao et al., 1994; Lindsay, 1999, 2002).

- Following the initial extensional phase (ca. 780-750 Ma), basin dynamics became largely contractional (recorded by shortening events, for example, in Northern Territory, Tasmania and Western Australia; Walter et al., 1995).
- The Neoproterozoic rift succession in the Georgina Basin consists of mostly marine siliciclastic sediments, and at least one, possibly two, glacial intervals (equivalent to Sturtian and Marinoan glaciation; Walter et al., 1995), deposited in half grabens (Ambrose et al., 2001).

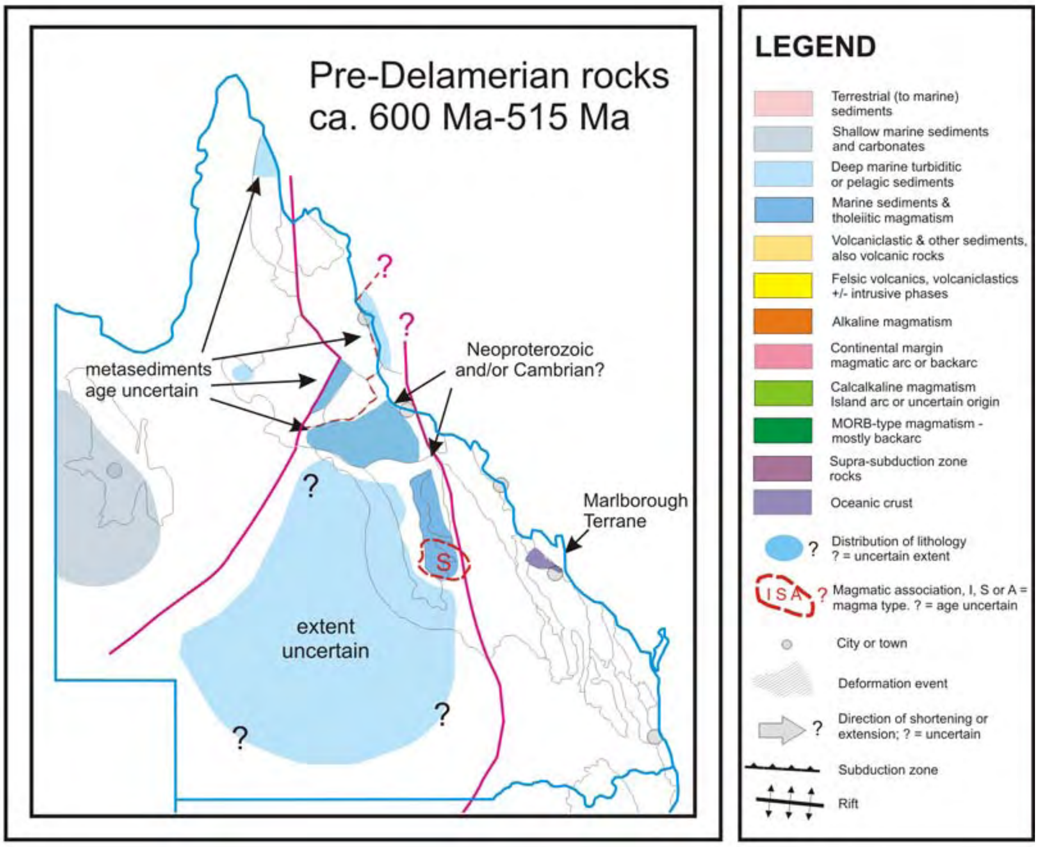

Figure 8. General distribution of Neoproterozoic to mid Cambrian (ca. 600 Ma to 515 Ma), pre-Delamerian rocks in eastern Australia. Refer to text for discussion.

- This depositional system was deformed and segmented by zones of basement uplift during the intraplate Late Neoproterozoic – earliest Palaeozoic Petermann Ranges Orogeny (Haines et al., 2001), which separated the Georgina and Amadeus basins (Ambrose et al., 2001). The unconformity between the Neoproterozoic rocks and the Early Cambrian rocks is attributed to the final stage of the Petermann Orogeny (Ambrose et al., 2001; Kruse et al., 2002) (Figure 10).
- Metamorphosed Neoproterozoic sedimentary rocks are also present in the Thomson Orogen (Draper, 2006) and Anakie Inlier (Withnall et al., 1995, 1996; Fergusson et al., 2001, 2009), indicating that Neoproterozoic deposition was even more widespread than the Centralian Superbasin (Draper, 2007).

1.3. Early to Middle Cambrian

Delamerian Orogeny: ca. 515 to 490 Ma

Geological and tectonic summary

The Delamerian Orogeny is poorly represented in North Queensland, partly reflecting the geochronological uncertainty of many of the units. The best evidence for this orogeny appears to be in the Greenvale region (metamorphic ages of ca. 520-510 Ma; Nishiya et al., 2003; Figures 9, 10) and in the Charters Towers region (metamorphic ages of ca. 495 Ma; Fergusson et al., 2007a). Potential Delamerian deformation events may occur in the Georgetown and Coen regions but geochronological control is absent. A number of deformations that could be interpreted as Delamerian have been shown recently, at least partly, to represent post-Delamerian extension (Fergusson et al., 2007a, b).

Geological history and Time-Space plot explanation

Greenvale region

- The Halls Reward Metamorphics have Cambrian metamorphic ages of ca. 520-510 Ma (Nishiya et al., 2003; Figures 9, 10), consistent with Delamerian deformation. Notably, Fergusson et al. (2007a) did not record evidence for Delamerian deformation in the nearby, pre-Delamerian, Oasis Metamorphics.
- Rocks of the Boiler Gully and Gray Creek Complexes appear to have similar deformation histories as the Halls Reward Metamorphics, and so the deformation observed in these complexes is inferred to be Delamerian in age. Recent Sm-Nd geochronology (D. Huston and R. Maas, unpublished data) suggest that the Grey Creek Complex may have an age of ~470 Ma, that is, postdates the Delamerian deformation. If correct, the same scenario would most likely apply to the Boiler Creek Complex also.

Georgetown region

- Widespread, north-south contractional(?), deformation and associated metamorphism (largely retrogressive) has poor age constraints in the eastern Georgetown region (Withnall et al., 1997a; Fergusson et al., 2007a; Figure 10), but according to Withnall et al. (1997a) is constrained to between ca. 970 Ma and early Palaeozoic.

Barnard region

- The Barnard Metamorphics record a deformation and metamorphic event (locally high-grade) that is not observed in the Early Ordovician granites (Garrad and Bultitude, 1999; Figure 10). This is the only time constraint.

Coen region

- Region-specific, deformation and associated metamorphic (greenschist or lower grade) events (Figure 10) with poor age constraints. According to Blewett et al. (1997), this deformation is constrained to between ca. 1550 Ma and Devonian (granite emplacement) for most of the Coen region, but between ca. 1130 Ma and Carboniferous for the Iron Range region (Sefton Metamorphics). The major fabric in the Sefton Metamorphics is east-west (Blewett et al., 1997).

Charters Towers region

- Fergusson et al. (2007b) document a ca. 495 Ma contractional deformation event with associated metamorphism in the Argentine Metamorphics (largely overprinted by slightly younger extension). Hutton et al. (1997) and Fergusson et al. (2007b) document similar deformation in the Charters Towers, Running River, and Cape River Metamorphics. Mafic and felsic intrusives of this age may also be present (Figure 9).

Georgina Basin

- Early Cambrian carbonate and siliciclastic rocks deposited in subtidal marine environments are generally restricted to the southern Georgina Basin (Walter et al., 1995; Ambrose et al., 2001; Kruse et al., 2002; Draper, 2007; Figure 10).
- Widespread Middle Cambrian sedimentation, representing the most extensive phase of deposition preserved in the basin (Southgate and Shergold, 1991; Draper, 2007; Figure 10). The Delamerian Orogeny had minimal impact in the Georgina Basin, with minor uplift and karstification, and a significant unconformity (below the Ninmaroo and Tomahawk Formations; Ambrose et al., 2001; Figure 10).

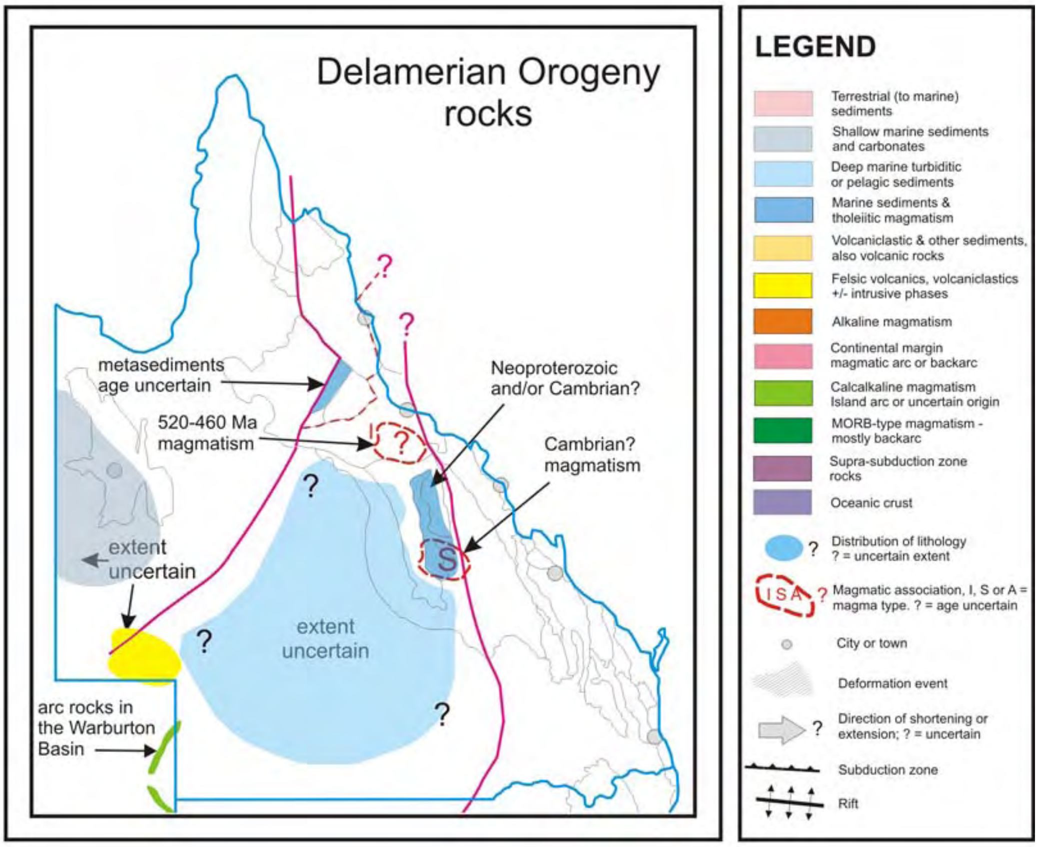

Figure 9. General distribution of Early to Late Cambrian (ca. 520 Ma to ca. 490 Ma), Delamerian cycle rocks in eastern Australia. Refer to text for discussion.

1.4. Middle Cambrian to earliest Silurian

Post-Delamerian to Benambran Orogeny: ca. 490 Ma to ca. 430 Ma

Geological and tectonic summary

The Middle Cambrian to earliest Silurian time period in North Queensland is dominated by three supracrustal successions and a major magmatic association:

- Lower to Middle Ordovician volcanic- or volcaniclastic-dominated assemblages with a calcalkaline signature, interpreted as backarc successions, e.g., Seventy Mile Range Group, Balcooma Metavolcanic Group, part of the Lucky Creek Metamorphic Group (Figures 10, 11).

- Deep water (turbiditic), dominantly quartz-rich sediments, locally with tholeiitic magmatic rocks, e.g., the Lucky Creek Metamorphic Group (Figures 10, 11).
- Calcalkaline volcanic and carbonate-dominated successions interpreted, in part, as continental or island arc successions, e.g., Everetts Creek Volcanics.
- Cambrian to Ordovician, mafic to felsic magmatic rocks – the Macrossan Province of Bain and Draper (1997) - are widely distributed throughout North Queensland, but best represented in the Charters Towers region. Magmatic ages range from ca. 490 Ma to ca. 455 Ma (e.g., Hutton et al., 1997; Figures 10, 11). The province is dominated by I-type and mantle-derived magmatism, although some S-types have been recorded.

The North Queensland region at this time has long been interpreted as a dismembered continental margin (e.g., Henderson, 1987). Many authors have suggested backarc, continental or island-arc affinities (e.g., Withnall et al., 1991, 1997b; Withnall and Lang, 1993; Henderson, 1986; Stolz, 1994), suggesting an environment not dissimilar to Lachlan Orogen rocks of the same age (e.g., Gray and Foster, 2004; Glen, 2005). Like the Lachlan Orogen, North Queensland rocks of this age are either quartz-rich sediments or volcanic-related rocks (Figure 11). Notably, however, unlike the Lachlan Orogen, there are north Queensland units, such as the Judea Formation (Withnall and Lang, 1993), which contain both quartz-rich marine sediments and volcanic rocks. Although the latter in the Judea Formation are tholeiitic, they do have geochemical signatures characterised by negative Nb anomalies (Withnall et al., 1997b) and so are consistent with primitive arcs. Their occurrence together with quartz-rich sediments suggests proximity between arc-related volcanism and craton-derived sedimentation.

Many of the North Queensland rocks were deformed in the Early Silurian (Figure 10) by a shortening event coupled with metamorphism – referred to as the Benambran Orogeny by Fergusson et al. (2007a). Evidence for this deformation is found in the Georgetown region where it is constrained by 430 Ma magmatic ages for syn-deformational I-type magmatism (Withnall et al., 1997a; Fergusson et al., 2007a). A similar deformation is recorded in the Charters Towers region, possibly ca. 440 Ma (Fergusson et al., 2007b). Deformation of this age appears to be largely absent in both the Hodgkinson and Broken River regions, although Fergusson et al. (2007a) suggested that island-arc terranes within the Camel Creek Subprovince (Broken River Province) - the Everetts Creek Volcanics and Carriers Well Formation – were accreted at this time. An angular unconformity recorded between the Judea Formation and Graveyard Creek Group may also relate to the Benambran Orogeny (I. Withnall, written commun., 2009). Contractional deformation is present within the Hodgkinson and Broken River regions but appears to be earlier – probably Late Ordovician (Figure 10). Garrad and Bultitude (1999) have suggested that there may be a time break between Ordovician and Silurian metasedimentary rocks in the Hodgkinson Province that corresponds to uplift (Benambran Orogeny) in the Georgetown region to the west.

Fergusson et al. (2007a, b) documented extensional deformation coupled with low-P high-T metamorphism, greenschist to amphibolite-facies, in both (interpreted) backarc successions in the Greenvale and Charters Towers regions (Figure 10). They dated these events at ca. 475 Ma and 480 Ma, but suggested extension was in operation from ca. 490 to 460 Ma. This metamorphism and extension was synchronous with granite emplacement, and most of the Macrossan Association magmatism is of this age.

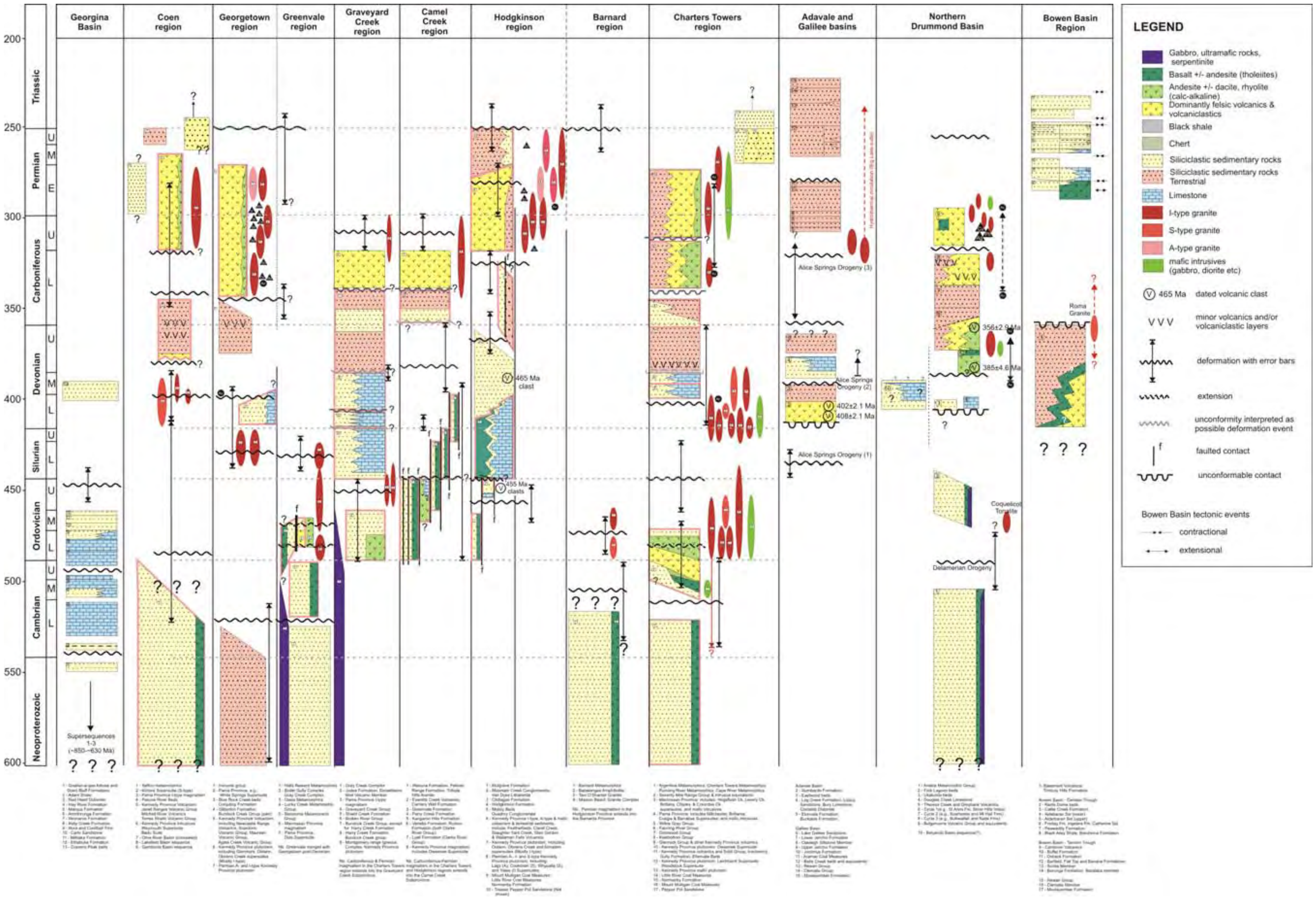

Figure 10. Late Neoproterozoic to Permian time-space plot for the north Queensland region, covering the North Queensland Orogen and Proterozoic basement to the west, and including the Georgina and younger basins. Refer to text for data sources and discussion. Regions are as outlined in Figures 2b, 3 and 4.

Importantly, the interpreted backarc volcanic rocks in the Charters Towers region and Greenvale Province have quite different orientations: ~east-west versus north-northeast–south-southwest, respectively (e.g., Bain and Draper, 1997). This clearly suggests either some later relative movement between the regions, due to deformation (e.g., Bell, 1980; Fergusson et al., 2007a), and/or perhaps the volcanism formed independently on different crustal fragments. Regardless, given a backarc origin for the volcanic rocks in the southern Charters Towers region, it is possible that Macrossan Association magmatism in the northern part of that region represents the actual magmatic arc (e.g., Henderson, 1980).

Geological history and Time-Space plot explanation

Greenvale region

- Metasedimentary to metavolcanic Lucky Creek Metamorphic Group and Balcooma Metavolcanic Group. Both groups include calcalkaline volcanics, although the Lucky Creek Metamorphic Group also contains tholeiitic rocks (Withnall et al., 1997a; Figures 10, 11). The Balcooma Metavolcanic Group is dated at ca. 470 to 480 Ma (e.g., Withnall et al., 1991). Age is uncertain for the Lucky Creek Metamorphic Group, but thought to be similar, at least in part, to the Balcooma Metavolcanic Group. Withnall et al. (1991) suggested that the calcalkaline volcanics were part of a volcanic arc, while Fergusson et al. (2007a) suggested a backarc environment. The latter is probably more consistent with similar interpretations for the Charters Towers area (Draper and Bain, 1997).
- Ordovician extension and related metamorphism and granite magmatism in the Greenvale region is dated at ca. 485 to 477 Ma (Fergusson et al., 2007a; Figure 10).
- Recent Sm-Nd dating (whole rock isochron) for the Grey Creek Complex suggests an age of ~470 Ma (D. Huston and R. Maas, unpublished data) for primitive (εNd ~8) mafic intrusions. If correct, this makes the complex younger than previously thought, and now of similar age to the Balcooma Metavolcanic Group. This suggests the complex probably represents primitive mafic melts intruded in a backarc setting. The same scenario would likely apply to the Boiler Gully Complex.
- Benambran age, east-west shortening and metamorphism, and interpreted associated syn-deformation I-type plutonism (Withnall et al., 1997a; Fergusson et al., 2007a). The granite magmatism has been dated at ca. 430 Ma (Withnall et al., 1997a; Figure 10) and is considered to be syntectonic. Recent geochronology, however, by Murgulov et al. (2007), in the Georgetown region, indicates some magmatism may extend to younger (post-Benambran) ages - ca. 418 Ma.

Georgetown region

- As for the Greenvale region, Benambran east-west shortening and metamorphism, and associated extensive syn- (to post-?) tectonic I-type granite magmatism dated at ca. 430 Ma (Withnall et al., 1997a; Murgulov et al., 2007; Figures 10, 11) is recorded in the Georgetown region. A second deformation event, tentatively dated at ca. 400 Ma (see next section), may also form part of the Benambran event (Withnall et al., 2007a).

Barnard region

- Macrossan Association S- and I-type magmatism, dated at ca. 485 and 464 Ma (Garrad and Bultitude, 1999; Figures 10, 11).
- Regional deformation and associated low- to possibly high-grade metamorphism with poor age constraints (Bultitude et al., 1997). The deformation event affects the local granites, implying a maximum age of ca. 460 Ma (Garrad and Bultitude, 1999).

Coen region

- Appears to record no definitive evidence of a Silurian deformational event. A poorly age-constrained deformation and associated metamorphic (greenschist or lower) event, constrained to between ca. 1130 Ma and Devonian (Blewett et al., 1997) may be of this age. Like the Georgetown region, deformation in the Coen region is associated with Pama Association magmatism. Unlike Georgetown, however, this deformation and magmatism is largely younger – ca. 407 Ma (post-Benambran) - based on magmatic ages (Blewett et al., 1997).

Charters Towers region

- The latest Cambrian(?) to largely Early Ordovician Seventy Mile Range Group consists of a lower succession of marine metasedimentary rocks (with little volcanic input) and an upper assemblage dominated by calcalkaline mafic to felsic volcanics and volcaniclastics (e.g., Henderson, 1986; Hutton et al., 1997; Figures 10, 11). The Group is commonly interpreted as forming in a backarc environment (e.g., Henderson, 1986; Stolz, 1994).
- Deformation and associated metamorphism occurs within the region, related to both extension (post-Delamerian) and younger north-south Benambran contractional deformation (Berry et al., 1992; Hutton et al., 1997; Fergusson et al., 2005, 2007; Figure 10).

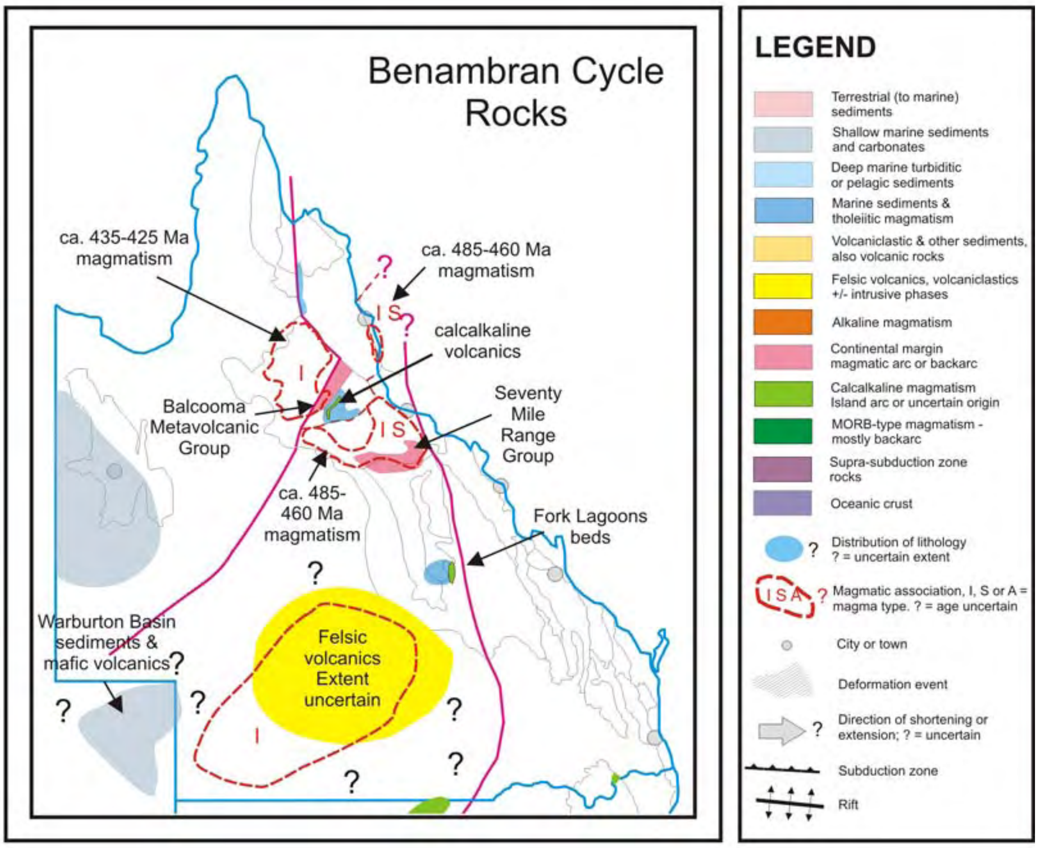

Figure 11. General distribution of latest Cambrian to Early Silurian Benambran (ca. 490 Ma – ca. 430 Ma) cycle rocks in Queensland. Refer to text for discussion.

- Magmatic rocks of the Macrossan Association (Figures 10, 11). In the Charters Towers region, these include granites of the widespread I-type Hogsflesh Creek and Lavery Creek Supersuites, as well as mafic intrusives. Hutton et al. (1997) suggested that the intrusives are of two ages – Late Cambrian to Early Ordovician, and mid Ordovician. Ages for the mafic intrusives are, in general, poorly constrained, and may be as young as Devonian.

Hodgkinson region

- Marine, quartz-rich, turbiditic sedimentary rocks with metabasalt occur in the Mulgrave Formation, preserved in fault-bounded blocks along the Palmerville Fault (Bultitude et al., 1997; Garrad and Bultitude, 1999; Figures 10, 11). These are considered to be Early Ordovician in age.
- Limestone and quartzofeldspathic deep water sedimentary rocks of Late Ordovician age are preserved in fault-bounded blocks along the Palmerville Fault (Bultitude et al., 1997; Garrad and Bultitude, 1999). Dacitic volcanic clasts in the Mountain Creek Conglomerate have been dated at ca. 455 Ma by Garrad and Bultitude (1999) who suggested correlation of these units with the limestone and volcanics of the Carriers Well Formation and Everett Creek Volcanics (Broken River region).
- Middle(?) Ordovician east-west shortening deformation. This deformation is only evident in the Early Ordovician(?) Mulgrave Formation (Garrad and Bultitude, 1999) and as such, is constrained to be older than Late Ordovician.

Graveyard Creek and Camel Creek regions

- Marine, quartz-rich, turbiditic sedimentary rocks, commonly with tholeiitic metabasalt, occur in both the Graveyard Creek and Camel Creek Subprovinces (Withnall and Lang, 1993; Withnall et al., 1997b; Figures 10, 11). Ages are generally poorly constrained but considered to be Ordovician (Withnall and Lang, 1993; Withnall et al., 1997b), although may extend into the Silurian. The Judea Formation is probably of Early Ordovician age (Withnall and Lang, 1993).
- Calcalkaline volcanics, volcaniclastics and limestone occur in both the Graveyard Creek and Camel Creek Subprovinces (Arnold and Fawckner, 1980; Withnall and Lang, 1993; Withnall et al., 1997b; Figures 10, 11). Ages range from Early Ordovician in the Graveyard Creek Subprovince, to Late Ordovician in the Camel Creek Subprovince. The calcalkaline rocks of the latter subprovince were suggested by Fergusson et al. (2007a) to represent island-arc remnants. A number of units appear to contain both quartz-rich marine sedimentary rocks and calcalkaline arc material (Withnall and Lang, 1993), suggesting if an arc was present then it was probably proximal.
- Minor sodic I-type granitic magmatism occurs in the Graveyard Creek Subprovince; it is considered to most probably be Ordovician in age (Withnall and Lang, 1993).
- As summarised by Arnold and Fawckner (1980) and Withnall and Lang (1993), the two subprovinces appear to have different structural histories (Figure 10). The Judea Formation (Graveyard Creek Subprovince) records subhorizontal, mélange-type deformation and low grade metamorphism, that is no younger than Late Ordovician (Withnall and Lang, 1993; Withnall et al., 1997b) and may be syn-sedimentary (e.g., Arnold and Fawckner, 1980). Withnall et al. (1997b) also record mélange-style deformation and low-grade metamorphism in the Camel Creek Subprovince. The age, however, is poorly constrained, and Withnall et al. (1997b) suggested much of this deformation occurred in the Devonian. This deformation may equate with similar aged deformation in the Hodgkinson Province (Figure 10).

Georgina Basin

- Following uplift and erosion associated with the Delamerian Orogeny, deposition recommenced with the Late Cambrian-Early Ordovician Tomahawk beds and laterally equivalent Ninmaroo Formation (Boreham and Ambrose, 2007; Figure 10).
- The Ordovician marine succession consists of limestones and dolostones deposited in a range of subtidal to supratidal environments with sandstones, siltstones and mudstones deposited in a range of high energy subtidal and shoreline environments (Ambrose et al., 2001; Kruse et al., 2002; Draper, 2007).
- Convergence-related uplift associated with the Alice Springs Orogeny occurred episodically from the Late Ordovician to the Late Devonian–Carboniferous (Haines et al., 2001). The

earliest record of the Alice Springs Orogeny, resulting in prolonged uplift and erosion at the end of the Middle Ordovician (Ambrose et al., 2001; Boreham and Ambrose, 2007), is recorded in the Georgina Basin with the deposition of the Ethabuka Sandstone (Figure 10; Late Ordovician Rodingan Movement ca. 450 Ma of Haines et al., 2001; Draper, 2007).

1.5. Middle Silurian to Middle-early Late Devonian

Post-Benambran to Tabberabberan Orogeny: ca. 430 Ma to ca. 380 Ma

Geological and tectonic summary

This time period in North Queensland is characterised by extensive marine sedimentation in the Hodgkinson and Broken River regions (along the eastern and southeastern margins of the Proterozoic Georgetown region), and also in the Charters Towers region (Figures 10, 12). Sedimentation includes marine siliciclastics and carbonates, along with locally abundant, tholeiitic mafic volcanics (Arnold and Fawckner, 1980). Sediment provenance is dominantly cratonic (e.g., Bultitude et al., 1997) but does include volcaniclastic material, some of which is older. Garrad and Bultitude (1999) record dacitic clast ages of 465 Ma in a conglomerate from the Hodgkinson Province.

Post-Benambran, Late Silurian to Early Devonian deposition is recorded within basins overlying the Thomson Orogen, e.g., Adavale Basin, largely in response to extension following orogeny (e.g., Olgers, 1972; Murray, 1994, 1997; Withnall et al., 1995; McKillop et al., 2005; Figure 10). These consist of marine and terrestrial sediments, of cratonic and/or volcanic provenance. They are associated with mafic and felsic volcanic rocks in the Anakie Inlier (Withnall et al., 1995), and felsic intrusives in the Thomson Orogen basement (e.g., Murray, 1994). Murray (1994) has suggested a continental setting.

Older (pre-Tabberabberan) deformation events, ca. 410-400 Ma, are recorded in the Georgetown, Coen and Charters Towers regions as well as in the Thomson Orogen basement, e.g., below the Adavale Basin. The Coen and Charters Towers deformation coincides with Pama Association magmatism in those regions. Bultitude et al. (1997) record a change in sedimentation in the Hodgkinson Province in the Late Lochkovian (ca. 412 Ma). Similarly, Withnall et al. (1997b) record a hiatus in sedimentation at this time in the Graveyard Creek Subprovince. Both Bultitude et al. (1997) and Withnall et al. (1997b) suggested that these changes were related to hinterland uplift. Notably, sedimentation appears to recommence at this time in the Charters Towers region. These ca. 410-400 Ma events most probably relate to the Bindian Orogeny. The latter is dated at ca. 420-410 Ma in the Lachlan Orogen (e.g., VandenBerg et al., 2000; Gray et al., 2003) and slightly younger in the Thomson Orogen (McKillop et al., 2005). Local folding and metamorphism, probably with associated felsic magmatism, also took place during the late Early Devonian in the Thomson Orogen. The timing of deformation is constrained by ca. 408 and 402 Ma undeformed volcanic rocks in the post-Bindian Adavale Basin (McKillop et al., 2005).

Apart from minor changes in sedimentation style and brief hiatuses, related to the Bindian Orogeny, deposition continued in the Hodgkinson and Broken River regions throughout the Tabberabberan cycle (Bultitude et al., 1997; Withnall et al., 1997b). Renewed extension, following the Bindian Orogeny, produced the Early to Late Devonian, terrestrial to shallow marine, Adavale Basin in the central Thomson Orogen (McKillop et al., 2005; Figures 2a, b), and the terrestrial to shallow marine sedimentation in the Burdekin Basin (Charters Towers region; Hutton et al., 1997). The Devonian Adavale Basin is a rift-related, predominantly non-marine basin, located inboard of a convergent plate boundary represented by silicic volcanic rocks of the New England Orogen (Remus and Tindale, 1988;

Scheibner and Veevers, 2000; Van Heeswijck, 2006). The Adavale Basin is thought to have formed in a continental setting, either as an intracontinental volcanic rift or an extensional basin (Murray, 1994; McKillop et al., 2005). According to Evans et al. (1990), following extension, the Adavale Basin became a foreland basin in the early Middle Devonian, with repeated basement thrusting from the southeast, causing deepening towards that direction and culminating in a major contractional orogeny in the mid Carboniferous. Felsic intrusive magmatism accompanied extension in the Thomson Orogen (e.g., Murray, 1994; Evans et al., 1990; Hutton et al., 1997). McKillop et al. (2005) suggest that extension may have been the result of more regional events such as subduction further to the east in the New England Orogen.

The geodynamic environment for the sedimentation in the Hodgkinson and Broken River regions is controversial. Tectonic models invoked for this part of North Queensland, to explain the sedimentation at this time, include backarc, forearc, and rifted continental margin models (see summaries in Arnold and Fawckner, 1980; Garrad and Bultitude, 1999). Arnold (in Arnold and Fawckner, 1980), Henderson et al. (1980) and Henderson (1987), amongst others, suggested that the Hodgkinson and Broken River Province sedimentation was part of a forearc and accretionary wedge. This model, however, has difficulties explaining the large areas of tholeiitic volcanism, especially in the Hodgkinson Province. The latter is more consistent with rift or backarc models (e.g., Fawckner in Arnold and Fawckner, 1980; Bultitude et al., 1997), although the volcanics could, perhaps, be interpreted as large accreted blocks (of oceanic crust). Resolution of the geodynamic environment has implications for the tectonic interpretation of the widespread Pama Association which consists of all the Silurian to Devonian magmatism in North Queensland (Bain and Draper, 1997). The Pama Association magmatism forms an extensive quasi-continuous belt around the Hodgkinson and Broken River Provinces, from Charters Towers in the south, north to Cape York (Figure 12). In forearc models, this belt is interpreted as the magmatic arc (e.g., Henderson, 1987), although, as pointed out by numerous authors, the chemistry of this magmatism, especially in the Coen region, is not consistent with that commonly found in magmatic arcs (e.g., Blewett et al., 1997). Pama Association magmatism is also diachronous. Well constrained magmatic ages range from ca. 430 Ma (syn-Benambran) in the Georgetown region, to ca. 425 to 405 Ma (and younger) in the Charters Towers region, to ca. 410 to 395 Ma in the Coen region. As pointed out by Champion and Bultitude (2003), these age differences are also matched by changes in geochemical signature. Notably, the early Pama magmatism (in the Georgetown region) does have geochemical signatures more consistent with arc magmatism. It is indeed possible, therefore, that the Hodgkinson (and Broken River) Province was in a forearc environment early (ca. 430 Ma), and then later evolved in a backarc environment (ca. 420-400 Ma and younger?).

The Tabberabberan Orogeny, as defined in the Lachlan Orogen, is constrained at ca. 385-375 Ma (e.g., VandenBerg et al., 2000; Gray and Foster, 2004; Glen, 2005), and appears to be just post-380 Ma (age of Mt Morgan Tonalite) in the New England Orogen (ca. 381 Ma; Golding et al., 1994; Yarrol Project Team, 1997, 2003). Deformation events of about this age in North Queensland are best represented in the Broken River and Hodgkinson provinces and also the Charters Towers region, where they include time breaks and slight angular unconformities (Withnall and Lang, 1993; Figure 10). Henderson (1987) suggested that this event resulted in the cessation of deep-marine sedimentation in the Camel Creek Subprovince in the Middle Devonian, and produced the angular unconformity observed in the Graveyard Creek Subprovince. Garrad and Bultitude (1999) record east to northeast thrusting and north-northwest-trending shear zones in the Hodgkinson Province. These authors suggested that these deformations were of Late Devonian age, possibly producing basin inversion. Although apparently slightly younger, these latter events probably equate with the Tabberabberan, especially given the strong commonalities between the Broken River and Hodgkinson Provinces, that is, it is probable that deep-water marine sedimentation ceased simultaneously in both. The Middle Devonian Tabberabberan Orogeny in the Thomson Orogen is either poorly developed or difficult to distinguish from other events (Withnall et al., 1995; Hutton et al., 1997). In the Adavale Basin, the orogeny appears to have resulted in an unconformity between terrestrial and overlying shallow marine sedimentary rocks, and a possible change to restricted basin conditions in the late Middle Devonian (McKillop et al., 2005).

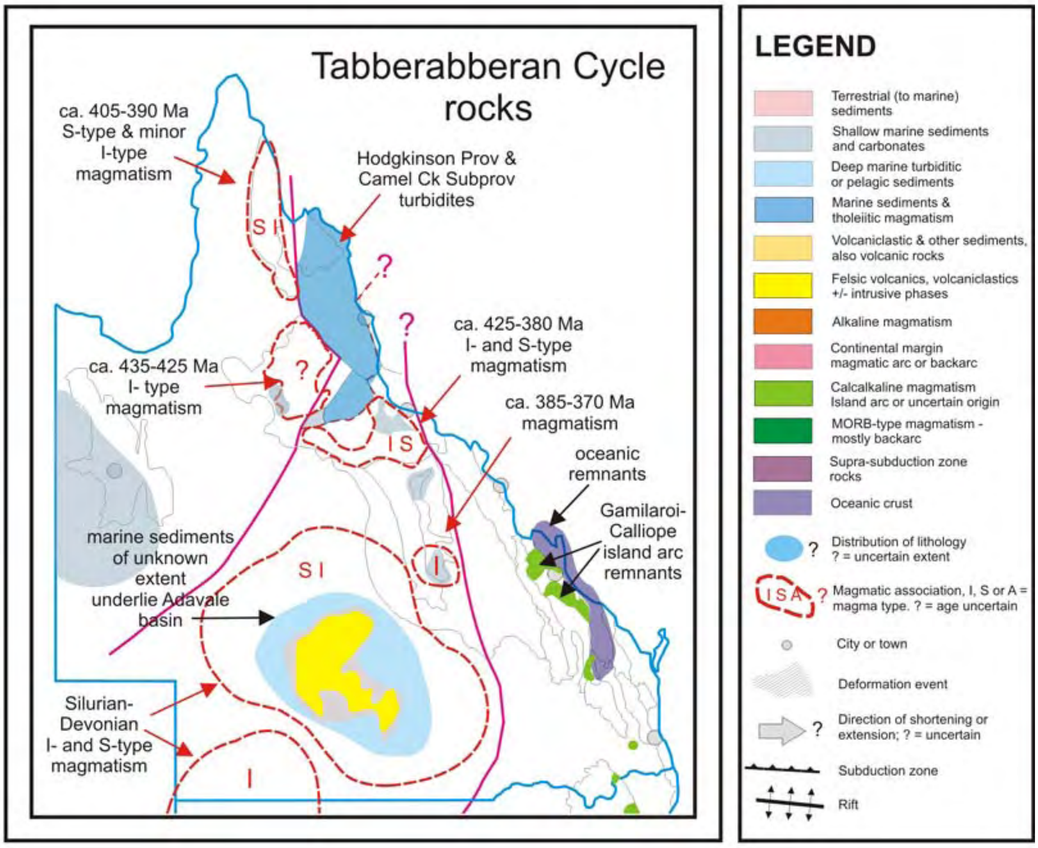

Figure 12. General distribution of Silurian to early Late Devonian (ca. 440 to 380 Ma), Tabberabberan cycle rocks in Queensland. Refer to text for discussion.

Geological history and Time-Space plot explanation

Georgetown (and Greenvale) region

- Isolated pockets of, largely Early Devonian, marine, and locally terrestrial, sediments and limestone occur within the Greenvale region (Withnall et al., 1997b).
- East-west shortening and greenschist metamorphism (Withnall et al., 1997a). This deformation is thought to relate to the Bindian Orogeny, is tentatively dated at ca. 400 Ma, as indicated by (reset) Rb-Sr and K-Ar ages (400-380 Ma) of older granites (Richards et al., 1966) and by Rb-Sr dating of Proterozoic metasedimentary rocks in the Georgetown region (Black et al., 1979). Although these ages could possibly relate to the 430 Ma Benambran event (Figure 10), the younger ages do, however, coincide with ages of lode Au mineralisation (410-400 Ma; Withnall et al., 1997a), and with extensive magmatism to the north in the Coen region.
- Pama Association magmatism in the Georgetown and Greenvale regions is thought to be largely syn-Benambran Orogeny in age, i.e., it predates the Tabberabberan cycle. Recent geochronology (Murgulov et al., 2007) indicates that the magmatism actually extends to younger ages, that is, ca. 418 Ma, and may, at least in part, be post-Benambran in age.
- Early Devonian shallow shelf to lagoonal sandstone, mudstone and limestone of the Conjuboy Formation unconformably overlying Oasis Metamorphics and Balcooma Metavolcanic Group (Withnall and Lang, 1993).
- Sandstone, siltstone, shale and limestone of the Blue Rock Creek beds were deposited in the Early Devonian on a shallow, muddy to siliciclastic shelf with local carbonate buildups, and unconformably overlie the Halls Reward Metamorphics (Withnall and Lang, 1993).

Barnard region

- Regional deformation and associated low to potentially high-grade metamorphism (Bultitude et al., 1997). This poorly constrained deformation event is bracketed between ca. 460 Ma and Permian (Garrad and Bultitude, 1999).

Coen region

- Voluminous, S-type-dominated, mostly felsic, magmatism of the Pama Association. Dominated by the S-type Kintore Supersuite (Figures 10, 12). Ages constrained between ca. 410 Ma and 395 Ma (Blewett et al., 1997).
- East-west shortening deformation and low-P high-T metamorphism (to upper amphibolite-facies) with some contemporaneous Pama Association magmatism – ca. 407 Ma (Blewett et al., 1997; Figure 10).
- East-west shortening and thrusting, which Blewett et al. (1997) equated with inversion of the Hodgkinson Province (Figure 10).

Charters Towers region

- Largely mixed siliciclastic marine sediments and carbonate successions of the Wilkie Gray and Fanning River Groups (Burdekin Basin; Draper and Lang, 1994; Hutton et al., 1997; Figures 10, 12). Although sedimentation in the Burdekin Basin essentially continues through to the Early Carboniferous, there is an unconformable contact and a significant change in sedimentation above the Fanning River Group (Hutton et al., 1997). Initiation of the Burdekin Basin - a backarc extensional basin (Draper and Lang, 1994) - occurred in the Early Devonian (Emsian). The onset of this rifting coincided with the youngest thermal event recorded in the Ravenswood Batholith of the Pama Association (Hutton, Rienks et al., 1994; Draper and Bain, 1997).
- Extensive magmatic rocks of the Pama Association. In the Charters Towers region, these include the widespread I-type Millchester Supersuite in the Ravenswood Batholith as well as I-type granitoids in the Reedy Springs Batholith. Ages are best constrained in the Ravenswood Batholith, where they range from ca. 425 Ma to ca. 405 Ma (Hutton et al., 1997). Similar ages appear to occur in the Reedy Springs and Lolworth batholiths, although the latter also include widespread younger (ca. 380 Ma) granites which include S-types (Hutton et al., 1997).
- Northeast to east-northeast faulting, with associated lode gold vein formation, ca. 400 Ma (e.g., Hutton et al., 1997).

Hodgkinson region

- Early Silurian to Early Devonian limestone, tholeiitic basalt and siliciclastic marine turbiditic sedimentary rocks of the Chillagoe Formation (Arnold and Fawckner, 1980; Garrad and Bultitude, 1999; Figures 10, 12).
- Extensive marine, largely siliciclastic, turbiditic sedimentary rocks – largely in the Hodgkinson Formation (Arnold and Fawckner, 1980; Bultitude et al., 1997; Garrad and Bultitude, 1999; Figures 10, 12), with minor tholeiitic metabasalts (Arnold and Fawckner, 1980). Upper and lower age limits are not well constrained but at least Early to Late Devonian in age (Garrad and Bultitude, 1999).
- Bultitude et al. (1997) record a change in sedimentation in the Hodgkinson Province in the late Lochkovian (ca. 412 Ma), which they suggested was related to hinterland uplift, that is, most probably related to the Bindian Orogeny.
- No deformation of Tabberabberan age appears to have affected the Hodgkinson Province as sedimentation continues throughout the Late Silurian and Devonian, although Arnold and Fawckner (1980) suggested syn-sedimentary mélange formation.

Camel Creek and Graveyard Creek regions

- In the Camel Creek Subprovince, continuation of marine, quartzose, turbiditic sedimentation, locally with tholeiitic metabasalt and limestone, possibly to as young as Early Devonian (Arnold and Fawckner, 1980; Withnall and Lang, 1993; Figures 10, 12).
- Largely mixed marine (to locally fluviatile) siliciclastic and carbonate successions (Withnall and Lang, 1993; Withnall et al., 1997b) in the Graveyard Creek Subprovince (Figure 12). This sedimentation appears to have continued through the Silurian to the Early Devonian, although Withnall and Lang (1993) record time breaks between the Graveyard Creek Group and Shield Creek Formation and Broken River Group (Lochkovian and early Emsian; Figure 10). The Lochkovian hiatus may relate to the Bindian Orogeny, as Withnall et al. (1997b) suggested these changes were related to hinterland uplift.
- Minor deformation is recorded in the eastern part of the Graveyard Creek Subprovince (e.g., Arnold and Fawckner, 1980). This deformation produced regional tilting and mild angular unconformities, and is constrained to be older than Early Frasnian (Withnall et al., 1997b; Figure 10). The Camel Creek Subprovince records two events – east-directed thrusting and folding, and southeast-northwest shortening with accompanying subgreenschist-facies metamorphism (Arnold and Fawckner, 1980; Withnall and Lang, 1993). As suggested by Withnall et al. (1997b), ages for these events are constrained between Early Devonian and Early Carboniferous, but both deformations may equate with that recorded in the Graveyard Creek Subprovince. Arnold and Fawckner (1980) suggested this deformation was Late Devonian in age. Henderson (1987) suggested that the southeast-northwest deformation affected both subprovinces, shutting off deep marine sedimentation in the Camel Creek Subprovince, and producing the angular unconformity in the Graveyard Creek Subprovince.

Georgina Basin

- Uplift and erosion at the end of the Middle Ordovician was succeeded much later by Devonian deposition of a mixture of sandstone, conglomerate and limestone of predominantly fluviatile origin (Dulcie Sandstone and its lateral equivalent, the Craven Peak beds) (Figure 10; Ambrose et al., 2001).
- The main phase of widespread syntectonic deposition related to the Alice Springs Orogeny occurred in the late Early Devonian (Haines et al., 2001). The uppermost conglomeratic part of the Cravens Peak beds is interpreted to be synorogenic with the Pertnjara-Brewer Movement (Alice Springs Orogeny; Draper, 2007).

Belyando Basin

- The rift-sag Belyando Basin, underlying the western Drummond Basin, is postulated to contain marine Devonian rocks (Draper et al., 2004; Figure 10).

Drummond Basin (Anakie region)

- The intracratonic Drummond Basin, a thick succession of continental sediments and volcanics, with marine interbeds at the base, developed in central Queensland between the Late Devonian and the early Carboniferous. In the Early Devonian, isolated marine deposition of siliciclastics (Ukalunda beds) was deposited on top of metasedimentary rocks in the Anakie Inlier, and granites and volcanics of the central Thomson Orogen basement (Olgers, 1972; Grimes et al., 1986; Murray, 1994; Figures 10, 12). The Ukalunda beds, a mixture of sandstone, siltstone, shale, limestone and minor conglomerate of Emsian age (corals and conodonts; Grimes et al., 1986; Brock and Talent, 1993), form basement to the Drummond Basin (Figure 10; Grimes et al., 1986; Hutton et al., 1998; Draper et al., 2004).

Adavale Basin

- Continental felsic volcanic and volcaniclastic rocks (acid crystal tuffs, ignimbrite, minor mafics) of the Gumbardo Formation formed during initial rifting and half graben formation in the late Early Devonian (Evans et al., 1990; McKillop et al., 2005; Figures 10, 12), possibly in response to subduction in the east (New England Orogen). The volcanics have been dated as late Early Devonian (Pragian to early-mid Emsian 402 Ma, 408 Ma; Gumbardo-1 and Carlow-1 wells; McKillop et al., 2005), and were deposited in fluvial or fluvial-lacustrine conditions (McKillop et al., 2005). A significant unconformity occurred in the early Eifelian, between the Eastwood beds and Log Creek Formation (McKillop et al., 2005).

- From the Early Middle Devonian deposition was dominated initially by fluvial sedimentation, but a subsequent marine incursion resulted in the development of a mixed carbonate-siliciclastic regime, with the carbonate rocks deposited in the more rapidly subsiding parts of the half grabens (Log Creek Formation, Lissoy Sandstone) (McKillop et al., 2005; Figure 10).
- In the Middle Devonian, the supply of clastics diminished, and a marine transgression produced a phase of shallow marine carbonate deposition (e.g., Bury Limestone) from the Early to Middle Devonian (McKillop et al., 2005).
- A major hiatus in the Adavale Basin is indicated in the late Middle Devonian (mid-late Givetian). The Alice Springs Orogeny (2) (~Tabberabberan Orogeny) is thought to have produced an unconformity between terrestrial and overlying shallow marine sedimentary rocks, and may have triggered the onset of restricted basin conditions in the late Middle Devonian (mid Givetian), which produced a sabkha environment with associated halite deposition (Figure 10; McKillop et al., 2005).

Bowen Basin

- Devonian(?) deep marine (turbidite?) metasedimentary rocks of the Timburry Hills Formation form basement to the Bowen Basin (Figure 10). The quartz-rich sandstone unit is uniform in character and suggests a continental source (Murray, 1997). A Devonian age is constrained by the presence of plant material and emplacement of the Roma Granites close to the Devonian-Carboniferous boundary (Murray, 1997).

1.6. Late Devonian to Early Carboniferous

Post-Tabberabberan to Kanimblan Orogeny: ca. 380 Ma – ca. 350 Ma

Geological and tectonic summary

This time period in North Queensland produced terrestrial and lesser amounts of marine sedimentation across all regions, best preserved in the lower successions of the Bundock, Clarke River and Burdekin basins of the Broken River and Charters Towers regions (Figures 10, 13). During the Late Devonian to Early Carboniferous, widespread deposition of volcanolithic sediments in association with lavas and pyroclastics occurred in the Burdekin, Bundock, Clarke River, Pascoe River and Gilberton basins (Figure 16). Minor andesitic volcanism is recorded in the Georgetown region (Withnall et al., 1997a).

At the same time, both terrestrial and marine sedimentation, often with accompanying volcanism, also occurred in the Thomson Orogen (e.g., Drummond Basin; Figures 10, 13), largely in response to intracratonic extension following the Tabberabberan Orogeny, but also backarc extension behind a Late Devonian to Early Carboniferous arc in the New England Orogen (e.g., Neef and Bottrill, 1991; Murray, 1994; Withnall et al., 1995, 2009c; Henderson et al., 1998; Draper et al., 2004; McKillop et al., 2005; Gilmore et al., 2007). This backarc extension resulted in rifting and initiation of the Drummond Basin in the Late Devonian (Henderson et al., 1998). The Drummond Basin consists of a thick succession of continental and lesser amounts of marine sediments and volcanics (Olgers, 1972; Hutton et al., 1998; Henderson et al., 1998). These have been subdivided into three major tectonostratigraphic cycles, separated by unconformities (e.g., Olgers, 1972). The lowermost cycle – cycle 1 (latest Devonian to Early Carboniferous) – consists of syn-rift related volcanic rocks and associated marine to terrestrial volcaniclastic sediments (Olgers, 1972; Henderson et al., 1998). Johnson and Henderson (1991) and De Caritat and Braun (1991) recognised that Cycle 1 was associated with active backarc crustal extension, reflected by a rift architecture of the basin floor. Early Carboniferous Cycle 2 rocks consist of a thick succession of terrestrial (and local marine) sediments which reflects an abrupt end to volcanism and a switch to a cratonic provenance (Olgers, 1972). Cycle 3 rocks (also Early Carboniferous) reflect a return to volcanism, which continued episodically with terrestrial sediments (Olgers, 1972). A thermal subsidence phase for the Drummond Basin was recognised by De Caritat and Braun (1991) as being represented by Cycles 2 and 3.

Felsic, and lesser amounts of intermediate and mafic, magmatism accompanied extension episodically throughout this cycle. This includes intrusive and related extrusive magmatism in the Anakie Inlier, (syn? to) post-Tabberabberan Orogeny, but prior to formation of the Drummond Basin. During the Late Devonian to Early Carboniferous, the Thomson Orogen also experienced regionally extensive felsic magmatism (e.g., Murray, 1994). Early Carboniferous granites were emplaced into Thomson Orogen basement and the Warburton Basin (e.g., Murray, 1994). During initial Late Devonian-Early Carboniferous backarc extension, silicic magmatism at this time was spread over a broad region in the Drummond Basin and may be related to episodes of silicic magmatism in the New England Orogen (e.g., Bryan et al., 2004). This magmatism largely predates the widespread Kennedy Association magmatism in Charters Towers and further north, although volcanism in cycle 3 of the Drummond Basin appears to correlate with volcanism in the upper parts of the Burdekin, Bundock and Clarke River basins in the Charters Towers and Broken River regions of North Queensland (e.g., Henderson et al., 1998; Figures 10, 13, 16).

Subsequent deformation is minor in nearly all areas, with the exception of the Hodgkinson Province and Graveyard Creek Subprovince (Broken River region). In the former, significant east-west shortening and further basin inversion occurred (Garrad and Bultitude, 1997; Figure 10), whilst in the latter deformation produced folds with northeast-trending axial surfaces (Withnall et al., 1997b). This deformation and time period immediately pre-dates the commencement of the voluminous and very widespread extrusive and intrusive magmatism of the Kennedy Association. The tectonic environment for the Kanimblan cycle in north Queensland is poorly constrained. The possible continuation of largely Tabberabberan Cycle turbiditic sedimentation in the Hodgkinson Province suggests a similar geodynamic regime to the previous cycle, that is, deposition in either a backarc or forearc environment (e.g., Arnold and Fawckner, 1980; Garrad and Bultitude, 1999).

The Early to ?Middle Carboniferous Kanimblan Orogeny, or Alice Springs Orogeny (3) as it is known in the Thomson Orogen, produced slight contraction in the Drummond Basin and regional-scale folding and subsequent erosion in the Adavale Basin (e.g., Olgers, 1972; Neef, 2004). Deformation in the Drummond Basin is recorded by an unconformity between the Drummond and Galilee Basin (Scott et al., in prep.).

Geological history and Time-Space plot explanation

Georgetown region (and Greenvale Province)

- Sporadic belts and blocks of terrestrial sediments (Withnall et al., 1997a; Withnall and Lang, 1993). Rocks are mostly non-volcanic but include locally abundant, andesite lavas (Withnall et al., 1997a).
- Poorly constrained, very open, north-south contractional deformation, thought to be mid Carboniferous in age - pre ca. 335 Ma (Withnall et al., 1997a).

- Quartz-rich to feldspathic sandstone and polymictic conglomerate of Late Devonian through to early Carboniferous age of the extensional Gilberton Basin (Figure 16). These continental fluvial sedimentary rocks are equivalent in age to successions in the Bundock, Clarke River and Burdekin basins (Withnall et al., 1997; Draper and Bain, 1997; Figure 16).

Barnard region

- Regional deformation and associated low to potentially high-grade metamorphism (Bultitude et al., 1997). This poorly constrained deformation event is bracketed between ca. 460 Ma and Permian (Garrad and Bultitude, 1999).

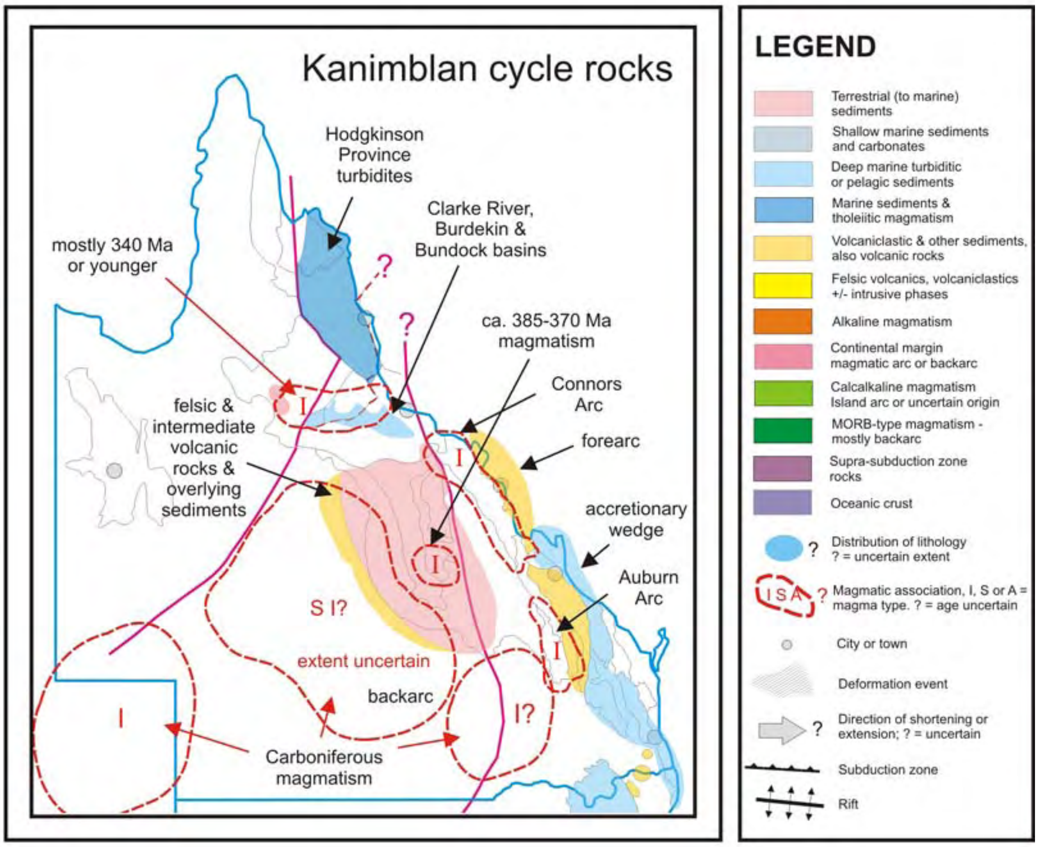

Figure 13. General distribution of Late Devonian to Early Carboniferous Kanimblan cycle (c. 380 Ma to c. 350 Ma) rocks in Queensland. Refer to text for discussion. The New England Orogen continued in the arc, forearc and accretionary wedge configuration until the Late Carboniferous.

Pascoe River Basin – Coen Region

- Widespread terrestrial sediments (>1000 km^2), including carbonaceous siltstone, shale, tuff, tuffaceous sandstone and thin coal beds of the Late Devonian to Early Carboniferous Pascoe River beds were deposited in fluvial to lacustrine environments (Pascoe River Basin; McConachie et al, 1997; Withnall et al., 1997c; Figures 10, 16). Volcanic detritus has been recorded in the succession, and it appears to include a lower volcanic unit of uncertain age (McConachie et al., 1997). The basin may have formed in response to the commencement of plate interaction and subduction off eastern Australia (McConachie et al., 1997).
- Poorly constrained minor deformation, thought to be Carboniferous and/or Permian in age (Blewett et al., 1997). McConachie et al. (1997) indicate that the Pascoe River beds are

deformed, suggesting that deformation was post-Early Carboniferous (Kanimblan?), and pre-dated granite intrusion (ca. 285 Ma).

Charters Towers Region

- Terrestrial and marine sedimentation, including volcaniclastic rocks in the Dotswood and Keelbottom Groups (Burdekin Basin; Figures 10, 16), with a number of transgressive-regressive cycles in the upper part (Early Carboniferous), e.g., Draper and Lang (1994), Hutton et al. (1997). A backarc extensional setting is favoured, with a continental arc to the east (Draper and Bain, 1997). Initial rift infill in the Burdekin Basin was followed by a thermal relaxation phase in the Early Carboniferous (Tournaisian).
- No apparent deformation of this age is recorded.

Hodgkinson Province

- Continuation of the extensive marine, largely siliciclastic, turbiditic sediments of the Hodgkinson Formation (Arnold and Fawckner, 1980; Bultitude et al., 1997; Garrad and Bultitude, 1999; Figures 10, 13). Upper age limits not well constrained but at least Late Devonian, and possibly very earliest Carboniferous in age (Garrad and Bultitude, 1999).
- Locally distributed marine and terrestrial to marginal marine sediments, thought to be mostly Early Carboniferous in age (Garrad and Bultitude, 1999).
- Significant Early to mid Carboniferous deformation (predates Late Carboniferous magmatism) which, according to Davis (1994) and Garrad and Bultitude (1999), produced significant east-west shortening. Bultitude et al. (1997) included north-south shortening during this period. Garrad and Bultitude (1999) suggested the latter was Permian in age. The north-south orientation, however, suggests the deformation is probably Carboniferous and equates to the Alice Springs Orogeny in Central Australia.

Broken River Province

- In both subprovinces, there are well developed successions of terrestrial and lesser marine sedimentation (Figures 10, 13). A very thick succession of mainly continental sediments and minor tuffs was deposited in the Bundock Basin in the Late Devonian and Early Carboniferous (Bundock Creek Group; Figure 10) (Withnall et al., 1997). Similarly, deposition began in the latest Devonian in the extensional Clarke River Basin (Figure 16), continuing into the Early Carboniferous. The basin developed on the Camel Creek subprovince, and contains Early Carboniferous fluviatile and minor shallow marine rocks and includes some ignimbrite and other volcaniclastic rocks (Venetia, Ruxton and Lyall Formations) (Withnall et al., 1997, Clarke River Region; Figure 10) formed in an intracratonic extensional setting (Draper and Bain, 1997). Sediments are mostly of cratonic provenance, though do have some volcaniclastic input (Withnall and Lang, 1993; Withnall et al., 1993). This style of sedimentation changes in the Visean with the commencement of widespread volcanism (Figure 10).
- The main deformation – a slaty cleavage forming event (I. Withnall, written commun., 2009) - within the Graveyard Creek Subprovince is suggested to have occurred at the end of this cycle possibly even as young as Visean given that the Bundock Basin sediments and underlying Graveyard Creek Group are similarly deformed (Withnall et al., 1997a). No significant deformation is recorded in the Camel Creek Subprovince as indicated by only weak deformation in the Clarke River Group (Withnall et al., 1997b).

Drummond Basin (Anakie region)

- The Drummond Basin was initiated during this cycle – probably in the latest Late Devonian (Henderson et al., 1998). The basin consists of a thick succession of continental sediments and volcanics, with minor marine interbeds towards the base of the succession (Olgers, 1972;

Hutton et al., 1998; Henderson et al., 1998; Figures 10, 13). The basin unconformably overlies the Early Devonian Ukalunda beds, the Retreat Batholith, and the older rocks of the Anakie Inlier (Olgers, 1972; Withnall et al., 1995). The Drummond Basin has been subdivided into three major tectonostratigraphic cycles, separated by unconformities (e.g., Olgers, 1972; Hutton et al., 1998; Scott et al., in prep.). The lowermost cycle – Cycle 1 (latest Devonian to Early Carboniferous) – consists of syn-rift related volcanics rocks - andesitic, dacitic and dominant rhyolitic lava, ignimbrite and tuff - and associated marine to terrestrial volcaniclastic sediments (Olgers, 1972; Henderson et al., 1998). Henderson et al. (1998) indicated that volcanism and deposition initiated first in the north. Early Carboniferous Cycle 2 rocks consist of a thick succession of terrestrial (and local marine) sediments – mostly quartz-rich sandstone, conglomerate and mudstone - which reflects an abrupt end to volcanism and a switch to a cratonic provenance (Olgers, 1972). Cycle 3 rocks (also Early Carboniferous) reflect a return to volcanism, reflected by volcaniclastic sediment, tuff and conglomerate (Olgers, 1972). Volcanism continued episodically throughout this cycle, although the upper parts are dominated by terrestrial sediments (Olgers, 1972). Most authors advocate an extensional backarc environment for the Drummond Basin (e.g., Henderson et al., 1998), with the arc situated within the New England Orogen.
- The Drummond Basin ceased development during mild contraction associated with a far-field expression of the Kanimblan Orogeny (de Caritat and Braun, 1992; Van Heeswijck, 2006), resulting in an angular discordance between rocks of the Drummond Basin and the overlying Late Carboniferous Bulgonunna Volcanic Group (dated at ~305-294 Ma; Black, 1994; Figure 10).

Adavale Basin

- During the Late Middle to Late Devonian, the accumulation of sandstones and shales of the Etonvale Formation is attributed to a second phase of foreland thrusting, followed by fluvio-lacustrine red-bed sandstones of the Buckabie Formation (Evans et al., 1990; McKillop et al., 2005; Figure 10).
- The entire Adavale Basin was deformed and deeply eroded by a third stage of foreland thrusting in the Carboniferous (Quilpie Orogeny of Finlayson et al., 1990). Termination of deposition and basin deformation occurred during Alice Springs Orogeny (3), with development of regional-scale folds followed by widespread erosion (McKillop et al., 2005).

1.7. Early Carboniferous to latest Permian

Post-Kanimblan to Hunter-Bowen Orogeny: ca. 350 Ma to 250 Ma

Geological and tectonic summary

From the Late Carboniferous to Early Permian, eastern Australia was dominated by extension and rifting, which initiated extensive intracratonic basin formation (e.g., Cooper and Galilee basins; Bain and Draper, 1997; Korsch et al., 1998; Korsch et al., 2009a), as well as extensive magmatism.

Continental extension in the Early Permian to Middle Triassic led to formation of the Bowen (and Gunnedah) basins in a backarc setting (Korsch et al., 2009a, b). Basins such as the Galilee and Cooper also formed on the craton but further west at this time (Draper and McKellar, 2002). Cessation of Drummond Basin sedimentation and uplift of the Anakie Inlier occurred in response to the mid Carboniferous Kanimblan Orogeny (Fenton and Jackson, 1989; de Caritat and Braun, 1992). Uplift of the Anakie Inlier during this contractional event may have led to the development of a flexural topographic depression to the west, which was subsequently filled by the lower Galilee Basin succession (de Caritat and Braun, 1992). The Bowen Basin formed in an extensional environment east of and overlying the Drummond Basin during or almost immediately following Late Carboniferous batholith emplacement (Esterle and Sliwa, 2000). Isotopic dating of Carboniferous and Permian igneous rocks by Allen et al. (1998) suggests a continuation of extension and arc conditions from the Late Carboniferous to Early Permian and indicates that the Bowen Basin formed in a backarc setting west of the arc in the New England Orogen. This is supported by the presence of bimodal and andesitic volcanics at the base of the Bowen Basin which suggest that Late Carboniferous to Early Permian crustal thinning was related to Bowen Basin rifting (Green et al., 1997b; Withnall et al., 2009c). By the Early Permian, the Bowen Basin, together with the Gunnedah and Sydney Basins, formed the 'East Australian Rift System' (Korsch et al., 1998; Korsch et al., 2009a).

Although sedimentation had ceased in the Drummond Basin by the Late Carboniferous, extension in west and central Queensland during the late Carboniferous to Early Permian led to widespread terrestrial sedimentation in the intracratonic Cooper and Galilee basins (de Caritat and Braun, 1992; Draper, 2002a, b; 2004; Figure 10). A connection between the Cooper and Galilee basins meant that the two basins experienced related sediment deposition (Scott et al., 1995). In the east, troughs created during early north-east to south-west extension of the Bowen Basin provided depocentres for initial terrestrial sedimentation and contemporaneous volcaniclastics (Green et al., 1997a; Korsch et al., 1998). Sedimentation in the Bowen Basin was contiguous with the Gunnedah Basin and both unconformably overlie the Drummond Basin (Green et al., 1997a; Scott et al., in prep).

The Galilee Basin extensively overlies the Drummond Basin and has been variously considered to be a pull-apart basin related to shearing along the eastern margin of the Drummond Basin (Evans and Roberts, 1980), a pericratonic basin (Veevers et al., 1982) or a foreland basin (De Caritat and Braun, 1992; Van Heeswijck, 2006). The basin was probably initially extensional, followed by subsidence driven by dynamic platform tilting (de Caritat and Braun, 1992; Waschbusch et al., 2009). The development of the Galilee Basin was partly synchronous with the formation and infill of the Bowen Basin. According to Van Heeswijck (2004, 2006), the Galilee Basin commenced as a foreland basin, expressing continuity with the late-stage development of the underlying Drummond Basin. Thermal subsidence related to the rift phase of the Drummond Basin continued as an influence in addition to foreland subsidence (Van Heeswijck, 2004).

This period in North Queensland is characterised by the commencement of the widespread and voluminous extrusive and intrusive Kennedy Association magmatism, plus associated, mostly minor sedimentation (Figures 10, 14). As documented by a number of authors (e.g., Richards et al., 1966; Champion and Bultitude, 2003), this magmatism is crudely diachronous, commencing earlier in the Georgetown, Broken River and Charters Towers regions (Figures 10, 14) in the Visean (ca. 340-335 Ma), and ranging to mid Permian in the Hodgkinson Province. There are also accompanying changes in geochemistry. Magmatism in the mid to Late Carboniferous is almost exclusively I-type in nature, with some mantle-derived magmatism. In the Early Permian, magmatism switched to A- and I-type in the Georgetown and western Hodgkinson regions, and to S- and I-type in the central and eastern Hodgkinson (Champion and Bultitude, 2003).

Magmatism of this age is also present further south in the Anakie, Drummond and Bowen regions, and also in the Warburton Basin (e.g., Gatehouse et al., 1995; Hutton et al., 1998; Sliwa and Draper, 2005). This activity is the same age as Kennedy Association magmatism in northern Queensland (Bain and Draper, 1997). I-type plutons (e.g., Joe De-Little Granite, Billy-can Creek Granite) intruded the Anakie region and were comagmatic with silicic volcanics and caldera complexes of the Bulgonunna Volcanic Group (Oversby et al., 1994; Hutton et al., 1998).

There are at least two deformations during this time period recorded in North Queensland. There is a widespread but minor north-south contraction, thought to be mid to Late Carboniferous in age, and commonly equated to the Alice Springs Orogeny, found in the Broken River, Hodgkinson and Georgetown regions (Withnall et al., 1997a, b; Bultitude et al., 1997; Figure 10). In addition, there is a more significant deformation in the Early Permian. This penetrative east-west shortening deformation is best documented in the Hodgkinson Province (e.g., Davis, 1994; Davis et al., 1996; Garrad and Bultitude, 1999; Figure 10). The Late Permian is characterised by east-west shortening deformation, especially in the Hodgkinson and Barnard provinces (Garrad and Bultitude, 1999). This deformation is equated with the Hunter-Bowen Orogeny.

The tectonic regime for this region is not well understood. Magmatism of the Kennedy Association, although dominated by crustal input, is generally thought to be broadly arc-related, possibly backarc (e.g., Champion and Bultitude, 2003). This is consistent with the New England Orogen, which at this time, was characterised by a convergent margin environment, alternating between extension and contraction (e.g., Van Noord, 1999).

Late Carboniferous (to Middle Triassic) deposition occurs throughout North Queensland in several isolated basins. The most complete record of sedimentation is in the Bowen and Galilee basins, which occur in the southernmost portions of North Queensland. The Lakefield Basin is the largest basin entirely within North Queensland. There are small Late Carboniferous and Early Permian basins in the Charters Towers and Clarke River regions, while isolated Late Permian basins occur further north (Withnall et al., 1997c; Bain and Draper, 1997).

Late Carboniferous deposition was restricted to isolated small basins (Sybil Group, Ellenvale beds, Insolvency Gully Formation and Silver Valley Conglomerate). The only exception is the Galilee Basin, which contains a considerable thickness of late Carboniferous fluvial deposits, although these deposits are restricted to the Kooburra Trough. Elsewhere in North Queensland, volcanics and intrusives of the Kennedy Association were being erupted and emplaced (Withnall et al., 1997; Bain and Draper, 1997).

Widespread infilling of intracratonic basins continued throughout the Permian and into the Triassic. Fluvial and lacustrine systems were associated with extensive swamps in the Cooper and Galilee basins, which resulted in the continuous deposition of plant-rich material suitable for coal generation (Cowley, 2007; Figure 10). In the Late Permian, coastal swamps formed in the subsiding Bowen Basin leading to an accumulation of extensive coal deposits (Shaw, 2002; Figure 10). Sedimentation in the Bowen, Cooper and Galilee basins continued throughout the Permian until the Middle Triassic (Scott et al., 1995; Bain and Draper, 1997; Green et al., 1997b; Draper, 2002a, b).

At this time, sedimentary basins experienced the Hunter-Bowen Orogeny (e.g., Harrington and Korsch, 1985; Korsch et al., 2009a, b), which is proposed to have extended from the Middle Permian to the Middle or Late Triassic (ca. ~265 Ma to ~230 Ma; Korsch et al., 2009a, b). The New England Orogen was thrust westward during this event, which resulted in tectonic loading and subsidence in the Bowen and Gunnedah basins. The tectonic regime of these basins switched from initial extension to contractional in the mid-Permian (Korsch et al., 2009a, b). In the mid to Late Permian, large volumes of volcaniclastic material were shed from the volcanic arc and deposited in the adjoining Bowen Basin during foreland loading (Green et al., 1997a). A well-developed mid Permian unconformity in the Bowen, Galilee and Cooper basins marks a change in tectonic regime (Bain and Draper, 1997). In the Bowen Basin, this change is characterised by crustal extension and volcanic eruption (e.g., Lizzie Creek Volcanics) in the Early Permian, below the unconformity. Above this unconformity, contractional tectonics commenced and influenced sedimentation in the basin (Bain and Draper, 1997; Korsch and Totterdell, 2009).

In the Late Triassic, a contractional event resulted in uplift and erosion, and the cessation of deposition in the Galilee, Cooper and Bowen basins (Apak et al., 1997; Korsch et al., 1998). This widespread event was felt across eastern Australia and also resulted in folding and uplift of parts of the Drummond Basin (Fenton and Jackson, 1989). Overall, the Permian-Triassic sedimentary successions underwent reactivation on existing structures, and both sedimentary and thermal subsidence (Draper and McKellar, 2002).

The Hunter-Bowen Orogeny is best developed in the southernmost part of North Queensland where the Bowen Basin, which was a foreland basin during the Late Permian and Early to Middle Triassic, was folded in the Middle to Late Triassic. Late Permian coal measures and Triassic fluvial sediments of the Galilee Basin were also deformed in the Middle and Late Triassic (Bain and Draper, 1997). The mid-Triassic end-phase of the Hunter-Bowen Orogeny also deformed the northern Drummond and Galilee basins. This episode post-dated deposition in the Galilee Basin and is represented by thrust faults and related folds that were propagated through the entire stratigraphy of the Drummond and Galilee basins (Van Heeswijck, 2006). Ongoing crustal contraction during the Hunter-Bowen Orogeny resulted in inversion of the Drummond and Galilee basins with the development of large-scale thrusts and associated fault bend anticlines (Johnson and Henderson, 1991; Van Heeswijck, 2006).

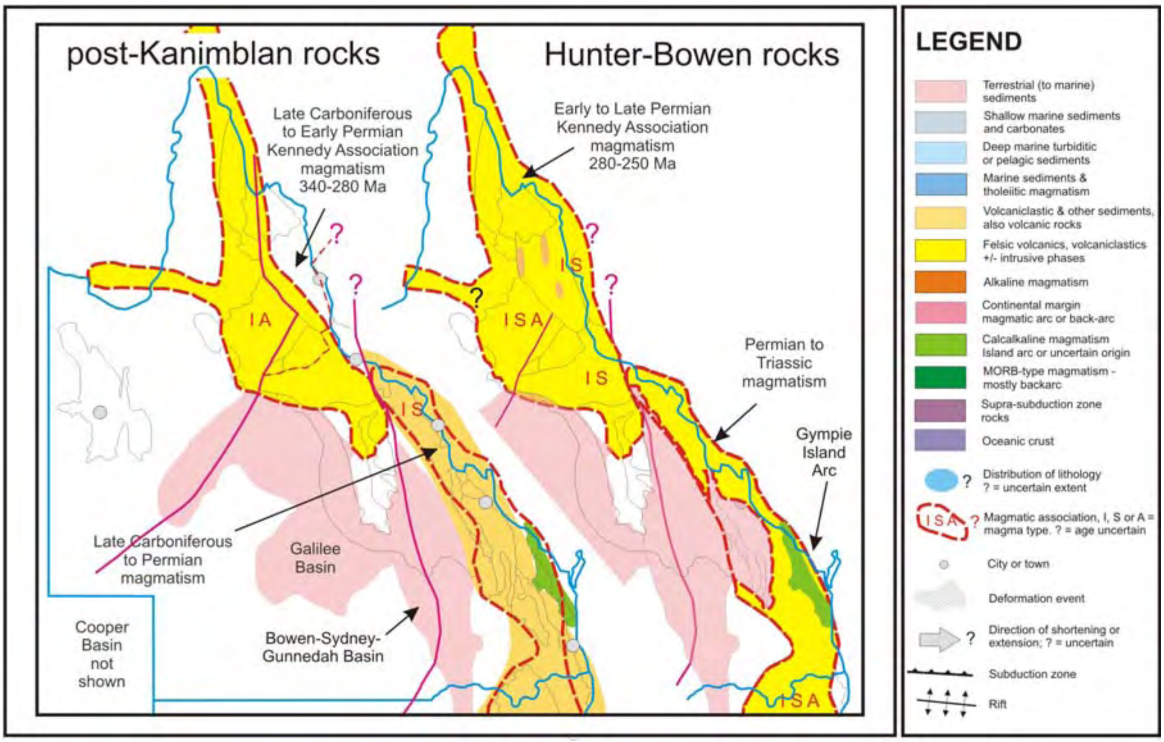

Figure 14. General distribution of Early Carboniferous to mid Permian rocks and early Late Permian to Middle-Late Triassic rocks of the Hunter-Bowen cycle in Queensland. Refer to text for discussion. The configuration shown for the New England Orogen reflects the latter (Late-Carboniferous and younger) parts of the cycle. Prior to this, the New England Orogen consisted of a continuation of the magmatic arc, forearc and accretionary wedge, as for the Kanimblan cycle (see Figure 13).

Geological history and Time-Space plot explanation

Georgetown (and Greenvale) region

- Mid-Carboniferous to Early Permian voluminous extrusive and intrusive magmatism of the Kennedy Association. Magmatism ranges in age from ca. 340 Ma to ca. 275 Ma (e.g., Withnall et al., 1997a; Figures 10, 13). It is mostly felsic, but includes minor mafic and intermediate products. Magmatism is dominantly I-type but includes widespread but generally small volumes of A-types (e.g., Champion and Bultitude, 2003). The I-type magmatism shows a broad decrease in age from ca. 340 Ma in the southwest to ca. 280 Ma in the northeast, e.g., Richards et al. (1966), Champion and Bultitude (2003). The A-types, where dated, however, are typically younger, ca. 290-275 Ma (Withnall et al., 1997a; Champion and Bultitude, 2003), and appear to occur across the region. Magmatic rocks of this age are extensively mineralised.

- Minor, dominantly terrestrial, sedimentation is associated with volcanic complexes.
- Poorly defined, east-west contractional deformation, thought to be Late Permian in age and equated with the Hunter-Bowen Orogeny (Withnall et al., 1997a).
- Various Late Carboniferous to Early Permian I- and A-type felsic to intermediate volcanic units (e.g., Pratt and Reamba volcanics; Scardons Volcanic Group 289±2 Ma, Newcastle Range Volcanic Group 329-283 Ma, Galloway Volcanic Group 290±3 Ma, Maureen Volcanic Group, Cumberland Range Volcanic Group, Butlers Volcanic Group ~330 Ma, Agate Creek Group) in the Georgetown Area, and I-type intermediate volcanics of the Mount Little Volcanic Group in the Croydon Area (Withnall et al., 1997).

Barnard Province

- Permian S-type, and less common, I-type Kennedy Association magmatism (Bultitude et al., 1997; Garrad and Bultitude, 1999).
- Regional deformation and associated low (to high?) grade metamorphism (Bultitude et al., 1997) related to the Hunter-Bowen Orogeny. This event strongly deforms Early Permian granites and so must postdate ca. 280 Ma (Garrad and Bultitude, 1999).

Coen Region

- Late Carboniferous to Early Permian Kennedy Association magmatism (extrusive and intrusive). Contains (intermediate to) felsic I- and A-types from ca. 310 Ma (in the Torres Straits; von Gnielinski et al., 1997) to Middle Permian (ca. 275 Ma, Blewett et al., 1997; Figures 10, 14).
- Permian terrestrial sediments, including coal, in the concealed Olive River Basin (McConachie et al., 1997; Figure 16). Drillhole data indicates the basin unconformably overlies the Pascoe River Basin, metamorphic basement, presumed early Permian volcanics and the Weymouth Granite (McConachie et al., 1997).
- Poorly constrained Carboniferous to Permian(?) deformation and low-grade metamorphism (Blewett et al., 1997). Both east-west and younger north-south deformations occur. The latter is most consistent with events equated to the Alice Springs Orogeny, and as such is probably early-mid Carboniferous in age. Younger events may be present; for example, McConachie et al. (1997) record unconformities above and below the Olive River Basin.
- Eruption of late Permian Volcanics adjacent to the Mitchell River in the southeastern Coen Region (Draper and Bain, 1997).
- Deposition of Permian to ?Triassic siliciclastic plus carbonaceous and tuffaceous sediments of the Lakefield Basin overlying Proterozoic rocks of the Yambo Subprovince (Wellman, 1995). Basin initiation by crustal extension possibly followed by thermal subsidence related to the Laura Basin (McConachie et al., 1997).

Clarke River region

- Late Carboniferous to Early Permian non-marine sandstones, siltstones and minor conglomerates of the Wade beds deposited on Clarke River Group. The Wade beds are of similar age to sediments in the Galilee and Sybil basins (Withnall et al., 1997b, Clarke River region).

Charters Towers region

- Terrestrial sedimentation and basaltic to felsic volcanics of the Early to mid Carboniferous Glenrock Group (Hutton et al., 1997). The Glenrock Group has a calcalkaline, subduction related geochemical signature (Withnall et al., 1997) and was most likely deposited during a renewed phase of rifting (Hutton, Draper et al., 1994). Of similar age (ca. 340-330 Ma) are comagmatic rhyolitic volcanism and felsic granites of the Oweenee Supersuite (Hutton et al., 1997), as well as other unrelated granites.
- Late Carboniferous to Early Permian felsic volcanism of the Kennedy Association and terrestrial sediments (Figure 14). These rocks appear to unconformably overlie the Early to mid Carboniferous Glenrock Group and other similar aged volcanics.
- Late Carboniferous to mid Permian mainly felsic I-type granites and associated (minor) mafic intrusives, of the Kennedy Association. Hutton et al. (1997) indicated magmatism broadly youngs in age from ca. 310 Ma in the west to ca. 265 Ma in the east. Younger magmatism has transitional A-type characteristics.
- Hutton et al. (1997) suggested a relatively stable backarc setting for the Kennedy Association magmatism with a dominant extensional environment throughout this period. The recognition of a potential unconformity between the Early to mid Carboniferous volcanics and overlying rocks may indicate some Kanimblan Orogeny effects.
- Deposition of Late Carboniferous to Early Permian intermediate to felsic volcanic, and volcanolithic and lithic sedimentary rocks, including the Sybil Group (Sybil Graben; Figure 16), the Ellenvale beds (Reid River Graben) and the Insolvency Gully Formation (Hutton et al., 1997).

Hodgkinson Province

- Extensive I- and A-type Kennedy Association extrusive and intrusive magmatism, and minor terrestrial sediments, concentrated in the western and southern part of the Hodgkinson Province (Champion and Bultitude, 2003; Figure 14). The I-types have the greatest age range - ca. 320 Ma to ca. 275 Ma (Garrad and Bultitude, 1999). The A-types are Permian (ca. 290 to 275 Ma; Garrad and Bultitude, 1999). The I-type intrusives, in particular are extensively mineralised.
- Permian S-type, and less common, I-type Kennedy magmatism in the eastern half of the Hodgkinson Province (Bultitude and Champion, 1992; Champion and Bultitude, 1994; 2003; Figure 14; Figures 10, 16). Magmatism appears to young to the northeast and east, from ca. 280 Ma to ca. 260 Ma and potentially younger (Richards et al., 1966; Garrad and Bultitude, 1999).
- Locally distributed, largely terrestrial sediments and coal measures of late Permian age (Normanby Formation, Little River Coal Measures, Mount Mulligan Coal Measures; Garrad and Bultitude, 1999; Figure 10).
- Regional (syn-granite emplacement) deformation (ca. 275-280 Ma; Figure 10), documented by Davis (1994). According to Davis (1994), the deformation, which produced north-south fabrics, was strongly partitioned and so is variably developed across the Province. This age corresponds closely to that of A-type magmatism in the western Hodgkinson Province and Georgetown region, which is commonly interpreted as being emplaced in an extensional environment.
- Significant Late Permian to Early Triassic transpressional(?) deformation and greenschist metamorphism thought to be related to the Hunter-Bowen Orogeny (Garrad and Bultitude, 1999; Figure 10). Bultitude et al. (1997) document K-Ar age resetting in granites ca. 250 Ma in age.
- Minor Triassic terrestrial sediments, which, at least locally, overlie older Permian rocks with an angular unconformity (Garrad and Bultitude, 1999; Figure 10).

Broken River Province

- Visean and younger terrestrial sedimentation and felsic volcanics in the upper parts of the Bundock and Clarke River Groups (Withnall and Lang, 1993; Withnall et al., 1997b). These rocks equate with the Glenrock Group in the Charters Towers region, though appear to lack the mafic-intermediate rocks found in the latter (Withnall and Lang, 1993; Withnall et al., 1997b; Hutton et al., 1997).
- The margins of the province shares similar Kennedy magmatism to that documented for the Hodgkinson and Charters Towers regions.

Drummond Basin and northern Anakie Inlier (Anakie region)

- Eruption of the dominantly felsic Bulgonunna Volcanic Group in the Late Carboniferous to Early Permian(?) (ca. 305 Ma; Hutton et al., 1998). The Group is dominated by felsic extrusives including rhyolite, ignimbrite and minor related sediments (Olgers et al., 1972; Hutton et al., 1998). The group unconformably overlies the Mount Wyatt Formation (northern Drummond Basin; Olgers et al., 1972).
- Late Carboniferous comagmatic, and Permian multiphase intrusions, smaller plutons and dykes occur on the margins of the Bulgonunna Volcanic Group, and have also intruded the Drummond Basin and Anakie Inlier (Olgers et al., 1972; Hutton et al., 1998; Figures 10, 14). Recorded ages range from ca. 308 Ma to ca. 287 Ma (Hutton et al., 1998; Scott et al., in prep).
- Regional Middle Triassic (255-230 Ma) east-west contraction resulted in folding, thrusting, sinistral strike-slip movement and erosion (Olgers, 1972; Murray, 1990; Johnson and Henderson, 1991).

Bowen Basin

- Late Carboniferous to Early Permian eruption of the basaltic to rhyolitic Combarngo and Camboon Volcanics may be related to initial rifting and formation of the Bowen Basin (Green et al., 1997b). Bimodal compositions suggest they were erupted in a continental backarc or continental margin arc setting (Green et al., 1997b; Withnall et al., 2009c).
- Eruption of the Late Carboniferous to middle Early Permian Lizzie Creek Volcanic Group, including the basaltic and andesitic Mount Benmore Volcanics and volcaniclastic rocks, rhyolite and dacite, prior to deposition of the Back Creek Group (e.g., Sliwa and Draper, 2005; Withnall et al., 2009c. Figures 10, 14).
- Early Permian sediments of the Reids Dome beds were deposited in alluvial plain to lacustrine environments within the developing depocentres of the Taroom and Denison troughs (Shaw, 2002; Figure 10).
- The Bowen Basin developed in an extensional setting in the Early Permian, firstly with volcanics followed by marine and non-marine deposition. During basin subsidence, widespread deposition of marine sediments of the upper Back Creek Group occurred (Shaw, 2002).
- Towards the end of the Permian, peat-forming wetlands and associated fluvial systems led to the development of extensive coal measures (Shaw, 2002; Figure 10).
- The onset of the Hunter-Bowen Orogeny is believed to correspond to a major unconformity surface within the Middle Permian Aldebaran Sandstone (Figure 10; Denison Trough area; e.g., Stephens et al., 1996; Korsch et al., 1998). This event resulted in the development of a foreland phase in the Bowen Basin.
- Uplift of the eastern arc in the Late Permian, resulted in shedding of large quantities of volcanolithic alluvial sediments and terrestrial deposition of the Early Triassic Rewan Group and the Gunnedah Basin equivalent, the Digby Formation (Green et al., 1997a; Shaw, 2002). This event led to marine conditions contracting to the central western part of the basin.

- Middle Triassic terrestrial (lacustrine) deposition of quartz-rich sandstone in the Clematis Group reflects a change in sedimentary source from the eastern arc to the uplifted craton in the west (Fielding et al., 1990).
- Middle Triassic fluvial and lacustrine deposition of the uppermost Moolayember Formation (Figure 10). Volcanic sediments are present in the succession and most likely originated from a volcanic arc source located in the east (Green et al., 1997a).
- Middle to late Triassic uplift and folding from regional contraction, resulted in a termination of deposition, followed by erosion and peneplanation (Bain and Draper, 1997; Green et al., 1997).

Galilee Basin

- Late Carboniferous to Early Permian terrestrial (fluvial) sediment deposition of the glacial Joe Joe Group and Early Permian Aramac Coal Measures (Scott et al., 1995; Figure 10).
- The lowermost unit of the Galilee Basin is the Late Carboniferous-Early Permian Joe Joe Group (basal Lake Galilee Sandstone, and overlying Jericho and Jochmus Formations; Figure 10), dominated by siliciclastic sandstones, volcaniclastic and fluvioglacial sediments. According to Van Heeswijck (2006), the geometry of the Jericho Formation reflects a foreland regime and that of the Jochmus Formation marks the waning of foreland basin development. Early Permian equivalents of the Galilee Basin include the Wade beds in the Charters Towers region, and sediments in the Sybil and Reid River grabens (Bain and Draper, 1997).
- Mid Permian tectonic quiescence marks a mid-stage of basinal development reflected in a regionally developed paraconformity and deposition of a basinwide coal measure sequence (Aramac Coal Measures) related to eustatic sea level rise over a stable substrate (Van Heeswijck, 2004).
- A hiatus marked by a disconformity below the Late Permian Betts Creek beds signals the cessation of subsidence driven by extension. For the southern Galilee Basin this disconformity occurs at the base of the Colinlea Sandstone and is also represented within the Aldebaran Sandstone of the Bowen Basin (Elliott, 1993). This hiatus is synchronous with an uplift event recognised in the New England Orogen (Holcombe et al. 1993) and represents a far-field expression of an early phase of Hunter-Bowen orogenesis that had an influence on relative sea level change in the Galilee and Bowen basins (Van Heeswijck, 2006).
- Late Permian terrestrial sediment and coal deposition (Colinlea Sandstone, Bandanna Formation; Betts Creek beds) occurred in a major fluvial system with associated peat swamps (Scott et al., 1995; Figure 10).
- The upper part of the Galilee succession represents a mild foreland phase of basin development, matching the history interpreted for the Bowen Basin (Fielding et al., 1995; Van Heeswijck, 2004), associated with the Hunter-Bowen Orogeny. The Late Permian-Early Triassic Rewan Group, Clematis Group and Moolayember Formation, predominantly consisting of sandstones and argillaceous sediments, are common to both basins (Van Heeswijck, 2006).
- A late Triassic contractional event resulted in folding and erosion of part of the Galilee Basin sequence prior to the deposition of the Eromanga Basin (Bain and Draper, 1997).

Lakefield Basin (Coen Region)

- Mid- Permian to ?Triassic sedimentary rocks, mainly interbedded sandstone, siltstone and conglomerate containing carbonised pollen of Permian age, and volcanics underlying the western part of the Laura Basin (Hawkins and Williams, 1990; Wellman, 1995a, b) formed through crustal extension, possibly in association with thermal sag of the Laura Basin (McConachie et al., 1997). Sedimentary rocks of the Normanby Formation, Little River Coal Measures and Mount Mulligan Coal Measures of the Hodgkinson Province are considered likely equivalents (see below; Wellman, 1995a, b). The eroded upper portion of the Lakefield

Basin may be of Triassic age; the time interval between the end of Lakefield Basin deposition and the start of Laura Basin sedimentation is Middle? Triassic to Middle Jurassic (Figure 10; Wellman, 1995a, b).

Gamboola Basin (Coen Region)

- An Early Permian (?) age for sedimentary(?) rocks of the concealed Gamboola Basin (Figures 10, 16). There is no information on the sedimentary succession, but is inferred to have been contemporaneous with the Lakefield Basin and to have formed by strike slip movement along the Gamboola Fault Zone (Wellman, 1995a, b; Withnall et al., 1997c; Draper and Bain, 1997).

1.8. Mesozoic

Triassic to Cretaceous - 250 Ma – ~65 Ma

Geological and tectonic summary

A depositional hiatus between the Middle Triassic to Early Jurassic in North Queensland was followed by a period of widespread fluvial and marine sedimentation in the Carpentaria, Eromanga and Laura basins in the Early Jurassic to mid Cretaceous (McConachie et al., 1997; Figures 15, 16). Originally, these basins probably covered more than 50% of the land area, because the Carpentaria and Laura Basins were contiguous during deposition, and isolated outcrops of Jurassic rocks are present in the Georgetown and Clarke River regions (McConachie et al., 1997).

The Eromanga Basin crops out in the southwestern portion of North Queensland and passes laterally into the Carpentaria Basin (over the Euroka Arch to the north), and unconformably overlies rocks of the Georgina and Galilee basins (Figures 15, 16). The Carpentaria Basin underlies most of the Gulf of Carpentaria and Carpentaria Lowlands regions and rests mainly upon an erosional surface of deformed Proterozoic rocks. McConachie et al. (1990) subdivided the Carpentaria Basin into four sub-basins on the basis of variations in lithology, provenance, thickness and diachronism. These complexities are not discussed here (refer to McConachie et al., 1990), but a number of broad depositional events can be identified. The Georgetown area contains Mesozoic rocks, with terminology relating to either the Eromanga or Carpentaria basin, or both (Draper, in Withnall et al., 1997c).

The Laura Basin is an equant intracratonic basin on the eastern side of Cape York Peninsula (Figures 15, 16). The basin overlies the late Paleozoic Lakefield Basin (Figure 16), Proterozoic metamorphic and Paleozoic igneous rocks of the Coen region, and deformed metasedimentary rocks of the Hodgkinson Province (Hawkins and Williams, 1990). The Laura Basin is believed to have been continuous with the Carpentaria Basin (over the Kimba Arch) during much of the time of basin fill.

The Mesozoic basins of northern Queensland all underwent a similar evolution. Subsidence was controlled by dynamic platform tilting (Waschbusch et al., 2009), a mechanism which supports the earlier suggestions of Gallagher (1990), de Caritat and Braun (1992) and Russell and Gurnis (1994). Fluvial deposition in the Eromanga Basin began in the Early Jurassic. By the Late Jurassic, fluviolacustrine deposition was more widespread in the Eromanga Basin, while in the southern Carpentaria Basin, Middle Jurassic deposition was restricted to isolated basins. Marine deposition occurred in the western Carpentaria Basin and marginal marine conditions were present in the Laura Basin (Draper and Bain, 1997). In the Late Jurassic and earliest Cretaceous, deposition of transgressive shoreline and nearshore sediments occurred throughout all three basins. While maximum transgression resulted in widespread marine deposition followed by several regressions and transgressions and an influx of volcanic detritus in Early Cretaceous times, several episodes of volcanic detritus also occurred at specific times in the Jurassic (Reid et al., 2009; Figure 17). A contractional event in the Cenomanian ended deposition, which was followed by uplift, folding and erosion (Draper, in Withnall et al. 1997c).

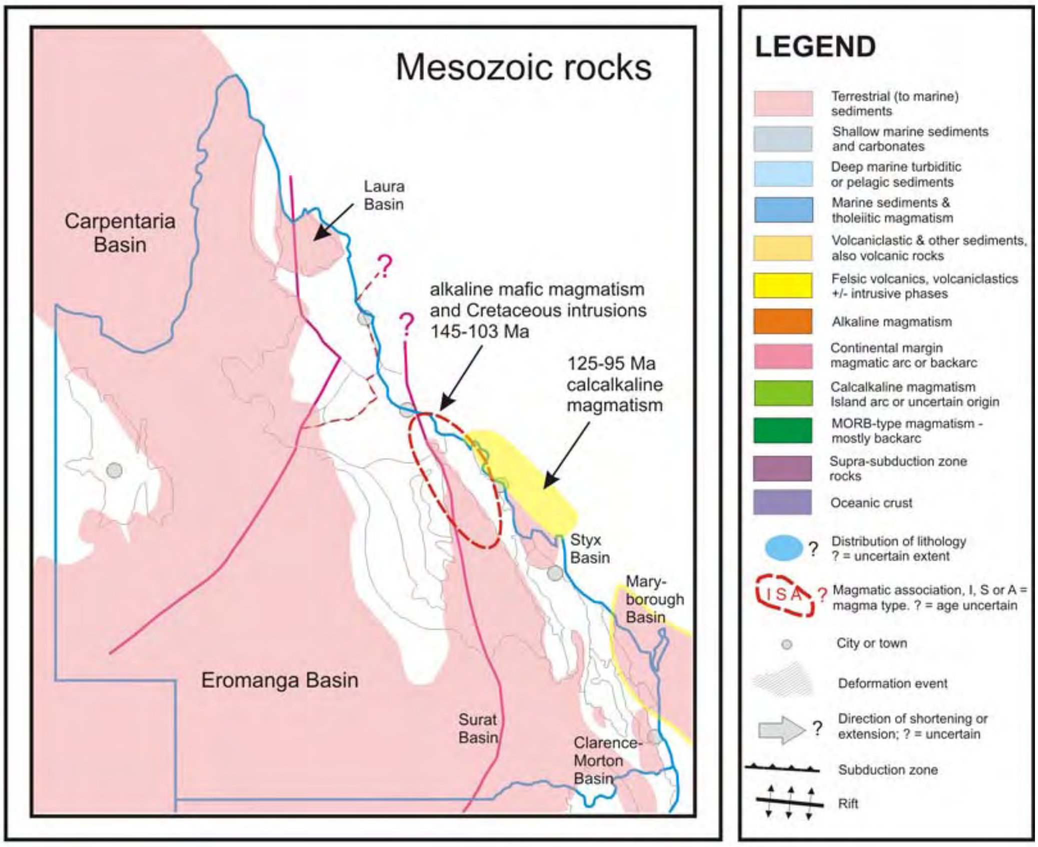

Figure 15. General distribution of Mesozoic rocks (~250 Ma - ~65 Ma) in North Queensland. Refer to text for discussion.

Volcanic rifts with bimodal suites of rocks form the Whitsunday Volcanic Province, part of an intermediate to silicic high-K calcalkaline volcanic belt, ranging in age from 125 Ma to 95 Ma (Bryan et al., 1996, 1997, 2000). Ignimbrite on the coast near Mackay is dated at ~138 Ma and is similar to rocks on Brampton Island (Withnall et al., 2009c). Onshore, Cretaceous intrusions ranging in age from 145 Ma to 103 Ma are found predominantly in the Bowen area (Allen and Chappell, 1996), with some extending as far north as Townsville. These Cretaceous volcanics are the expression of a continental extensional event (ca. 125-95 Ma Whitsunday Event, e.g., Korsch et al., 1998), part of Gondwana supercontinent breakup associated with the onset of rifting in the Tasman and Coral seas, and their ages coincide with the period of rapid subsidence and the timing of volcanolithic influx in the Eromanga, Carpentaria and Laura basins (Draper and Bain, 1997). Although having a calcalkaline signature, the volcanics are considered extensional in origin, being part of a rift system extending along the east coast of Australia, for some 2500 km or more along eastern Gondwana, with their chemistry inherited from an arc-like basement (Ewart et al., 1992; Bryan et al., 1996, 1997, 2000). Continental extension continued through to seafloor spreading (at ca. 84 Ma with the opening of the Tasman Sea in the south; the generation of new sea floor off Queensland starting at ca. 65 Ma; Veevers et al., 1991). A major contractional event (~95-90 Ma Moonie Event of Korsch et al., 1998) in the early Late Cretaceous took place within this overall extensional regime (see below; Korsch et al., 2009a, b), and sedimentation in the Eromanga, Carpentaria and Laura basins effectively ceased.

Geological history and Time-Space plot explanation

Hodgkinson Province

- Late Permian to Triassic Mt Mulligan Coal Measures and Pepper Pot Sandstone (Figure 10; Bultitude et al., 1996a) including coal seams, sandstone and conglomerate deposited in a mature, continental environment (lacustrine, meandering alluvial complex, estuarine; Bultitude et al., 1997).
- Late Permian fluvial deposition of the Little River Coal Measures in a half graben along the Palmerville Fault (Bultitude and Draper in Withnall et al., 1997).

Charters Towers region

- Early Cretaceous granite intrusion (K-Ar age of 129 Ma; Trezise et al., 1989) west-southwest of Townsville of unknown extent, thought to represent an extension of the Cretaceous granite suites intruding the Bowen Basin and Connors Arch (NEO) to the south (Allen and Chappell, 1996), suggested to be the products of rifting associated with the formation of the Tasman and Coral seas (Allen et al., 1998).

Eromanga Basin

- Subsidence controlled by dynamic platform tilting (Waschbusch et al., 2009) of much of eastern Australia initiated the Eromanga Basin and continental sedimentation began in the Early Jurassic (Questa, 1990). Fluvial quartz-rich sandstones (Hutton Sandstone) infilled valleys on an unconformity surface (Figure 17; Smart and Senior, 1980). Continental fluvial, lacustrine and deltaic successions were accumulated until the Late Jurassic (e.g., Hooray Sandstone), but ceased just prior to the southern breakup of the Australian continent from Antarctica (Green et al., 1992).
- The development of paralic conditions throughout the Eromanga Basin in the Late Jurassic to Early Cretaceous reflects the transgression of a northern seaway by early Aptian time, with marine conditions prevailing through much of the Cretaceous (Draper, 2002a) The Cadna-owie Formation, a paralic sequence of sandstones and siltstones with foraminifera, represents the transition between continental conditions and marine conditions (Figure 17; Gray et al., 2002).
- The Rolling Downs Group was deposited in two transgressive-regressive cycles in the Aptian. The first cycle deposited muds and silts of the Wallumbilla Formation in a transgressive sea, which receded by the Early Albian (Smart and Senior, 1980). This regressive phase is marked by the appearance of significant volcanic detritus of andesitic origin (Exon and Senior, 1976; Smart and Senior, 1980). The onset of volcanogenic sedimentation in the Rolling Downs Group near the beginning of the Aptian provides evidence for the major Whitsunday volcanic event starting at ~125-120 Ma (Bryan et al., 1997). The second transgression produced carbonaceous and carbonate facies of the Toolebuc Formation, deposited under shallow, low energy marine conditions (Figure 17; Questa, 1990).
- Regression and increased subsidence in the Cenomanian led to the deposition of a thick, non-marine succession (i.e., Winton Formation, Rolling Downs Group; Questa, 1990).
- After deposition of the Winton Formation, the Eromanga Basin was deformed by a widespread contractional event in the early Late Cretaceous (Hoffmann, 1989; Korsch et al., 1998), succeeded by weathering and erosion (Figure 17). This deformation is constrained by the Cenomanian Winton Formation and the overlying Lake Eyre Basin of Paleocene age (Drexel and Priess, 1995; Draper, 2002a), and corresponds to the Moonie Event of Korsch et al. (1998), recognised in the Bowen, Surat and Maryborough basins.

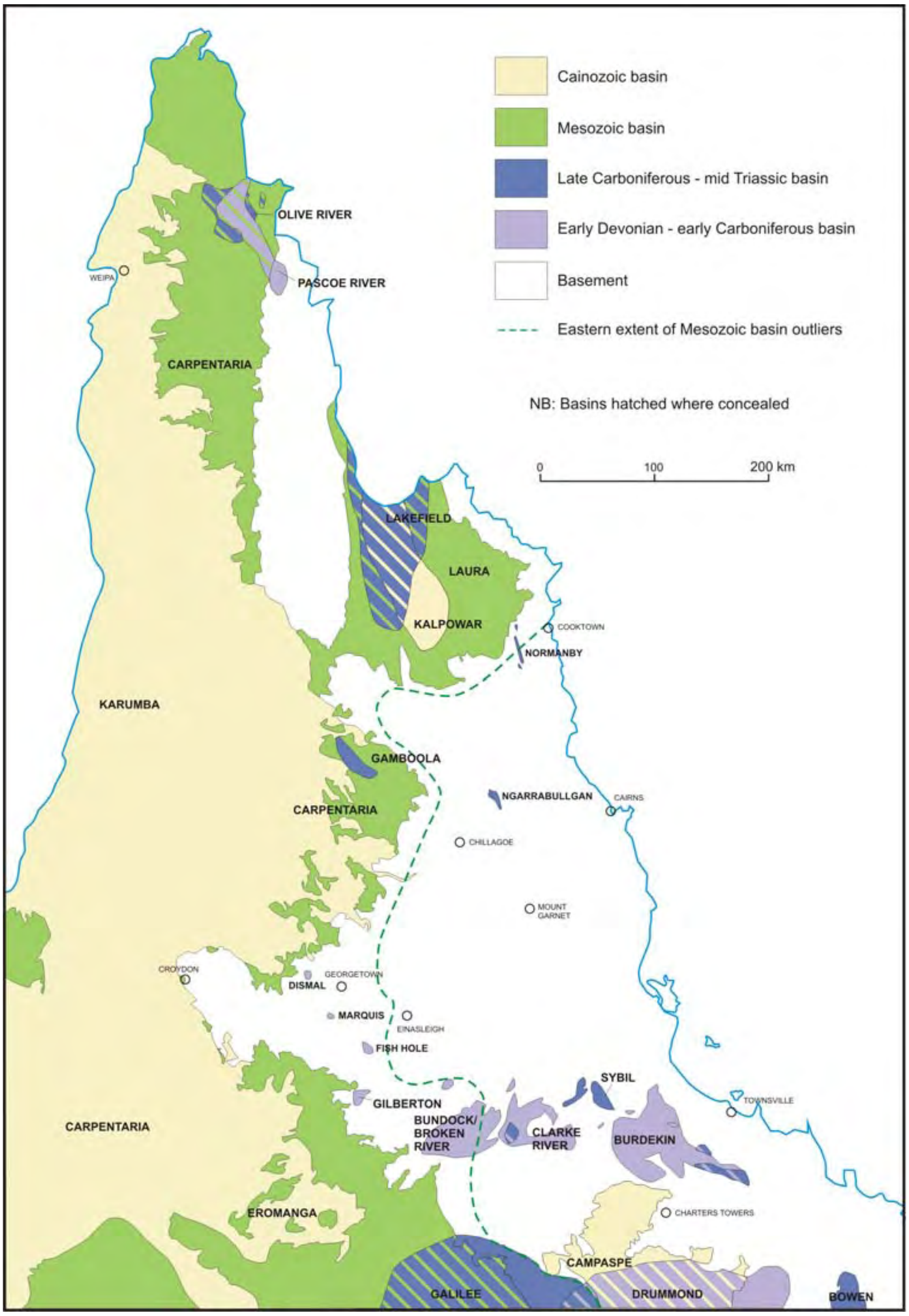

Figure 16. North Queensland sedimentary basins (modified after Withnall et al., 1997c).

Laura Basin

- Development of the Laura Basin as a broad shallow, thermal subsidence basin occurred in the Middle Jurassic (Wellman, 1995a, b). Deposition commenced with the Middle to Late Jurassic Dalrymple Sandstone, a sequence of high energy fluviatile quartz-rich sandstones and conglomerates (Figure 17; McConachie et al., 1997). The Dalrymple Sandstone is a biostratigraphic and lithostratigraphic equivalent of the Loth Formation (Eulo Queen Group) in the southern Carpentaria Basin and the Westbourne Formation of the Eromanga Basin (McConachie et al., 1997).

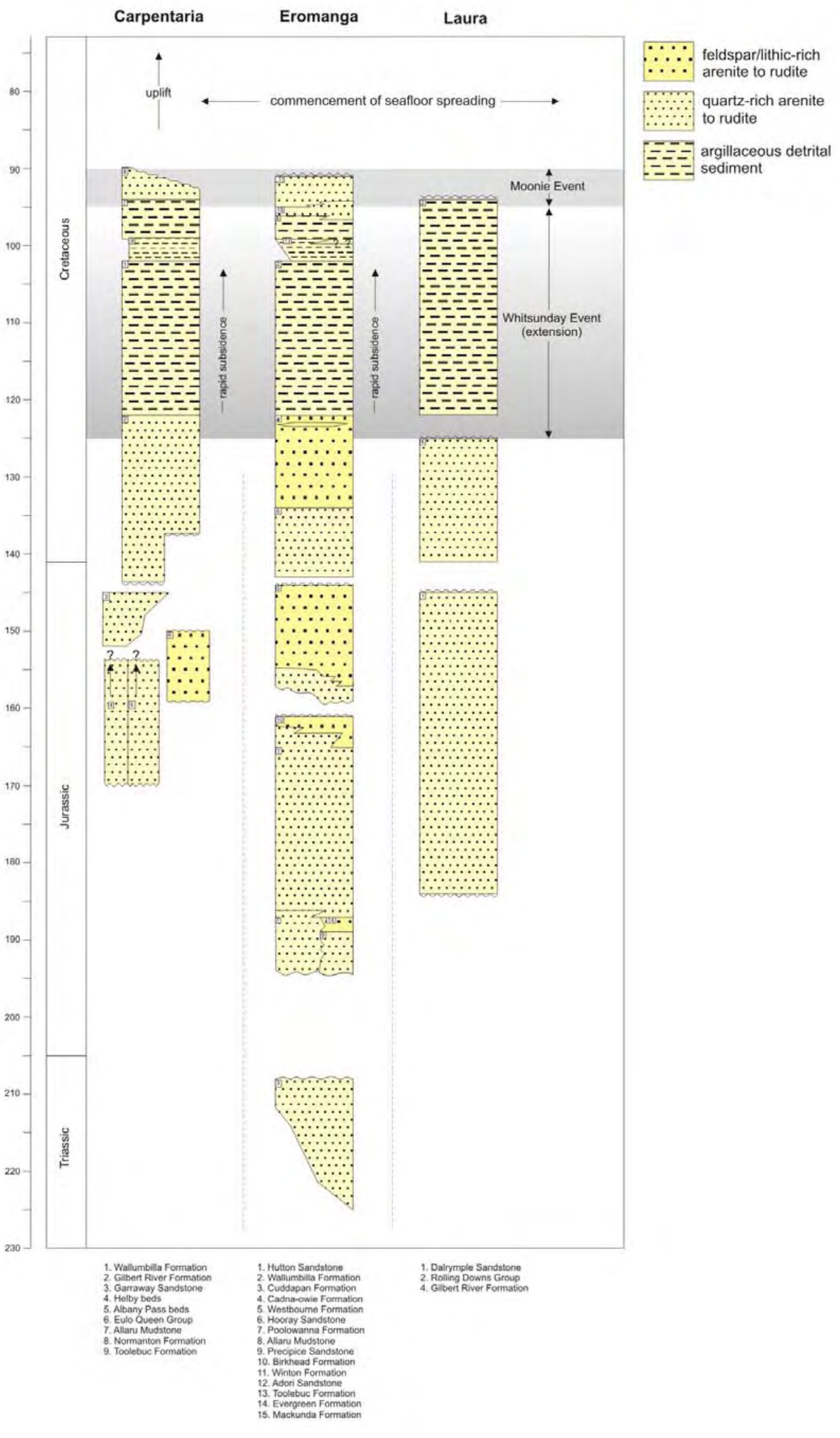

Figure 17. Time-space plot of Mesozoic basins in North Queensland.

- Latest Jurassic – earliest Cretaceous deposition of fluviatile to marginal marine, dominantly sandstone units of the Gilbert River Formation, a biostratigraphic and lithostratigraphic correlative of the Gilbert River Formation in the Carpentaria Basin (Smart and Senior, 1980; Wellman, 1995a, b; Figure 17).
- A hiatus was followed by a widespread marine transgression in the Early Cretaceous, resulting in deposition of the argillaceous Rolling Downs Group (Smart and Senior, 1980). Deposition continued in nearshore to neritic marine conditions, with moderate to high terrestrial input (Hawkins and Williams, 1990). Sedimentology and biostratigraphy indicate that shallow marine conditions prevailed during the Aptian to Albian, with a regressive phase at the top of the Rolling Downs Group (Hawkins and Williams, 1990; Withnall et al., 1997c).
- Sedimentation ceased in the Late Cretaceous, related to the cessation of subduction, or a jump in the subduction zone, well to the east of Australia (see above; Waschbusch et al., 2009). Uplift continued in the Cenozoic, and erosion is continuing (Bultitude et al., 1997).

Carpentaria Basin

- Deposition began initially in isolated fault-controlled sub-basins (Western Gulf, Weipa and Staaten Sub-basins) during the Middle to Late Jurassic (McConachie et al., 1990). The terrestrial Eulo Queen Group was deposited in the southern Staaten Sub-basin. A possible equivalent, the Garraway Sandstone, of fluvial-lacustrine origin, was deposited in central Staaten Sub-basin and the Weipa Sub-basin. The marine Helby beds and the fluvial Albany Pass beds were deposited in the Western Gulf Sub-basin (McConachie et al., 1997; Figure 17).
- The next depositional event is represented by quartz-rich sandstone and minor interlayered conglomerate and siltstone, mudstone and shale of the Gilbert River Formation deposited in a fluviatile (lower part) to shallow marine (upper part) environment (Smart et al., 1980; Bultitude et al., 1997). The transgression was from north to south, as shown by age variations for the unit (Jurassic-Cretaceous in the Weipa and northern Staaten Sub-basins, but Cretaceous elsewhere; McConachie et al., 1997).
- Transgression continued in the Early Cretaceous with deposition of the Wallumbilla Formation (late Neocomian to early Barremian), of the Rolling Downs Group, which was deposited initially in the Weipa Sub-basin, but by the Aptian had spread across the basin. The organic-rich, calcareous Toolebuc Formation was deposited during the Albian in a restricted environment (McConachie et al., 1990). The marine Alluru Mudstone, followed by the near-shore to paralic Normanton Formation, were deposited in the Albian to Cenomanian (McConachie et al., 1990; 1997; Figure 17).
- Sedimentation ceased in the Late Cretaceous, with uplift developed adjacent to the Coen Region. The margins of the basin were locally faulted, uplifted and eroded prior to the commencement of sedimentation in the overlying Karumba Basin (McConachie et al., 1990; 1997).

1.9. Cenozoic

65 Ma to Recent

Geological and tectonic summary

The Cenozoic in North Queensland is characterised by the initiation of, and widespread fluvial sedimentation in, the Karumba and Kalpowar basins and the Charters Towers region, extensive mafic volcanism, and several periods of weathering and erosion (Grimes, 1980; Figures 18, 19, 20).

The Miocene(?) to Recent, fluvial to marine, Karumba Basin (Figure 19) was initiated after a Late Cretaceous period of erosion and local faulting along the margins of the Carpentaria Basin. The

Karumba Basin unconformably overlies most of the Carpentaria Basin (Figure 16; Smart et al., 1980), with a significant time break (~95 to 15 Ma) between the youngest preserved Carpentaria Basin succession and the oldest dated Karumba Basin succession. Development of the Karumba Basin has been proposed to have been cyclic (e.g., Grimes, 1980; although cf. Withnall et al., 1997c), with each cycle beginning with active erosion and deposition and terminating in the formation of a planar land surface that was subsequently affected by lateritic weathering subsequent to the next cycle. Initiation of these cycles may have been related to activity at the margins of the Australian plate and its interaction with the Pacific Plate to the northeast (Smart et al., 1980).

Much less is known about the coeval Kalpowar Basin; it overlies the central part of the Laura Basin, but is poorly exposed (Figures 16, 19). Early Tertiary subsidence, triggered by reactivation of underlying faults in the Laura Basin is considered the main control on basin development (McConachie et al., 1997). The uplift of the Coen Region at ~65 Ma resulted in the separation of the Kalpowar and Karumba basins, although their stratigraphic sequences are similar (McConachie et al., 1997).

Early Tertiary and late Tertiary fluvial sedimentation was also widespread in the Townsville hinterland, e.g., the fluvial Pliocene Campaspe Formation (Hutton et al., 1997), and to the south of Charters Towers (Draper in Withnall et al., 1997c). The sediments are interbedded with basalt flows and were subjected to several periods of weathering (Grimes, 1980; Withnall et al., 1997c).

Cenozoic basalts in North Queensland cover an area of ~23 000 km^2 with a total volume of >650 km^3 and extend close to 1200 km north-south (Stephenson et al., 1980; Stephenson, 1989; Zhang et al., 2001; Figures 18, 19, 20). They make up the northern part of the much larger intraplate Eastern Australian Volcanic Province (EAVP) which extends southward to Tasmania and South Australia for over 4000 km (Johnson et al., 1989). The predominantly Pliocene to Recent lava-field type volcanism of North Queensland, represented by numerous provinces (e.g., the Atherton, McBride, Chudleigh, Nulla and Sturgeon provinces; Figure 18), is characterised by the sporadic and rapid eruption of mafic alkaline magmas as shield, composite and scoria volcanoes and long lava flows (Stephenson et al., 1989; Withnall et al., 1997a). The magmatism occurred in two episodes, at 44-25 Ma and 8 Ma to 10 ka (Stephenson, 1989), with the latter representing a major magmatic event in North Queensland (Stephenson et al., 1998; Figures 18, 20).

The older magmatism is generally thought to relate to migration of mantle hot spots, as magmatism progressively youngs to the south (Wellman and McDougall, 1974). Origins of the younger magmatism (i.e., 8.0 Ma to 10 ka) are more problematical, in particular, the mechanisms to explain the recurring, intermittent volcanism, especially short lived eruption events of significant volume (Stephenson et al., 1989). A number of origins for the intraplate magmatism have been proposed. O'Reilly and Zhang (1995) related basaltic lava field activity to irregular small mantle plume upwellings. Sutherland (1998) proposed progressive magmatism over underlying mantle plumes activated by tensional stress. Sun et al. (1989) attributed low abundances of incompatible elements in the tholeiitic basalts to derivation from a hot and deep asthenospheric source with no apparent connection to plume activity. As several of the provinces are located close to the intersection of two major tectonic blocks, Johnson et al. (1989) suggested that any readjustment of these blocks could be expected to cause rifting and the possible opening of deep crust-mantle fractures, resulting in the generation of deeply sourced basaltic magmas. Whitehead et al. (2007) have suggested that changes in North Queensland lithospheric stresses, caused by far field effects such as the docking of the Ontong Java Plateau, and the subsequent development of northward subduction (San Cristobal Trench), allowed magma ascent from deep mantle levels in North Queensland.

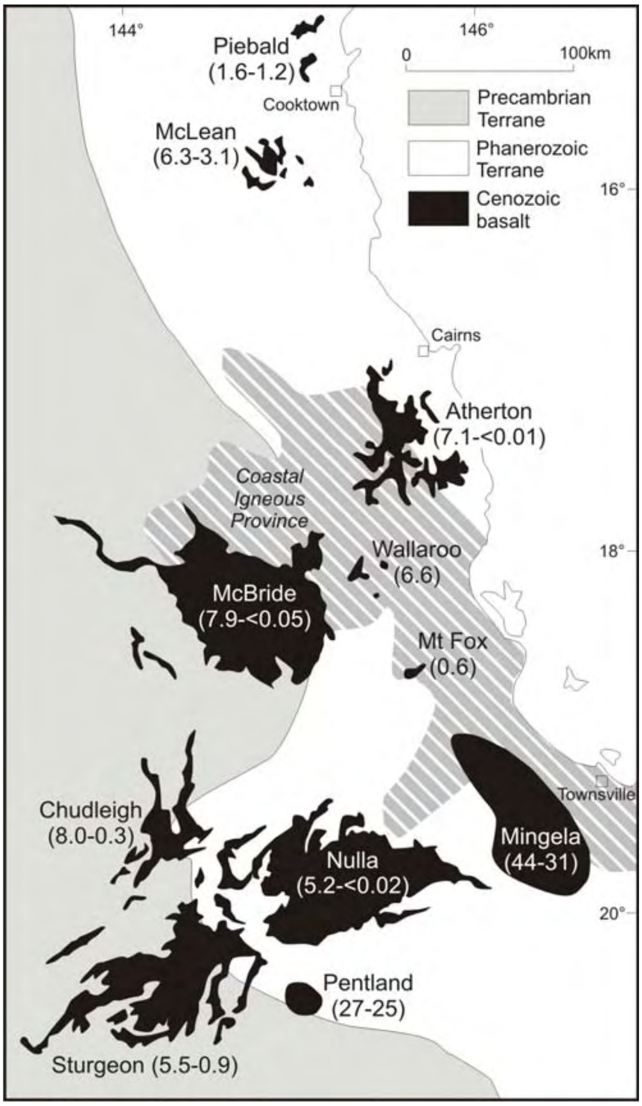

Figure 18. Location map showing distribution and age (in Ma) of the basaltic provinces in North Queensland (Modified after Stephenson, 1989 and Zhang et al., 2001).

Geological history and Time-Space plot explanation

Karumba Basin

- Widespread deposition of interbedded quartz-rich sandstone, conglomerate, claystone and coal beds of the Bulimba Formation (Early to Middle Tertiary Bulimba Cycle) in a basin-wide fluvial environment (Smart et al., 1980). Termination, exposure and weathering of the Bulimba Cycle in the Early to Middle Tertiary formed the Aurukun Surface (Smart et al., 1980). Doutch (1976) considered the origin of the Bulimba Cycle was related to the separation of Australian from Antarctica in Late Cretaceous and early Tertiary times, and to the beginning of the northerly migration of the Australian plate.
- Oligocene tectonism initiated the Miocene to Early Pliocene Wyaaba Cycle (Doutch, 1976; Smart et al., 1980), consisting of a succession of clayey sandstone, granule conglomerate, and interbedded sandy claystone of predominantly continental fluvial origin (Wyaaba beds), and offshore limestone equivalents. Sedimentation was terminated, exposed and weathered with the development of the Pliocene Kendall Surface (Grimes, 1980). Basaltic volcanism (see below) occurred sporadically within this, and the following cycle.

- Uplift in the Pliocene initiated the Claraville Cycle, and led to the deposition of a series of alluvial fan deposits in the Gilbert and Mitchell River areas, and fluvial sands, muds and gravels of the Pleistocene Claraville beds, and marine equivalents (Smart et al., 1980). This cycle continues to the present day, incorporating Pleistocene to Holocene fluvial and aeolian deposits (Smart et al., 1980). This final cycle is not well understood, but is considered to contain two terminal surfaces: the Campaspe Surface caps an unnamed sequence of alluvial fans, and the Holroyd Surface caps the Claraville beds (Grimes, 1980; Smart et al., 1980).

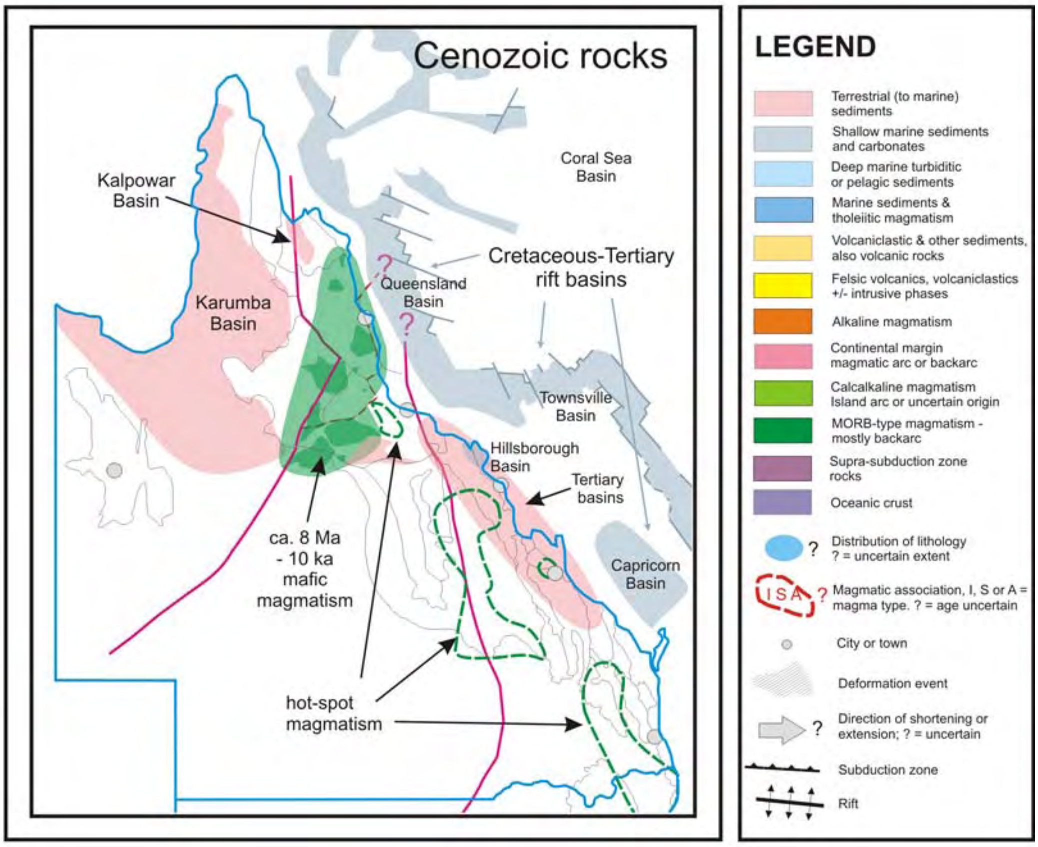

Figure 19. General distribution of Cenozoic rocks (~65 Ma to Recent) in North Queensland. Refer to text for discussion. Tertiary basins generalised from Grimes (1980). Hot spot magmatism generalised from Bryan (2005) (http://www.largeigneousprovinces.org/05aug.html).

Kalpowar Basin

- Early Tertiary subsidence, probably triggered by reactivation of underlying faults, led to the deposition of fluvial sandstones and conglomerates (Fairview Gravel) (Draper and McConachie, in McConachie et al., 1997). The Fairview Gravel may be the remnant of a more extensive fluvial basin that occupied the eroded central area of the Laura Basin. Although of unknown age, it is a likely equivalent of the Bulimba Formation in the Karumba Basin (Grimes, 1980; Figure 20).
- Recent fluvial and coastal deposits can be considered to represent the latest phases of sedimentation in the Kalpowar Basin (Grimes, 1980). Sediments younger than the Fairview Gravel include Tertiary to Quaternary alluvium and alluvial fans capped by ferricrete. Quaternary to Recent sediments comprise alluvial and colluvial deposits and coastal deposits (McConachie et al., 1997)

Charters Towers region

- Early Eocene or Paleocene deposition of sandstone and pebbly sandstone with minor siltstone, mudstone and conglomerate of the Southern Cross Formation in a fluviatile or lacustrine environment (Henderson and Nind, 1994), followed by deep weathering and ferricrete development (Featherby Surface of Grimes, 1980; Figure 20).
- Deposition of a continental fluviatile assemblage, the Campaspe Formation (Nind, 1988), consisting of mainly sandstone and pebbly sandstone with minor siltstone intercalations followed by an episode of deep weathering and ferricrete development (Campaspe Surface of Grimes, 1980; Figure 20). The age of the Campaspe Formation is probably Pliocene (Nind, 1988), based on K–Ar dating of bounding basalt flows (see below).

Mingela Province

- The Mingela Province is characterised by several plugs and dykes of basanite, alkali basalt, hawaiite and minor tholeiitic basalt concentrated in the Arthur Peak and Mingela areas within a 50km southwest-trending belt, inland from Townsville (Figure 18; Stephenson et al., 1980; Stephenson, 1989). Age data indicate a span of activity between 44 Ma and 31 Ma (Figure 20). This province contains the oldest basaltic remnants of the EAVP in North Queensland, and this group includes rocks of the Pentland area (27-25 Ma) and several isolated residual plugs and/or flow remains west of Atherton and near Einasleigh and Mount Fox (Zhang et al., 2001). Basalts of the Mingela and Pentland provinces are contemporaneous with plume-related central-volcano basalts from Nebo, Peak Range and Springsure (33-24 Ma) and lava-field basalts from Anakie (31-19 Ma) (Zhang et al., 2001).

Chudleigh Province

- The Chudleigh Province (Figure 18) is characterised by broad lava plains, numerous pyroclastic cones, some composite cones and several lava shields (46 vents recognised) ranging in age from 8.0 to 0.26 Ma (Figure 20), overlying the Etheridge Province, granites of the Pama and Kennedy associations and Eromanga Basin sedimentary rocks (Stephenson et al., 1980; Stephenson, 1989; Withnall et al., 1997a)). Rock types include nephelinite, basanite, alkali basalt, hawaiite and minor mugearite which host an abundance of mantle-(dominant) and lower-crustal xenoliths (Stephenson, 1989; Rudnick et al., 1986; Rudnick and Taylor 1987).

Piebald Province

- Remnants of scoria cones and small shield volcanoes, dominated by nephelinite, basanite, alkali basalt, hawaiite and tholeiitic basalt, range in age between 1.6 Ma and 1.2 Ma (14 vents recognised; Stephenson et al., 1980; Stephenson, 1989; Figures 18, 20).

McBride Province

- The McBride Province comprises 164 vents (shield and composite volcanoes, scoria cones and plugs) plus some very long lava flows (up to 160 km, Undara and Kinrara flows) (Figure 18; Stephenson et al., 1980; Stephenson, 1989) overlying Proterozoic rocks of the Etheridge Province and the early Paleozoic Thalanga Subprovince. Age data indicate activity between 7.9 and <0.05 Ma, with essentially continuous activity over the last 2.7 Ma (Stephenson, 1989; Figure 20). The Undara Basalt is the most extensive unit of the subprovince with an age of around 0.19 Ma (Griffin and McDougall 1975). Rock types include nephelinite, basanite, hawaiite and mugearite and show little geochemical variation with age (Stephenson 1989). Mantle and lower-crustal xenoliths are especially abundant in a number of pyroclastic cones and have considerable compositional diversity (Stephenson et al., 1980; Stephenson, 1989).

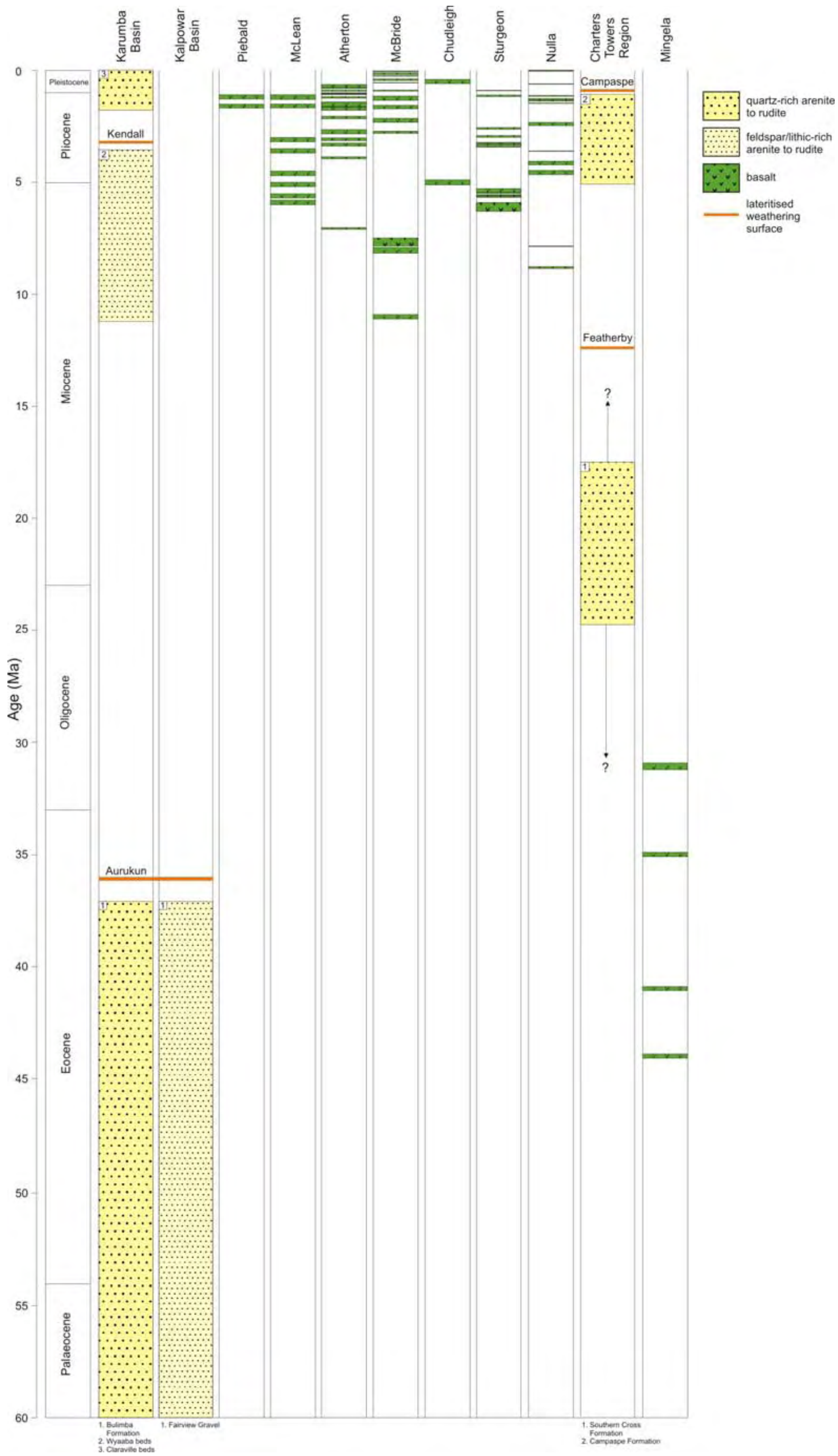

Figure 20. Time-space event plot of Cenozoic sedimentation and basalt volcanism in North Queensland.

Atherton Province

- The Atherton Province is characterised by a range of volcano types, including shield volcanoes, scoria cones, maars, diatremes and broad lava plains, which overlie Paleozoic metamorphic and volcanic rocks and granites (Figure 18; Stephenson, 1989). Age data indicate intermittent extrusion of dominantly potassium-rich alkali olivine basalts, with lesser basanite and tholeiitic basalt between 7.1 Ma and 10 ka (Stephenson et al., 1980; Stephenson, 1989; Bultitude et al., 1997; Whitehead et al., 2007; Figure 20), with volumetric peaks in activity occurring at 3.5-3 Ma and 2-1 Ma (Whitehead et al., 2007).
- A change in the style of volcanism over time is recognised by Whitehead et al. (2007), from eruptions of voluminous lava flows that built large shield volcanoes, to lesser lava production associated with pyroclastic volcanoes (c.f. Newer Volcanics, Victoria-South Australia), coupled with a tholeiitic-alkalic trend from the early shield volcanoes to the later cinder cones (Zhang et al., 2001; Whitehead et al., 2007).
- Zhang et al. (2001) suggested that Atherton Province basalts were produced via mixing of upwelling asthenosphere with a subduction-modified subcontinental lithospheric mantle and, according to Whitehead et al. (2007), such a source region must have been carried along with the lithosphere to produce the volcanism observed in this province. Whitehead et al. (2007) suggest that changes in North Queensland lithospheric stresses, caused by the docking of the Ontong Java Plateau, and the subsequent development of northward subduction (San Cristobal Trench), allowed magma ascent from deep mantle levels.

Nulla Province

- The Nulla Province is dominated by shield volcanoes, but includes a small scoria cone and one long lava flow (Toomba ~120 km) (46 vents recognised; Stephenson et al., 1980; Stephenson, 1989; Figure 18). Age data indicate continuous and spasmodic activity between 5.2 Ma and <2 ka (Stephenson, 1989; Figure 20), with the youngest volcano (Toomba) some 13000 years old (Stephenson et al., 1980; Stephenson, 1989). Isotopically enriched basanite, alkali basalt, nepheline hawaiite and hawaiite are consistent with contributions from a subcontinental lithospheric mantle modified by subduction-related metasomatism (Withnall et al., 1997c; Zhang et al., 2001).

McLean Province

- Scoria cones and composite volcanoes, maars, diatremes and several short lava flows that make up the McLean Province (18 vents recognised) range in age between 6.3 to 3.1 Ma, although some undated cones may be less than 1 Ma (Stephenson et al., 1980; Stephenson, 1989; Figures 18, 20).

Sturgeon Province

- The Sturgeon Province (Figure 18) consists of 46 volcanic centres featuring wide lava plains dominated by hawaiite, which form a broad topographic dome interpreted as Miocene uplift (Stephenson and Coventry, 1986). Age data indicate three main periods of volcanism each separated by periods of erosion between 5.5 Ma and 0.92 Ma (Stephenson et al., 1980; Stephenson, 1989; Figure 20).

SECTION 2. THE TECTONIC DEVELOPMENT OF THE NORTH QUEENSLAND REGION

Introduction

As discussed in Section 1, the North Queensland region varies in age from Paleoproterozoic (ca. 1710 Ma), to Recent. The tectonic development of the region can be subdivided into five periods, namely:

- Paleoproterozoic-Mesoproterozoic development; little direct evidence for subduction-related tectonics.
- Rodinian breakup (rifting) and ensuing passive margin - ca. 825 to 515 Ma, that is, formation of the paleo-Pacific Ocean; also corresponds broadly to development of the Australian component of the Gondwana margin (e.g., Li and Powell, 2001; Cawood, 2005).
- Tasman Orogen – Delamerian to Hunter-Bowen Orogenies. Alternating extensional and convergent orogenic cycles commencing in the Cambrian and continuing through to the Mesozoic, resulting in accretionary growth – as evidenced in the Lachlan, Thomson and New England orogens.
- Mesozoic basin development, i.e., Eromanga and related basins and Late Mesozoic magmatism, that is, the Whitsunday Event, related to initiation of the break-up of Gondwana (e.g., Bryan et al., 1997; Veevers, 2004).
- Tertiary rift basins and within plate magmatism (± hotspot activity), in part related to opening of the Coral Sea (and Tasman) Basins, via sea-floor-spreading, ca. 80 to 55 Ma (Falvey and Mutter, 1981).

Preliminary results from the 2006 and 2007 reflection seismic surveys (see Korsch et al., 2009c, d and related papers) in the Mt Isa-Georgetown–Charters Towers regions are also discussed, as they have important implications for the crustal structure and tectonic interpretation of this area.

As for the previous sections, geology is discussed in terms of geographic regions (Figure 4) rather than provinces. Where used, however, Province and Subprovince nomenclature follows the Withnall et al. (2009a) modification of the original Bain and Draper (1997) definitions (see Figure 3).

2.1. Paleoproterozoic-Mesoproterozoic Geodynamics

Introduction

There are few tectonic reconstructions concentrating on northeastern Queensland during the Proterozoic (Draper and Bain, 1997; Blewett et al, 1998). The Etheridge Province, however, is often included in more regional geodynamic considerations of the North Australian Craton (NAC), e.g., Betts et al. (2002, 2006), Wade et al. (2006), Betts and Giles (2006), Gibson et al. (2008), as well as global considerations on formation and breakup of the proposed Columbia (also called Nuna) and Rodinia supercontinents (e.g., Karlstrom et al., 2001; Rogers and Santosh, 2003; Zhao et al., 2004; Li et al., 2008).

Important constraints on the Etheridge Province are provided by Withnall et al. (1988) and Blewett et al. (1998), as well as papers in Bain and Draper (1997). More recent work on the metamorphism and deformation (e.g., Boger and Hansen, 2004; Cihan et al., 2006), as well as new geochronology on igneous and intrusive rocks (Nishiya et al., 2003; Fergusson et al., 2005, 2007a, b, c; N. Neumann unpublished data in Withnall et al., 2009b) have better defined the stratigraphy and evolutionary history of the region. Boger and Hansen (2004) have documented both high-P, low-T (P=6-7 kb; T=600-650˚C) and younger low-P high-T metamorphism in the Georgetown region. Cihan et al. (2006) dated these as ca. 1600-1580 Ma and ca. 1550 Ma, respectively, consistent with previous estimates for metamorphism and deformation (e.g., Black et al. 2005). Importantly, Ellis (in Blewett et al., 1997) also document similar high-P low T metamorphism in the Coen region contemporaneous with that in Georgetown. This timing also corresponds to orogenies elsewhere, e.g., the Isan Orogeny (Page and Sun, 1998; Gibson et al., 2008) and the Olarian Orogeny in Broken Hill (Page et al., 2005). Recent reflection seismic lines from Mount Isa to Georgetown and Charters Towers regions have also better defined crustal structure in these areas and delineated a number of crustal blocks (Henson et al., 2009; Korsch et al., 2009c, d). Most importantly, the seismic data have identified a number of possible sutures, including a reflector that penetrates the upper mantle and which has been interpreted as a fossil subduction zone (Korsch et al., 2009c; Figure 21). The Isa-Georgetown seismic lines also place constraints on the nature, age and extent of the (pre-1710 Ma) basement to the Etheridge Province and the relationship of the latter to the Paleoproterozoic to Mesoproterozoic Mount Isa Province to the west.

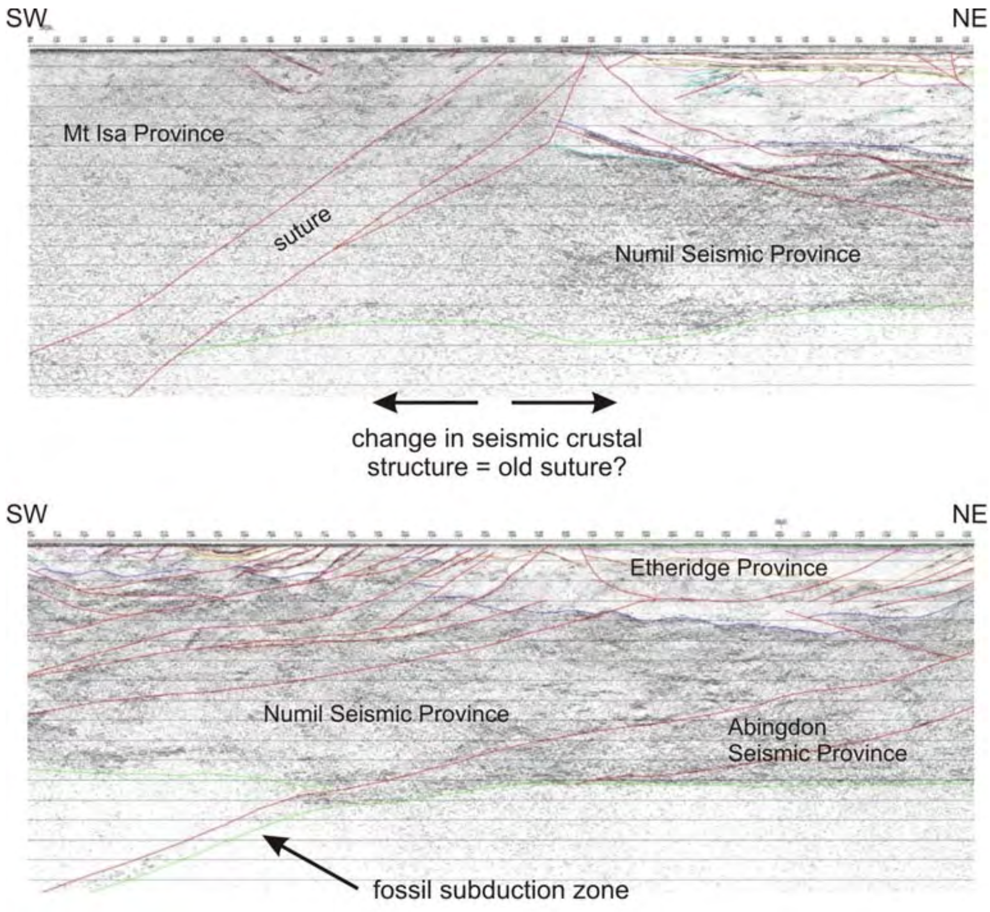

Figure 21. Segments of deep seismic reflection line 07GA-IG1 (modified from Korsch et al., 2009c).

Global considerations

The tectonics of Georgetown, Mount Isa and Australia have been discussed in a number of works concerned with global viewpoints, particularly regarding supercontinent formation and break-up in the Proterozoic (e.g., Karlstrom et al., 2001; Li et al., 2008). Two supercontinents are postulated to have occurred within this time period: Columbia (also called Nuna) – ca. 1800-1600 Ma, and Rodinia – ca. 1100-800 Ma. The better known of these is Rodinia, for which various reconstructions have been suggested, and which, depending on the reconstruction, place northern Australia next to southern or northern North America (or Laurentia as its called; SWEAT, Moores, 1991; AUSWUS, Burrett and Berry, 2000; AUSMEX, Wingate et al., 2002), or south China (see arguments and review in Li et al., 2008 and references therein). Given the Grenvillian age for the Rodinian supercontinent, it does not bear significantly on what happened in the Paleo- and Mesoproterozoic in north Queensland (ca. 1900-1400 Ma), though it is of potential significance to what may form basement to the Thomson Orogen. Of more importance, but less well constrained, are reconstructions for the postulated Columbia or Nuna Supercontinent, for example, Rogers and Santosh (2003), Zhao et al. (2004). Again, reconstructions are variable and various fits are given for Australia, for example, with the USA. What these reconstructions do, is document the apparent widely distributed anorogenic magmatism and continental rifts during this time, for example, 1.6 Ga to 1.2 Ga (e.g., Anderson, 1983; Zhao et al., 2004), thought to be related to breakup of the supercontinent (Windley, 1995; Condie, 2002; Rogers and Santosh, 2003). This global record is also consistent with the overall magmatic and sedimentary evidence for much of the Proterozoic in northern Australia during this period, for example, Bultitude and Wyborn (1982), Etheridge et al. (1987), Wyborn et al. (1988); Blewett et al. (1997), Withnall et al. (1997a), Gibson et al. (2008). An important feature of these reconstructions, and implicit in the assemblage of any supercontinent, is the requirement for Wilson-cycle ocean basin closure and related subduction. The latter requirement touches on an area of contention in both global and especially Australian Proterozoic geology, that is, whether or not modern-style plate tectonics, or something similar, was operative in the Paleoproterozoic and Mesoproterozoic. For this report, we take the viewpoint, as also supported by paleomagnetic evidence for relative continental drift, when only the most robust data is used (Evans and Pisarevsky, 2008), that plate tectonics was operative in this period. As suggested earlier, however, much of the Georgetown and Mount Isa Proterozoic geology is dominated by extensional environments more consistent with a continental break-up interpretation.

The evidence for subduction?

The geodynamic environment for the Proterozoic of northern Australia is contentious, with interpretations (and models) ranging from no subduction (e.g., Etheridge et al., 1987) to common subduction (e.g., Betts et al., 2002; see discussion in Fraser et al., 2007). This argument commonly extends to different interpretations of the same rocks – a relevant case in point being the Kalkadoon-Leichhardt magmatism in the western Mount Isa Province (Figure 22), which has been interpreted both as intracontinental (e.g., Wyborn, 1988) and as a continental arc (e.g., McDonald et al., 1997; Cawood and Korsch, 2008). Inspection of available (OZCHEM) chemical data for felsic and mafic magmatism for this area suggests the former is more likely, though a backarc environment is also permissible. Providing some support for the arc interpretation is the 2007 Mount Isa-Georgetown seismic traverse and accompanying magnetotelluric (MT) study, which both show a major crustal discontinuity – a change in seismic and MT character with an accompanying rapid change in crustal thickness - on the eastern margin of the Mount Isa Province (Henson et al., 2009; Korsch et al., 2009d; Figure 21). We interpret this as support for a crustal suture and, by implication, evidence for a continental arc environment and subsequent collision (e.g., Korsch et al., 2009d) between the Mount Isa Province and what is called the Numil Seismic Province (Korsch et al., 2009d; Figures 21, 22). Even if the latter interpretation is correct, there are few constraints on the absolute timing of such events, with the most favourable interpretation being that this suture was produced some time ca. 1.85 Ga or older (Korsch et al., 2009d; Figure 22) – possibly as old as Late Archean (e.g., McDonald et al., 1997). We certainly concur with McDonald et al. (1997) who provided evidence for older (<1.97 Ga) arc environments in this region to which this suture may relate. This suture could also possibly relate to the ca. 1870 Ma Barramundi Orogeny which affected much of the North Australian Craton (Etheridge et al., 1987) and, as pointed out by O'Dea et al. (1997), is approximately contemporaneous with orogenies in Laurentia and Baltica.

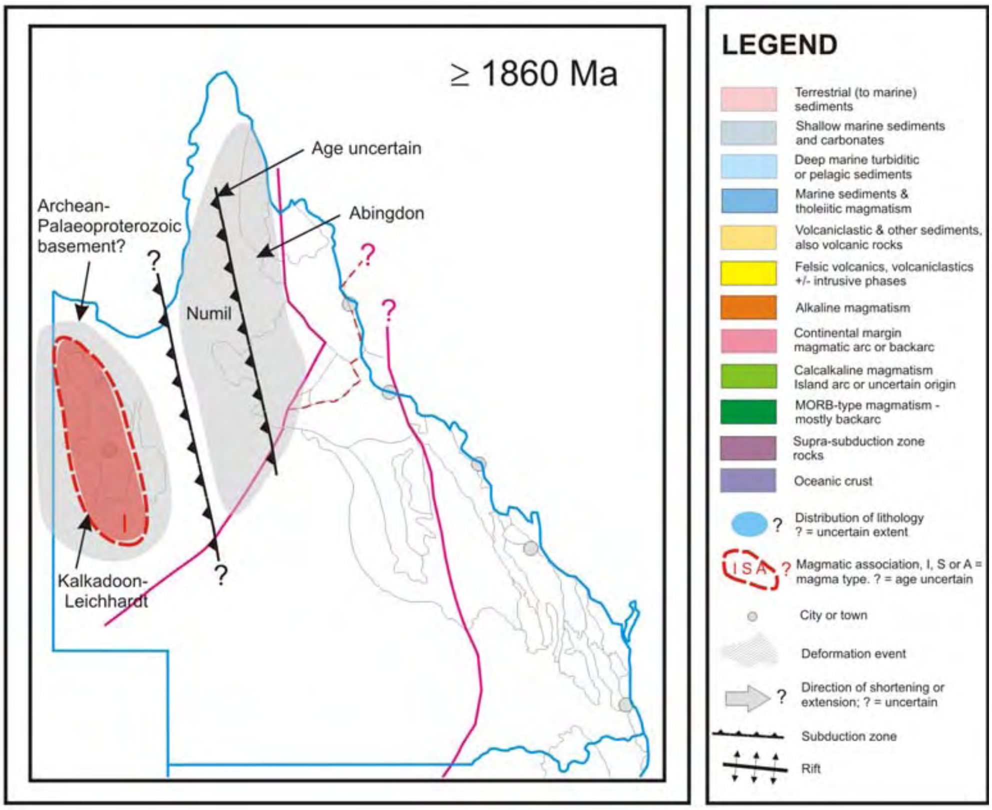

Figure 22. Interpreted geology and tectonic model for the >1860 Ma time period in North Queensland. Refer to text for detailed discussion. The grey polygons illustrate suggested pre-existing older crust, based on isotopic and seismic interpretation.

Also evident on the 2007 Isa-Georgetown seismic transect is the presence of a west-dipping reflector that penetrates into the upper mantle and is coincident with a step in the MOHO. This has been interpreted as a fossil subduction zone by Korsch et al. (2009c, d; Figure 21), based on interpretations for similar reflections elsewhere, such as McGeary and Warner (1985) and Cook et al. (1998). Importantly, as discussed by Korsch et al. (2009d), seismic interpretation in this region appears to suggest that the lower Etheridge Group covers the termination of the fossil subduction zone, that is, the maximum age of ca. 1710 Ma for the Etheridge Group (Withnall et al., 2009a) provides a minimum age for the interpreted subduction zone/suture. Like the eastern Mount Isa suture, there are no constraints on maximum age. Although the fossil subduction zone may be as young as ca. 1720 Ma it, like the Mount Isa suture, may be significantly older and predate much or all of the exposed geology. Crustal blocks east and west of the fossil subduction zone have been called the Numil and Abingdon Seismic Provinces, respectively (Korsch et al., 2009d; Figures 21, 22, 23). These provinces have a very similar seismic reflective character to each other, which led Korsch et al. (2009d) to suggest that the two provinces (Numil and Abingdon) may originally have been one crustal block, that is, the block contains evidence for a Wilson Cycle with rifting, ocean formation and subsequent closure by subduction (Figures 22, 23). Timing for these speculative events are poorly constrained but are thought to have occurred pre-1710 Ma.

ca. 1850 Ma to ca.1600 Ma

The post 1850 to ca. 1600 Ma geological record in the Mount Isa Province and the (post-1710 Ma) Etheridge Province is dominated by extension-related sedimentation (Leichhardt, Calvert and Isa Superbasins in Mount Isa, Etheridge, Langlovale and related Groups in Georgetown and Coen; Figures 23, 24, 25) with intermittent associated, dominantly tholeiitic mafic (often with associated felsic) magmatism (Bultitude and Wyborn, 1982; Ellis and Wyborn, 1984; Blake, 1987; Wyborn et al., 1988;

Blewett et al., 1997; Withnall et al., 1997a; Southgate et al., 2000). The geology provides little direct evidence for any nearby subduction-related geodynamic environment (e.g., O'Dea et al., 1997), although whether it represents a backarc or a far field backarc environment (Betts et al., 2002, 2006; Forbes et al., 2008) or intracontinental extension and/or rift ± plume environment (Wyborn et al., 1988; O'Dea et al., 1997) is equivocal. This is best illustrated by the mafic magmatism, which in the Etheridge Province (ca. 1680 and 1655 Ma in Georgetown; Black et al., 1998; and ca. 1590-1550 Ma in Coen; Blewett et al., 1997) is tholeiitic in character (e.g., Withnall et al., 1984, 1997a; Blewett et al., 1997), consistent with continental flood basalts or continental rifts, and could be construed as backarc in origin. Mafic magmatism in the Mount Isa Province is similarly dominated by tholeiitic compositions (e.g., Glikson et al., 1976; Bultitude and Wyborn, 1982; Ellis and Wyborn, 1984). The Mount Isa Province, in this period, is also characterised by episodic felsic magmatism, which is also contemporaneous with extensional sedimentation and has been shown to be anorogenic in nature (Wyborn et al., 1988; Figure 23). Any arc, if present (i.e., if the region is interpreted as (far-field?) backarc, e.g., Betts et al., 2006), was probably either to the south, related to an arc in the southern Northern Territory (e.g., ca. 1770 Ma mafic and felsic magmatism in the Arunta Block of the southern Northern Territory has arc-affinities; Sivell, 1988; Foden et al., 1988; Zhao, 1994) or perhaps to the east (e.g., Gibson et al., 2008; Figures 23, 24).

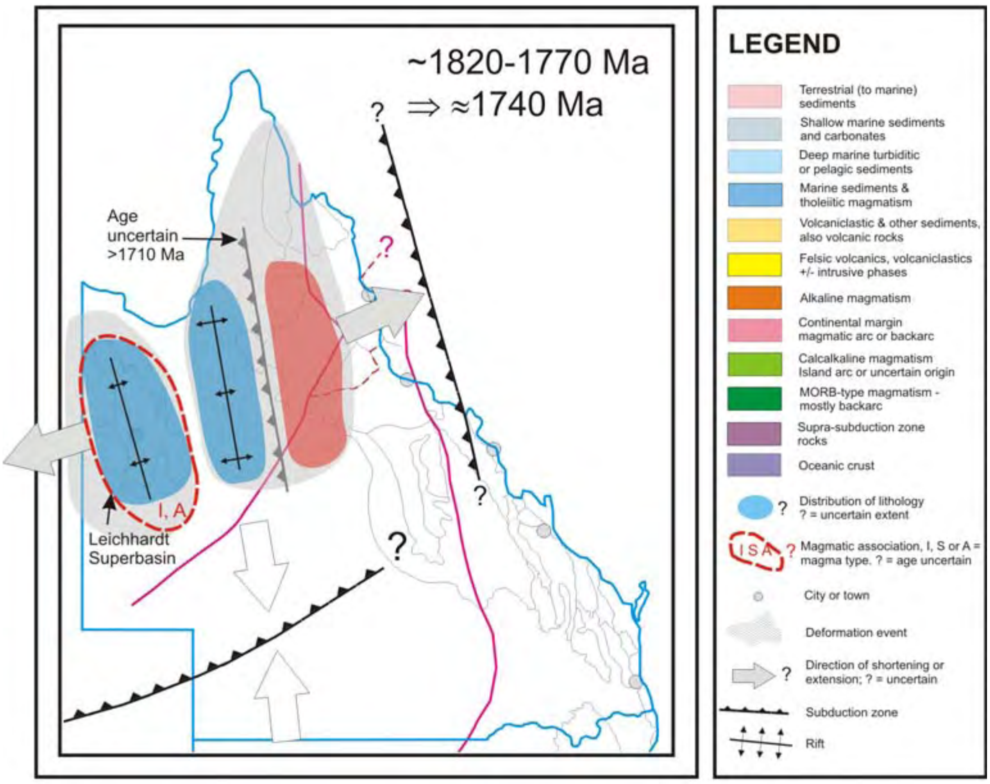

Figure 23. Interpreted geology and tectonic model for the ~1820-1770 Ma (possibly to ~1740 Ma) time period in North Queensland. Refer to text for detailed discussion.

Possible supporting evidence for a southern arc is provided by the north-south D1 deformation in the Etheridge Province (Withnall et al., 2009b) and the Mount Isa Province (e.g., Betts et al., 2006). As indicated by Withnall et al. (2009b), this event in the Georgetown region postdates deposition of the Etheridge Group and predates the Langlovale Group and, as such, is constrained between ca. 1650 and ca. 1600 Ma (Figure 25). Similar north-south contractional deformation – ca. 1640 Ma - has been suggested for the Mount Isa Province (e.g., Betts et al., 2006). Scrimgeour et al. (2005) also record north-south contractional deformation and associated metamorphism at ca. 1640 Ma in the southern (Northern Territory) part of the North Australian Craton, which they related to collision of the

Warumpi Terrane with the NAC. It could be speculated that the related arc continued to the east, south of Mount Isa and Georgetown (as shown in Figure 25).

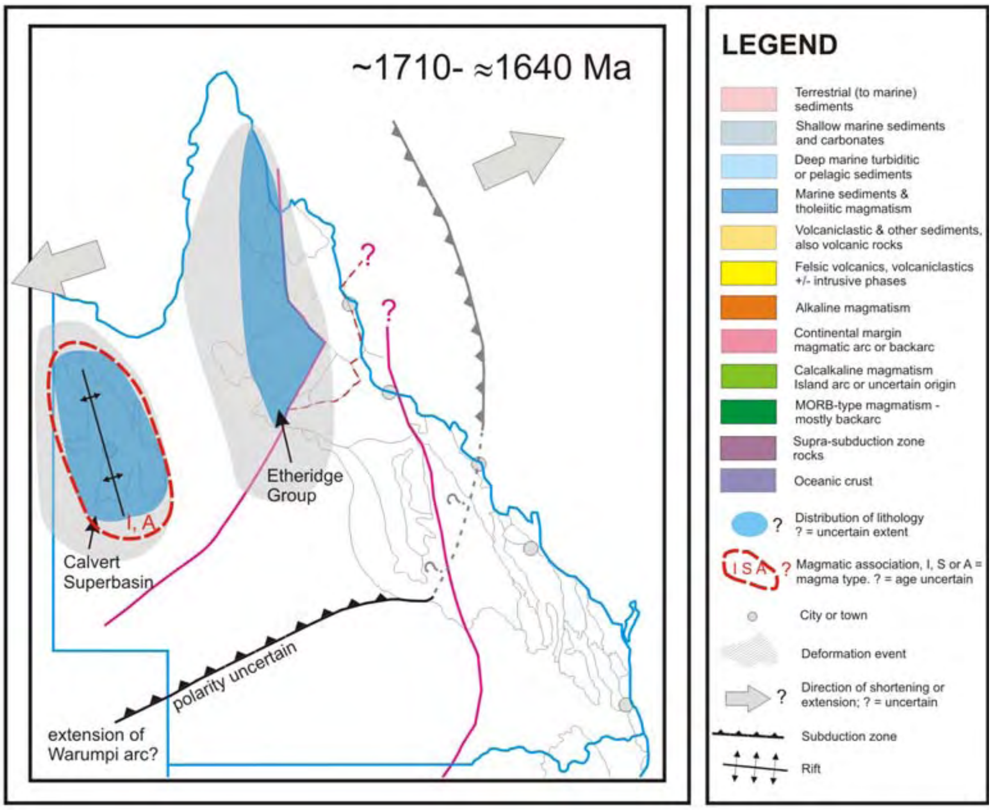

Figure 24 . Interpreted geology and tectonic model for the ~1710-1640 Ma time period in North Queensland. Refer to text for detailed discussion. Grey areas designate areas of potential older (Archean?) basement to Mount Isa and Georgetown. Although the Warumpi Arc is interpreted to be south-dipping by Scrimgeour et al. (2005), the ca. 1640 Ma north-south deformation in Georgetown and Mt Isa is more consistent with a north-dipping slab (i.e., deformation in the upper plate).

ca. 1600 - 1400 Ma: Orogeny and extension

Both the Mount Isa and Etheridge Provinces underwent major orogenesis - deformation and metamorphism - in the period ca. 1600 Ma to ca. 1550 Ma (Figure 26). Two contractional deformations with associated metamorphism are recorded in the Etheridge Province (D2/M2, D3/M3; see Withnall et al., 2009b). Peak metamorphism, associated with east-west contractional deformation, in the Etheridge Province (D2-M2) is recorded at ca. 1590 Ma (Blewett et al., 1998; Black et al., 2005; Cihan et al., 2006). Boger and Hansen (2004) and Ellis (cited in Blewett et al., 1997) indicate that this metamorphism was high-pressure, moderate-temperature, up to 7 kb. Cihan et al. (2006) indicate clockwise PTt paths for D2-M2 in the Georgetown region. Subsequent high-temperature-low pressure metamorphism associated with northwest-southeast contraction (D3-M3) occurred ca. 1560-1550 Ma (Boger and Hansen, 2004; Cihan et al., 2006; Withnall et al., 2009b). The Mount Isa Province similarly records a broadly contemporaneous (constrained to ca. 1590 to 1500 Ma, e.g., O'Dea et al., 1997) contractional orogenesis - the Isan Orogeny (Blake and Stewart, 1992). The Isan Orogeny records a number of similarities, as well as differences, with the Georgetown deformation. These include:

- The Isan Orogeny, like the Etheridge Province, includes a number of contractional events (D2, D3, etc, e.g., O'Dea et al., 1997).
- Unlike D2 and D3 in the Etheridge Province, the Isan Orogeny includes north-south (mostly confined to D2) as well as east-west contraction, although O'Dea et al. (1997) suggests the net result of the orogeny was up to 40-50% east-west shortening.

- The Isan Orogeny is characterised by low pressure, high-temperature metamorphism with anti-clockwise PTt paths (Rubenach, 1992; Rubenach and Barker, 1998), in contrast to the clockwise, medium-high pressure metamorphism of D2 in the Etheridge Province.
- The timing of peak metamorphism in the Mount Isa Province is similar to the Etheridge Province, and is generally thought to have been ca. 1590 Ma (e.g., Page and Sun, 1998; Gibson et al., 2008). Peak metamorphism may, however, have been younger (ca. 1540 Ma) in the western part of the Mount Isa Province (Connors and Page, 1995).
- Significant felsic I- and S-type magmatism accompanied orogenesis in Georgetown (mostly 1560-1550 Ma, e.g., Withnall et al., 1997a), Coen (mostly ca. 1580 Ma; Blewett et al., 1997) and Mount Isa (ca. 1550-1530 Ma; Page and Sun, 1998).
- Deposition of the marine to terrestrial Langlovale Group (Withnall et al., 1997a, 2009b), and possibly parts of the Holroyd and Coen Metamorphic Group in Coen (Blewett et al., 1997), probably occurred between D2 and D3 (Figure 26).
- Unlike the Etheridge Province, orogeny in the Mount Isa Province appears to have lasted longer. Post-orogenic felsic magmatism was earlier in the Georgetown region - ca. 1550 Ma relative to Mount Isa - ca. 1520 to 1490 Ma (Wyborn, 1998; Withnall et al., 1997a, 2009b).

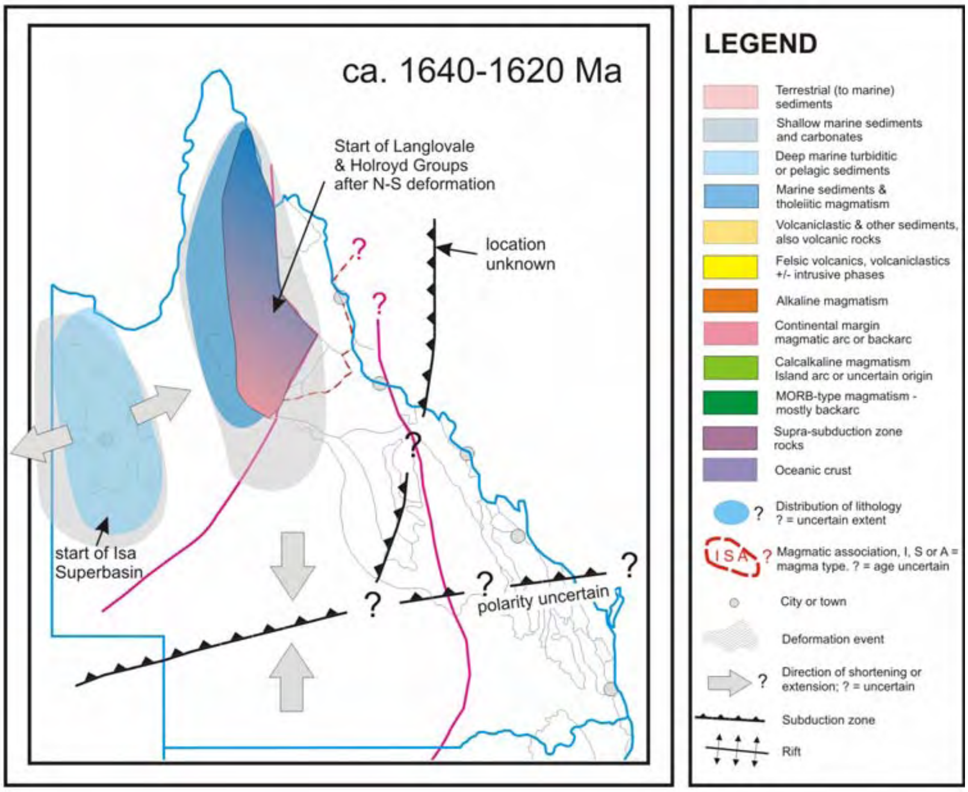

Figure 25 . Interpreted geology and tectonic model for the 1640-1620 Ma time period in North Queensland. Refer to text for detailed discussion. The colour change from blue to red represents a change from marine to non-marine conditions.

Geodynamic drivers for this orogenesis (ca. 1590 to 1500 Ma) are contentious. A number of authors have suggested it was related to an arc present to the south of Georgetown and Mount Isa (Betts et al., 2002, 2006; Wade et al., 2008), possibly related to an easterly extension of the Musgrave arc (e.g., Wade et al., 2006, 2008; Figure 26). The dominant east-west contraction in both Georgetown, and Mount Isa (e.g., O'Dea et al., 1997), would appear to largely contradict this, i.e., an east-west arc should produce contraction with a significant north-south component (depending on the angle of convergence). Betts et al. (2006), for example, appear to overcome this problem by depicting contraction as being north-south in both Mount Isa and Georgetown. Although there is a component of north-south contraction in Mt Isa (Giles et al., 2006), none is apparent in Georgetown during this time. Of interest to this argument are the presence of LILE-poor sodic granites with a high pressure signature in the Georgetown region (e.g., Forest Home and Brandy Hot Suites, e.g., Champion, 1991; Withnall et al., 1997a) and southeast Mount Isa Province (volumetrically minor tonalites, Mark, 2001). These granites require formation by melting of a basaltic protolith at high pressure – either within thickened crust or perhaps slab melting (Champion, 1991; Mark, 2001). Both scenarios are possible, although the presence of these sodic granites have been used to support models which show an east-west subduction zone south of Isa-Georgetown at this time (e.g., Wade et al., 2006; Cawood and Korsch, 2008). Alternatively, both the presence of these granites and the dominant east-west contraction may be more consistent with arc-related convergence to the east of the currently exposed Etheridge Province (Figure 26), for example, related to convergence of Australia and Laurentia (Betts et al., 2006). Another possible geodynamic driver for orogenesis would be intracratonic deformation or far-field effects, for example, related to thermal weakening of the crust (McLaren et al., 2005). The geodynamic interpretation is further complicated by the possible relationships of the Mount Isa and Georgetown provinces with the Broken Hill Province, which also records a similar aged orogeny (Olarian Orogeny - see Betts et al., 2006; Gibson et al., 2008, for alternate viewpoints).

ca. 1550-1500 Ma and younger? Post orogenic magmatism and sedimentation

Post D3 felsic magmatism is present in both the Etheridge and Mount Isa Provinces (Withnall et al., 1997a, 2009b; Blewett et al., 1997; Wyborn, 1998), whereas sedimentation is apparently confined to the former though appears to have moved northward (Figure 27). Within the Etheridge Province, marine sedimentation with accompanying tholeiitic mafic magmatism is recorded in the Holroyd Group in Coen (Blewett et al., 1997). This contrasts with terrestrial volcanism and associated intrusive magmatism in the Croydon Subprovince in the Georgetown region (Withnall et al., 1997a, 2009b, Figure 27). As indicated by Withnall et al. (1997a), the Croydon Volcanic Group is flat lying, with little evidence of subsequent deformation (in the Mesoproterozoic or younger). This contrasts with the Holroyd Group and related rocks in the Coen region, which are strongly deformed, although this deformation, and associated metamorphism, may be largely Devonian in age (R. Blewett, pers. comm., 2009).

Apart from minor younger magmatism , for example, a possible magmatic age of ca. 1410 Ma in the Coen region (L. Black, OZCHRON), the youngest significant Proterozoic magmatism in the Isa-Georgetown region is the ca. 1520-1490 Ma anorogenic mafic and felsic magmatism in the Isa region (Wyborn, 1998). The geodynamic environment at this time is poorly constrained. There is no evidence for nearby subduction, and the geology could reflect either a (far-field?) backarc environment or intracontinental extension. Possible evidence for the latter comes from global considerations. Rogers and Santosh (2004), for example, document widespread major continental rifting and breakup at ca. 1470 Ma. Blewett et al. (1998) have speculated, based on matching event ages in the Etheridge Province with anomalous detrital zircon populations within the Belt Supergroup in northern America, that North Queensland and North America were once joined. More recent work by Ross and Villeneuve (2003) on detrital muscovite and zircon ages adds support to this idea, although the latter authors suggested the Belt Supergroup may more relate to backarc extension (and not continental rifting).

Although the Sefton Metamorphics in the Coen region have ~1200 Ma detrital zircons (Blewett et al., 1997), there is little preserved evidence for significant geological activity in the Mount Isa or Etheridge Provinces post-1400 Ma until the Late Neoproterozoic (O'Dea et al., 1997; Withnall et al., 1997a; Fergusson et al., 2007b, c). As indicated by O'Dea et al. (1997), this is somewhat surprising given the significance of Grenville-aged orogenesis around the world (Li et al., 2008), and in Australia (e.g., Albany-Fraser and Musgrave; see Cawood and Korsch, 2008). It is possible that much of this Grenville geology lies to the south within the Thomson Orogen (e.g., Fergusson et al., 2006), including the newly identified Agwamin Seismic Province which forms basement in the Charters Towers region (Withnall, 2009a; Figure 27).

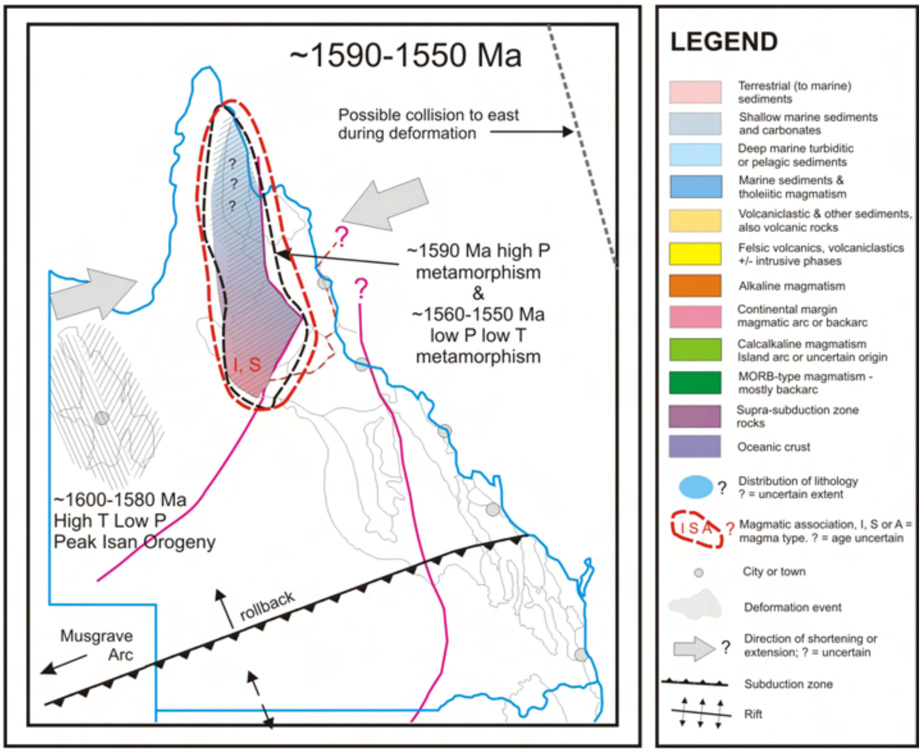

Figure 26. Interpreted tectonic model for the ~1590-1550 Ma time period in North Queensland. Refer to text for detailed discussion. The colour change from blue to red represents a change from marine to non-marine conditions.

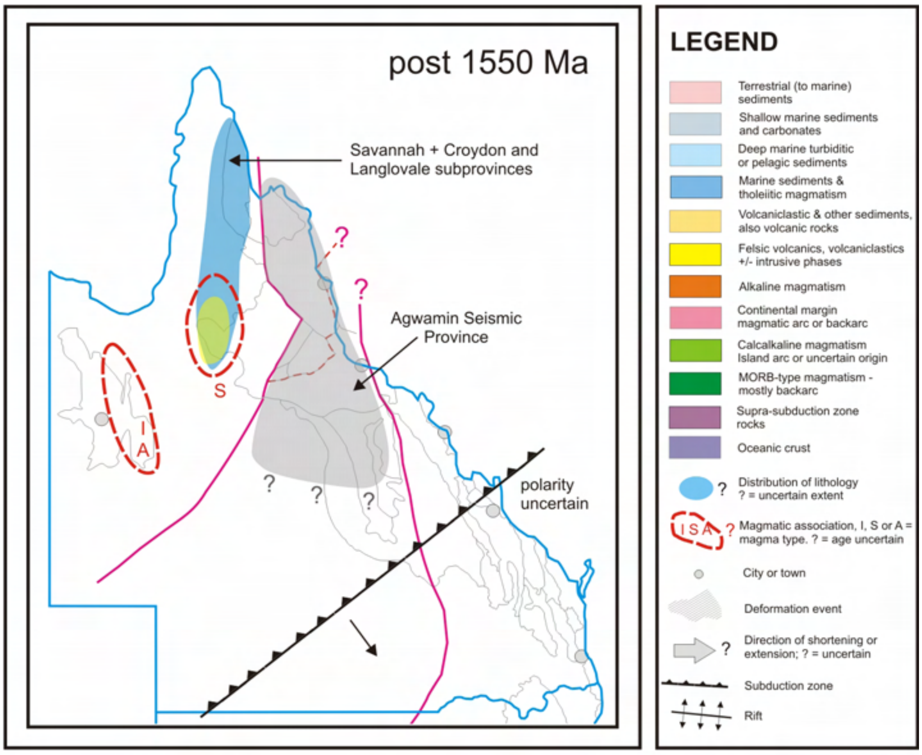

Figure 27. Interpreted geology and tectonic model for post-1550 Ma in North Queensland. Refer to text for detailed discussion.

2.2. Rodinia breakup and establishment of the Tasman Orogen

The geology and tectonic development of eastern Australia, during the Tasman Orogen (Scheibner and Veevers, 2000; Veevers, 2000, 2004; Cawood, 2005; Glen, 2005), has been the focus of numerous studies, with a voluminous literature, including numerous orogen-based or more regional reviews (e.g., Murray, 1986; 1997; Murray et al., 1987; Coney, 1992; Seymour and Calver, 1995; Bain and Draper, 1997; Gray et al., 1997, 2003; Gray, 1997; Gray and Foster, 1997; 2004; Scheibner and Basden, 1998; Foster and Gray, 2000; VandenBerg et al., 2000; Veevers, 2000; Li and Powell, 2001; Crawford et al., 2003a; Glen, 2004; Cawood, 2005). The focus of this research has led to a plethora of tectonic models with perhaps the majority of differences focussed on the Lachlan Orogen (e.g., see Gray, 1997; Gray and Foster, 2004; Figure 28). Importantly, despite the differences, there is a general consensus that since the Late Neoproterozoic, eastern Australia, broadly, has gone through three tectonic states:

- Rodinian breakup (rifting) and ensuing development of passive margin – in its simplest form, basically formation of the paleo-Pacific Ocean; also corresponds broadly to development of the Australian component of the Gondwana margin (e.g., Li and Powell, 2001; Cawood, 2005).
- Repetitive orogenic cycles typically comprising initial extension and subsequent contraction (Glen, 2005), commencing in the Cambrian and continuing through to the Mesozoic, resulting in accretionary growth – as evidenced in the Lachlan, Thomson and New England orogens. Orogenic events include the Cambrian Delamerian through to the Permian-Triassic Hunter-Bowen orogenies. These cycles effectively ended with cratonisation, with the main arc system moving further offshore (subduction zone rollback; e.g., Collins and Vernon, 1994; Jenkins et al., 2002; Collins and Richards, 2008).
- Rifting and passive margin (± hotspot activity), related to rifting of crustal fragments (possibly initially in a backarc environment), and opening of ocean basins, especially related to Gondwana break-up (e.g., Veevers, 2004).

Although broadly simple, in detail the tectonic evolution of eastern Australia in the Phanerozoic is clearly complex. Not only is there evidence for diachronous events (Gray et al., 2003), and possible switches in the polarity of subduction zones (e.g., Murray, 2007), it is also clear that the current makeup of eastern Australian provinces (especially Paleozoic to early Mesozoic) represents an amalgamation of terranes that were not necessarily originally juxtaposed, that is, there are both allochthonous and autochthonous terranes. Controversy and uncertainty involves the identification of such potentially allochthonous blocks, as well as the nature and age of the basement of such blocks. Another area of controversy concerns the actual positions of magmatic arcs and discriminating between arc-forearc and backarc environments. Perhaps the best example of this is the (unresolved) debate regarding the interpretation of the sediments in the Hodgkinson Province (e.g., Henderson, 1980; Bultitude et al., 1993; 1997).

Further uncertainty concerns the Thomson Orogen, which is largely undercover and, as such, poorly understood. Recent seismic reflection results across the southern margin of this orogen suggest that this boundary is not simple: the MOHO thickens to the north and the boundary may represent collision between the Lachlan and Thomson Orogens (e.g., Glen et al., 2007c). As pointed out by Glen et al. (2007c), the presence of ocean island basalt magmatism in the southern Thomson may actually reflect accretion onto an 'east-west convergent margin'; Gray and Foster (2004) notably invoked a similar tectonic scenario for the southern Thomson Orogen, which they appear to link to the Larapinta seaway and younger structural events in central Australia (Figure 28). Glen et al. (2007c) suggested that any collision probably predated the Late Devonian, as sedimentary rocks of this age are found in both the Thomson and Lachlan Orogens. The possibility of such a scenario raises questions about the Thomson

Orogen as a whole, and how it relates to northern Australia, especially the 'Tasman Line', and the geological interpretation of the latter.

Finally, it is evident that the considerable amount of studies on the tectonic evolution of eastern Australia has largely focussed on the Lachlan and New England Orogens. It is noteworthy that the geological record of the Tasman Orogen in southern Australia is represented by a wide zone stretching from east of Adelaide to the east coast – this same time period in North Queensland is significantly condensed into a narrow zone that never significantly migrated away from the Paleo-Mesoproterozoic (Rodinian breakup) margin, until the Late Paleozoic-Mesozoic.

2.3. Late Neoproterozoic to Early Cambrian

Rodinian breakup - pre-Delamerian Orogeny: ca. 600 Ma to ca. 520 Ma

Overview

The Late Neoproterozoic (ca. 600 Ma) to mid Cambrian geological history of eastern Australia is best represented in southeastern Australia. That region records episodic glacial and marine sedimentation, thought to be related to global glaciation events (e.g., Hoffman and Schrag, 2002), as well as a cycle of continental rifting and ocean opening, related to the breakup of Rodinia. The latter resulted in formation of passive margins and initiation of the paleo-Pacific Ocean (e.g., Li and Powell, 2001; Cawood, 2005; Li et al., 2008). This regime continued in eastern Australia until it was effectively ended by initiation of subduction (starting at ca. 515 Ma in the southern Delamerian Orogen; Foden et al., 2006) and arc-continent collision, ca. 510-505 Ma (Crawford and Berry, 1992), related to the Delamerian Orogeny. Glen (2005) called this interval the Delamerian Cycle, and suggested that it lasted more than 300 Ma, beginning ca. 830-780 Ma (see also Li et al., 2008). Rocks of this cycle are poorly represented in the North Queensland region and the Rodinia breakup record there is fragmentary, often masked by later events. Correlation with the rock record in southern Australia, however, provides clues to unraveling the history in North Queensland.

Glaciation

Marine sedimentary successions of the Delamerian cycle occur throughout eastern and central Australia (e.g., Li and Powell, 2001; Figure 29). Neoproterozoic successions, such as the ca. 700 Ma Sturtian and ca. 600-580 Marinoan glacial successions of South Australia (e.g., Walter et al., 2000) and similar rocks in Tasmania (Calver and Walter, 2000; Calver et al., 2004), are suggested to be related to 'snowball earth' and subsequent deglaciation events (e.g., Hoffman and Schrag, 2002). Rocks possibly related to these events appear to be absent from the North Queensland region, though are preserved within the Georgina Basin and other depocentres within the Centralian Superbasin (e.g., Ambrose et al., 2001; Lindsay et al., 2005).

Rifting

Also present within the Delamerian cycle are widely distributed marine sediments which contain evidence for continental breakup related to Rodinian rifting (e.g., Cawood, 2005; Crawford et al., 2003a). Deposition within the Centralian Superbasin was apparently initiated in response to Rodinian rifting at ca. 830 Ma (Dunster et al., 2003; Lindsay et al., 2005). Syn-Rodinian breakup sedimentation continued episodically within the Georgina Basin, which records two deformational events during this cycle, including the Late Neoproterozoic-Early Cambrian Petermann Orogeny (Ambrose et al., 2001).

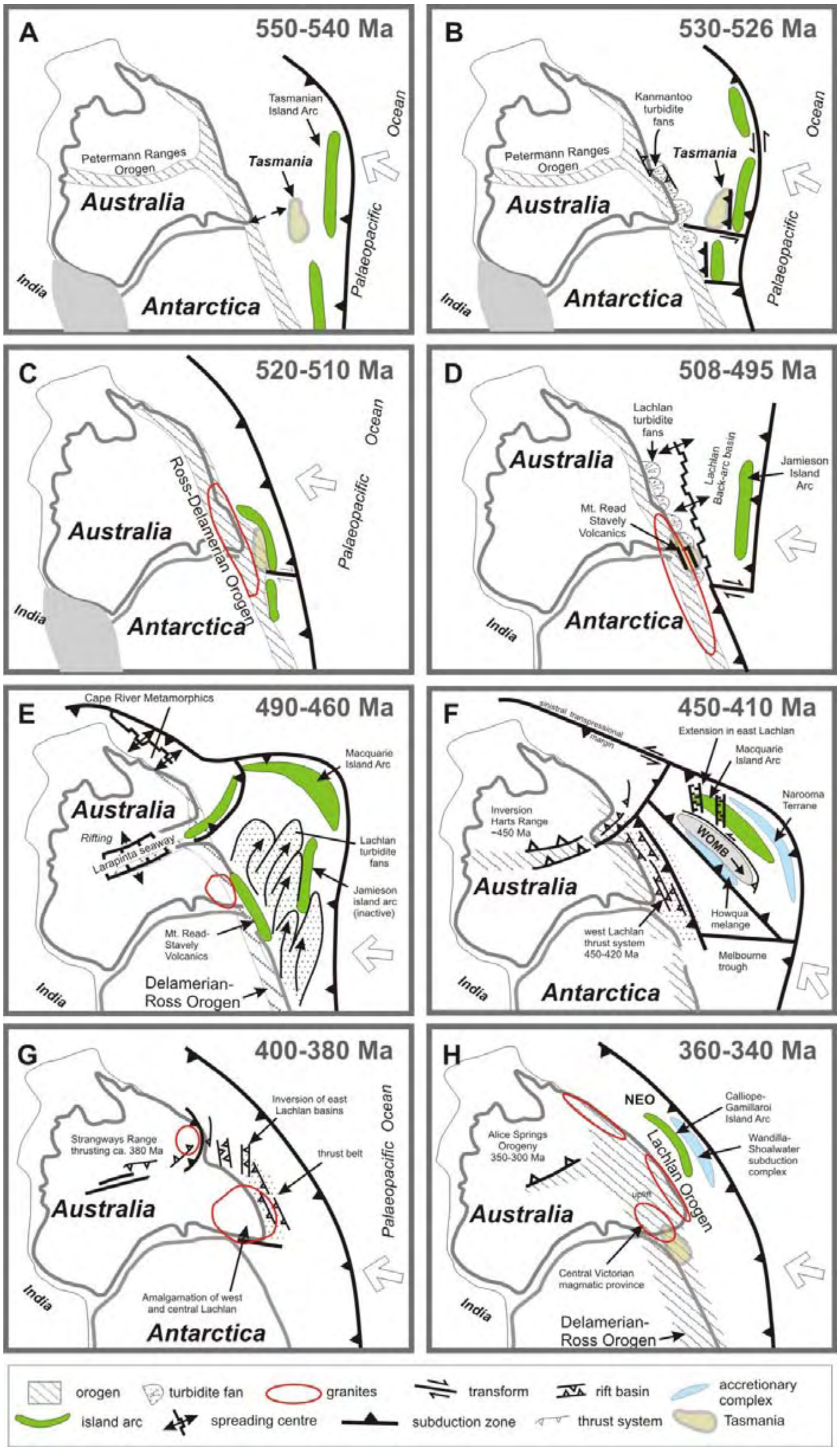

Figure 28. Tectonic evolution model of eastern Australia, modified from Gray and Foster (2004). WOMB - Wagga-Omeo Metamorphic Belt.

Perhaps the best evidence for rifting is preserved in rocks ca. 600 Ma in age and younger (to 500 Ma), in western Tasmania and King Island (e.g., Calver and Walter, 2000; Calver et al., 2004; Meffre et al., 2004), South Australia (e.g., Drexel and Preiss, 1995; Foden et al., 2001), western Victoria (VandenBerg et al., 2000; Crawford et al., 2003b), the Koonenberry region, western New South Wales (e.g., Crawford et al., 1997; Gilmore et al., 2007), and in the Anakie Inlier, central Queensland (Withnall et al., 1995; Figures 29, 30). As summarised by Crawford et al. (1997, 2003a, b) and Fergusson et al. (2007a, 2007c), many rocks of this age contain alkaline and/or tholeiitic assemblages consistent with rift tectonics and a passive margin, and mantle-plume magmatism. Crawford et al. (2003a) suggested rifting was oriented largely northwest-southeast to explain the distribution of rift volcanism in southern Australia at this time. Rocks of this age also occur in North Queensland, within the Charters Towers region, for example, the Cape River Metamorphics, older part of the Argentine Metamorphics (Hutton et al., 1997; Fergusson et al., 2001; 2007c), and possibly within the eastern margin of the Georgetown region, for example, the Halls Reward Metamorphics (Fergusson et al., 2007a). Mafic igneous rocks occur within these packages and record evidence for both tholeiitic and alkaline magmatism (e.g., Hutton et al., 1997), consistent with the interpreted continental rifting occurring at this time.

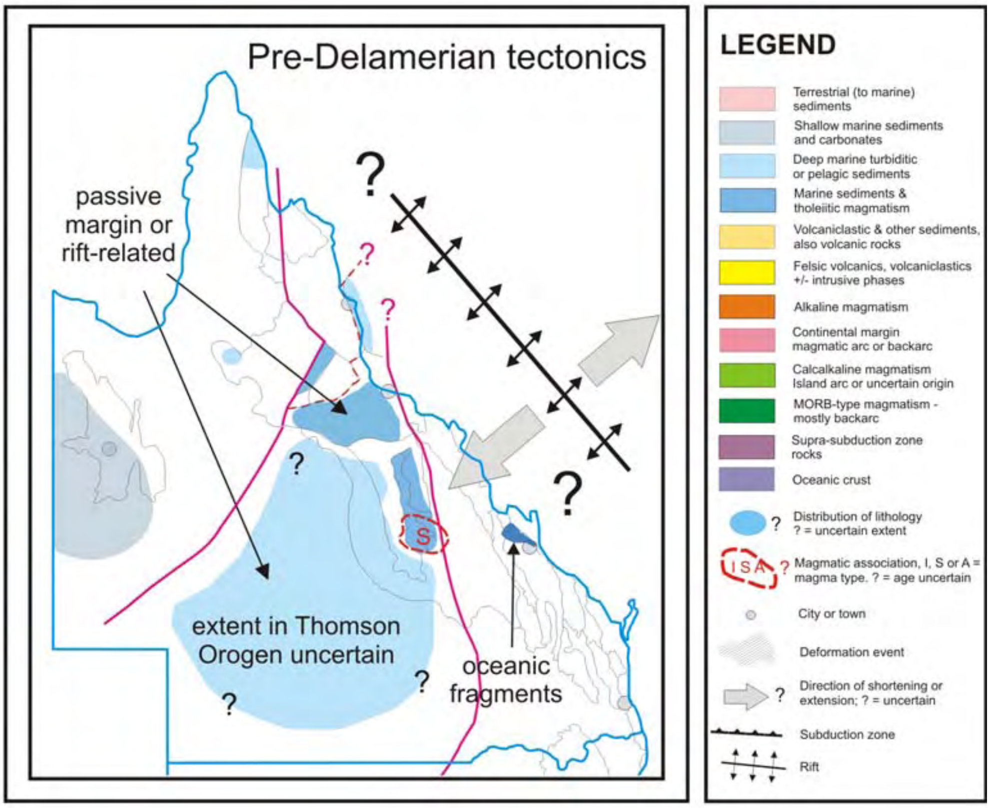

Figure 29 . Interpreted tectonic environment of Queensland for the pre-Delamerian period (Neoproterozoic to mid Cambrian - ca. 600 Ma to Ma 515 Ma). Refer to text for discussion of tectonic interpretation.

Paleogeographic reconstructions of Rodinia often suggest that breakup occurred early (c. 725 Ma) and that rifting was well offshore of Australia by 600 Ma (e.g., Li and Powell, 2001; Li et al., 2008). The abundance of 600-570 Ma rift-related magmatism in eastern Australia would appear to indicate, as suggested by Crawford et al. (2003a), that actual (or renewed) breakup may have begun ca. 600 Ma. Fergusson et al. (2008) report MORB-like chemistry within Neoproterozoic basaltic rocks of the Bathampton Metamorphics, Anakie Inlier, and suggested that they may be related to younger (ca. 600 Ma) rifting of a microcontinent (see also Fergusson et al., 2001), after initial Rodinian rifting at ca. 725 Ma. Evidence for such microcontinent rifting may be preserved within the Selwyn Block of the

Lachlan Orogen (VandenBerg et al., 2000), which is thought to represent older continental basement beneath the Melbourne Zone and its continuation in western Tasmania (Cayley et al., 2002). Crawford et al. (2003a) have suggested that the Selwyn Block represented part of Australia rifted off during the 600 Ma breakup event. As suggested by Fergusson et al. (2001, 2008), the Anakie Inlier may have formed in a manner similar to the Selwyn Block, rifted from the Gondwana margin. The sparse available data for the Thomson Orogen make this interpretation difficult to test.

Detrital zircon ages obtained by Fergusson et al. (2007c) in the Thomson Orogen and southern North Queensland Orogen show that the late Neoproterozoic (ca. 600 Ma) rocks (e.g., Cape River Metamorphics, lower Argentine Metamorphics (Charters Towers region) and Bathampton Metamorphics (Anakie Inlier) generally contain abundant ca. 1200-1000 Ma (Grenville-age) detrital zircons and only minor 1870-1550 Ma zircons, indicating at best only minor input from (present-day nearby) cratonic regions such as Mount Isa and Georgetown. Fergusson et al. (2007c) suggested the ca. 1200 Ma zircons were possibly derived from an extension of the Late Mesoproterozoic (1200–1050 Ma) orogenic belt represented by the Musgrave Province (central Australia) 1500 km to the west. Maidment et al. (2007) have suggested that similar zircon populations in the Amadeus Basin, central Australia, reflected uplift and erosion of the Musgrave Province during the Petermann Orogeny.

2.4. Early to Middle Cambrian

Delamerian Orogeny: ca. 520 Ma to ca. 490 Ma

Overview

The breakup of Rodinia and associated passive margin of eastern Australia between the Late Neoproterozoic (ca. 600 Ma) and the Early Cambrian was halted with the onset of subduction and accompanying contractional orogenesis – called the Delamerian Orogeny. This orogeny is best represented in southeastern Australia. In South Australia, western Victoria and Tasmania, the Delamerian Orogeny (Tyennan Orogeny in Tasmania) commenced at ca. 515 Ma (e.g., Foden et al., 2006; Seymour and Calver, 1995). Evidence for the Delamerian Orogeny is also found in New South Wales and Queensland. Although broadly similar ages to South Australia and Victoria have been recognised, deformation appears to have been shorter-lived farther to the north (Foden et al., 2006; Black, 2007; Fergusson et al., 2007a, b).

Northeastern Australia

The Delamerian Orogeny deformed and metamorphosed rocks of the Anakie Inlier, the Charters Towers region (see below), the Koonenberry Belt and the central Thomson Orogen (Murray and Kirkegaard, 1978) and caused uplift in parts of the Georgina Basin (Ambrose et al., 2001; Figure 31). In northern Australia, the Delamerian Orogeny is best recorded in basement rocks of the Anakie and Koonenberry regions. Based on comparative evidence from the Anakie Inlier, Draper (2006) suggested that deformation of subsurface metasedimentary rocks in the eastern Thomson Orogen was also likely to have occurred during the Delamerian Orogeny. The contractional event was predominantly east-west in the Thomson Orogen, and northwest-southeast in the Koonenberry Belt (Gilmore et al., 2007). The Delamerian Orogeny is poorly recorded in the Warburton Basin in general (e.g., Murray and Kirkegaard, 1978), although uplift and erosion of the basin was apparently coincident with the orogeny (recognised as the Mootwingee Movement; Gravestock and Gatehouse, 1995). Effects of the Delamerian Orogeny in the Georgina Basin were also minimal, expressed by minor uplift and a significant unconformity (Ambrose et al., 2001).

Delamerian deformation was accompanied by syn- to postorogenic calcalkaline magmatism in the Anakie Inlier and Koonenberry Belt (Withnall et al., 1995; Crawford et al., 1997; Gilmore et al., 2007), and in the Warburton Basin (Gatehouse, 1986). As suggested by Gatehouse (1986), the calcalkaline volcanism may relate to an arc present at this time. Although the Bourke-Louth regions are adjacent to the Koonenberry Belt, rocks of this age do not appear to have been recorded in the former. The possible presence of an arc in the Warburton-Koonenberry region at this time, well west of the Anakie Inlier, is problematical. Withnall et al. (1995) suggested this may have either reflected a very wide Delamerian Orogen or subsequent (post-Delamerian) extension and rifting of the Anakie Inlier eastwards. The latter, however, does not appear to be consistent with the recent discovery of flat-lying Ordovician volcanic rocks overlying deformed and metamorphosed metasedimentary rocks in the central Thomson Orogen (Draper, 2006).

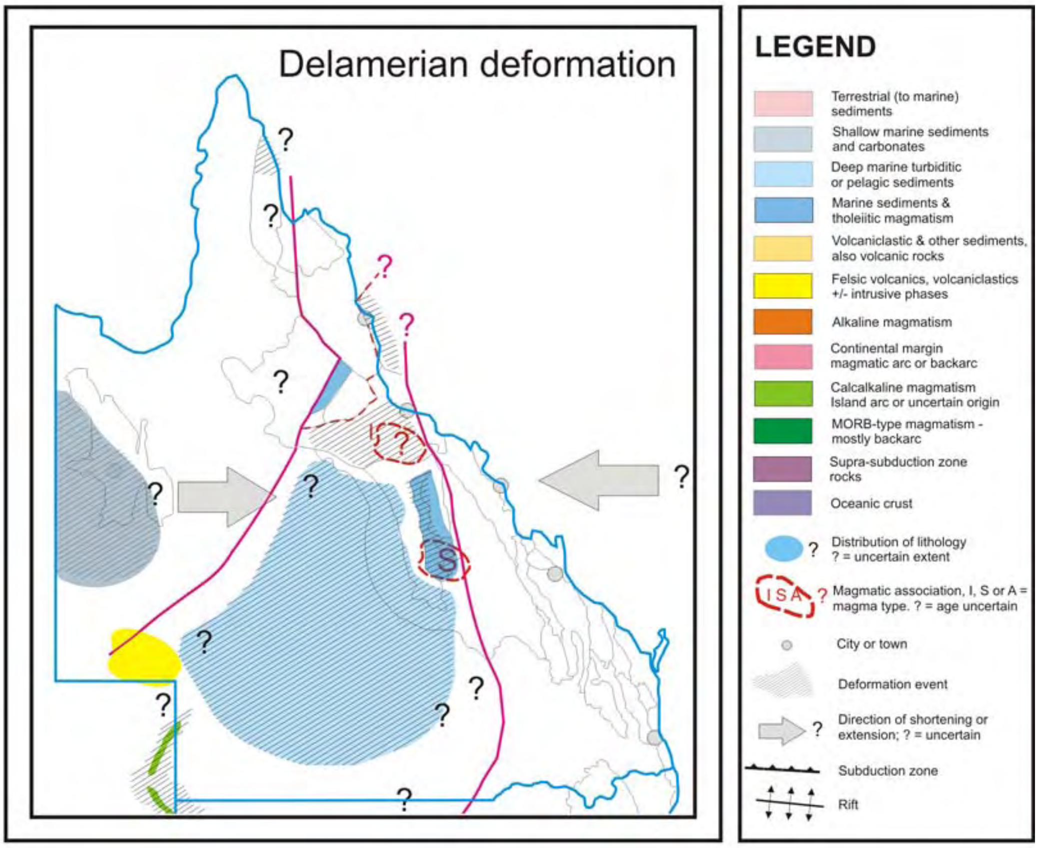

Figure 30. Generalised (approximate) distribution of deformation within the Delamerian Orogeny (ca. 520-490 Ma) as defined by outcrop and drill hole information (Thomson Orogen). For all areas, actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. See text for data sources.

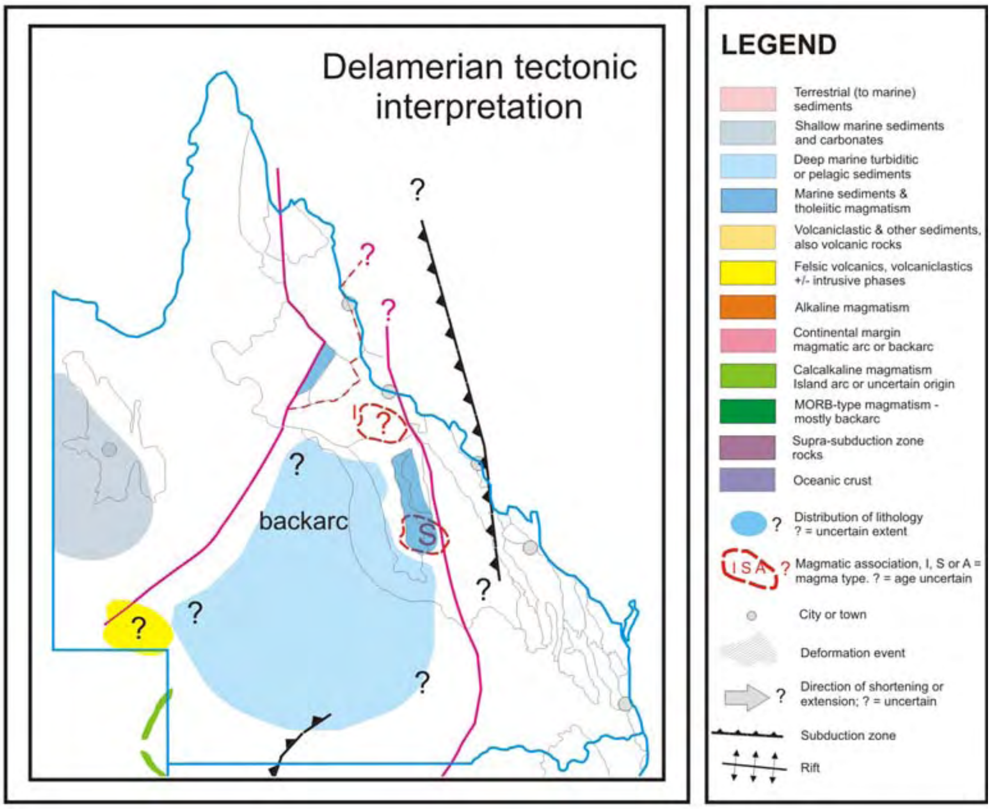

Figure 31. Interpreted tectonic model for the Delamerian Orogeny of Queensland (ca. 520-490 Ma). Refer to text for detailed discussion.

The Delamerian Orogeny is poorly represented in northern Queensland, partly reflecting the geochronological uncertainty of many of the units. The best evidence for the orogeny appears to be within the Greenvale Province (ca. 520-510 Ma; Nishiya et al., 2003) and in the Charters Towers region (ca. 495 Ma; Fergusson et al., 2007a). Potential Delamerian deformational events may occur in the Georgetown and Coen regions, but geochronological data are absent. A number of deformations that could be interpreted as Delamerian have been shown, at least partly, to represent post-Delamerian extension (Fergusson et al., 2007a, b). There is little definitive evidence for the existence of an arc environment at this time in North Queensland. Probably the best indication of such an arc is the existence of post-Delamerian, latest Cambrian-Early Ordovician, volcanic successions in the Georgetown and Charters Towers regions (Henderson, 1986; Withnall et al., 1991; Stolz, 1994), usually interpreted as backarc settings.

2.5. Late Cambrian to earliest Silurian

Post-Delamerian to Benambran Orogeny: ca. 490 Ma - ca. 430 Ma

Overview

Eastern Australia through the Benambran Cycle (post-Delamerian Orogeny to Benambran Orogeny) is dominated by two contrasting rock packages:

- Deep water, quartz-rich turbidites of cratonic provenance and associated pelagic sediments, commonly interpreted as a backarc and/or passive margin environment.

- Calcalkaline magmatism and volcaniclastics and marine sediments with common carbonates, variously interpreted as having formed in oceanic arcs, and/or backarc environments.

These contrasting rock packages are best exemplified in the Lachlan Orogen, but occur through eastern Australia. Widely distributed post-Delamerian intrusive, mostly felsic, magmatism also occurred in this cycle, though it is largely confined to northern- and central-eastern Australia.

Sedimentation and volcanism (but not intrusive magmatism) in eastern Australia largely ended with the Early Silurian Benambran Orogeny (Figure 32). Many of the North Queensland rocks were also deformed and metamorphosed in the Early Silurian (ca. 430 Ma) by a shortening event equated with, and called, the Benambran Orogeny by Fergusson et al. (2007a). The Benambran Orogeny resulted in a complex arrangement of terranes, particularly in eastern New South Wales and Victoria, but probably also in North Queensland, and perhaps in the southern and eastern Thomson Orogen (Figure 33). The orogeny was accompanied by intrusive magmatism (ca. 430 Ma and younger). This represents the first manifestation of the voluminous post-Benambran Silurian to Devonian magmatism present within the Lachlan, Thomson and North Queensland orogens (e.g., Chappell et al., 1988; Murray, 1994; Bain and Draper, 1997; Figure 12).

Overall, during the Benambran cycle eastern Australia records a relatively simple passive margin to deep marine environment and an oceanic arc environment, often depicted as a backarc (marginal basin) behind an oceanic arc and west-dipping slab (e.g., Glen et al., 1998; Li and Powell, 2001; Cayley et al., 2002; Fergusson, 2003; Gray et al., 2003; Gray and Foster, 2004; Glen, 2005; Figure 28).

North Queensland Region

Although largely dismembered (e.g., Henderson, 1987), the North Queensland region, like the Lachlan Orogen, consists of both quartz-rich sediments and calcalkaline volcanism (Figure 11). The region contains Ordovician deep water (turbiditic), dominantly quartz-rich sediments, preserved within fault-bounded remnants east of, and probably derived from, the exposed Mesoproterozoic basement in the Georgetown and Coen regions (e.g., Withnall and Lang, 1993; Garrad and Bultitude, 1999; Figure 11). The sedimentary successions in North Queensland also contain interlayered tholeiitic magmatism (Withnall and Lang, 1993; Bultitude et al., 1997; Withnall et al., 1997a), consistent with an extensional environment. Contemporaneous calcalkaline magmatism is also preserved as Early to Middle Ordovician volcanic- or volcaniclastic-dominated successions (e.g., Seventy Mile Range Group, Balcooma Metavolcanic Group - Henderson, 1986; Withnall et al., 1991; Fergusson et al., 2007a) and Early and Late Ordovician volcanic and carbonate-dominated successions, for example, in the Broken River Province (Withnall and Lang, 1993; Figures 11, 33). Many authors have suggested backarc, continental-margin arc or island-arc affinities for the sediments and calcalkaline successions (e.g., Withnall et al., 1991, 1997b; Henderson, 1986; Stolz, 1994), suggesting an environment not dissimilar to the same age rocks in the Lachlan Orogen (e.g., Gray and Foster, 2004; Glen, 2005). Unlike the Lachlan Orogen, however, units in North Queensland locally contain both quartz-rich marine sediments and calcalkaline volcanics (e.g., the Judea Formation and Everetts Creek Volcanics; Withnall and Lang, 1993), as well as volcanic clasts in conglomerate which appear to correlate with known calcalkaline volcanic units in the region (Garrad and Bultitude, 1999). These features suggest proximity between arc-related volcanism and cratonic-derived sedimentation, and support, though do not necessarily confirm, suggestions that the quartz-rich sediments were deposited within a backarc environment. A similar scenario is recorded within the Anakie Inlier (eastern Thomson Orogen), which contains Late Ordovician marine sediments, including carbonates, and associated mafic to intermediate volcanic rocks (Fork Lagoons beds, Withnall et al., 1995; Figures 11, 33). The sediments appear to be derived from cratonic and volcanic provenances (Fergusson et al., 2007c) and the volcanic rocks have geochemistry consistent with either arc or backarc environments (Withnall et al., 1995). Notably, calcalkaline volcanics, interpreted as arc-related, are also recorded in the southern Thomson Orogen, in New South Wales (e.g., Burton et al., 2008). According to Watkins (2007) and Burton et al. (2008), these appear to be chemically similar to rocks within the Macquarie Arc. Contemporaneous within-plate magmatism is also recorded, which Watkins (2007) suggested was in a backarc environment. Evidence for partly contemporaneous Late Ordovician and Silurian, probably oceanic, arc magmatism is also recorded within accreted blocks within the New England Orogen (e.g., Cawood and Leitch, 1985).

Post-Delamerian intrusive magmatism occurred across northern Australia in this cycle. In North Queensland, these include ca. 490 Ma to ca. 455 Ma (e.g., Hutton et al., 1997), dominantly felsic I-type, and mafic, (mantle-derived) magmatism of the Macrossan Association (Bain and Draper, 1997; Figures 11, 33). These magmatic rocks are best represented in the Charters Towers region. Intrusive magmatism of this age recently has been confirmed in the southern parts of the Thomson Orogen (e.g., Draper, 2006), although the actual extent is uncertain (Murray, 1994). The Ordovician magmatism in North Queensland is temporally and, at least partly spatially, associated with extensional deformation and low-P high-T metamorphism documented by Fergusson et al. (2007a, b) for the volcanic and sedimentary successions in the Greenvale and Charters Towers regions. Fergusson et al. (2007a, b) suggested this extension was related to formation of these rocks (and areas) within a back-arc environment. Such a scenario for the southern Charters Towers region suggests that the Macrossan Association magmatism in the northern part of the region may represent the actual magmatic arc (e.g., Henderson, 1980; Figure 33). Early to Middle Ordovician felsic (rhyolitic) volcanism and associated granites, also occur within the central Thomson Orogen. Chemical affinities are unknown. Draper (2006) suggested the magmatism there may also relate to extension and crustal thinning in the Ordovician. West of the Thomson Orogen, this time period corresponds with the onset of more widespread marine basin sedimentation following the Delamerian Orogeny and intracratonic rifting, for example, in the Georgina (Ambrose et al., 2001; Kruse et al., 2002) and Warburton basins (Gatehouse and Cooper, 1986). Progressive marine incursion caused an expansion of basins across central Gondwana as a shallow sea (Larapinta Sea; Webby, 1978), believed to link the Warburton, Amadeus and Canning basins (Webby, 1978; Li and Powell, 2001; Gravestock and Gatehouse, 1995; Maidment et al., 2007). This sedimentation continued until interrupted by the Benambran/Alice Springs (1) Orogeny which caused uplift and associated regression of the Larapinta Sea (Webby, 1978; Gravestock and Gatehouse, 1995).

Benambran Orogeny

Many of the rocks in North Queensland were also deformed in the Early Silurian by a shortening event coupled with metamorphism – called the Benambran Orogeny by Fergusson et al. (2007a). Evidence for this deformation is found in the Georgetown region, dated at ca. 430 Ma, synchronous with (and slightly pre-dating) I-type magmatism (Withnall et al., 1997a; Fergusson et al., 2007a). A similar deformation is recorded in the northern Thomson Orogen in the Charters Towers region, possibly at ca. 440 Ma (Fergusson et al., 2007b). Contractional deformation, related to the Benambran Orogeny(?), is also present within the Hodgkinson and Broken River Provinces, but appears to be earlier – probably Late Ordovician. Garrad and Bultitude (1999) have suggested that there may be a time break between Ordovician and Silurian rocks in the Hodgkinson Province, which corresponds to uplift in the Georgetown region to the west. Early Silurian contraction is also recorded in the Warburton Basin, Koonenberry Belt and possibly the eastern Thomson Orogen (Gatehouse, 1986; Withnall et al., 1995; Gilmore et al., 2007). Based on metamorphic ages, it is also presumed that the orogeny affected rocks of the central Thomson basement (e.g., Draper, 2006), although the areal extent of the deformation cannot be resolved. Deformation around this time within the Georgina Basin has been attributed to early episodes of the Alice Springs Orogeny (e.g., Boreham and Ambrose, 2007).

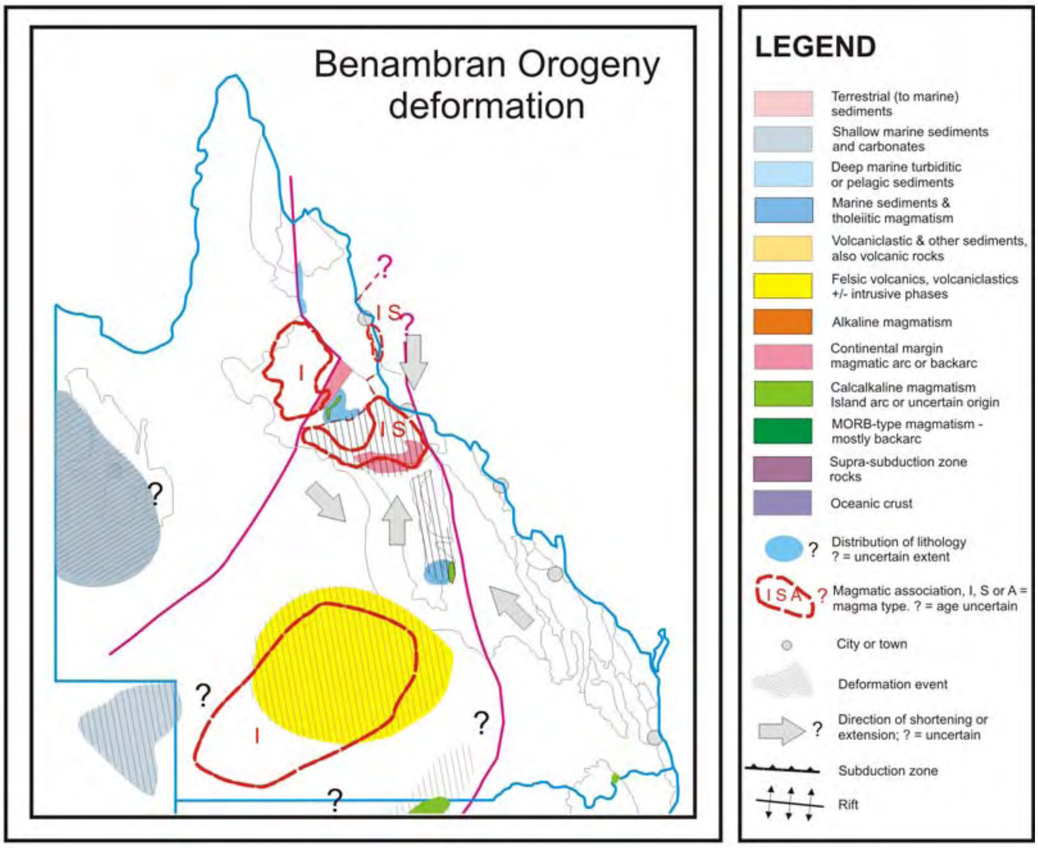

Figure 32. Generalised (approximate) distribution of deformation within the Benambran Orogeny (ca. 455 Ma – ca. 430 Ma) as defined by outcrop, drill core and extrapolation – actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. Also highlighted in continuous red lines are regions with syntectonic, ca. 430 Ma granites. See text for data sources. Refer to Figure 11 for additional geological explanation.

Younger, syn- (to post-) Benambran (ca. 430 Ma and younger) intrusive magmatism occurs throughout eastern Australia, and represents the first manifestation of the voluminous Silurian to Devonian magmatism present in the Lachlan, Thomson and North Queensland orogens (e.g., Chappell et al., 1988; Murray, 1994; Bain and Draper, 1997; Figures 11, 12, 33, 36). This includes the dominantly I-type magmatism in North Queensland (Georgetown and possibly the Charters Towers region; Withnall et al., 1997a; Hutton et al., 1997; Fergusson et al., 2007a; Figure 33), the undercover parts of the Thomson Orogen (ca. 430 Ma; Draper, 2006), and largely S-type magmatism of early Silurian age in the Central and Eastern Lachlan Orogen (e.g., Collins and Hobbs, 2001).

In North Queensland, calcalkaline rocks in the Broken River region are interpreted to represent island arc remnants accreted during the Benambran Orogeny (Fergusson et al., 2007a; Figure 33). In addition, the interpreted backarc volcanic rocks in the Charters Towers region and Greenvale Province have quite different present-day orientations – ~east-west versus north-northeast–south-southwest, respectively (e.g., Bain and Draper, 1997; Figure 33). This suggests either later relative movement between the regions, due to deformation (e.g., Bell, 1980; Fergusson et al., 2007a), and/or perhaps the volcanism formed independently on different crustal fragments. Possible island arc successions also occur in the eastern Thomson Orogen (e.g., Withnall et al., 1995). These rocks include interpreted fault-bounded serpentinite rocks (Withnall et al., 1995), consistent with accretion. The east-west orientation of possible arc rocks in the southern Thomson Orogen also require subsequent accretion, especially if they represent an oceanic arc, as suggested by Watkins (2007). It is possible, however, that they represent an in-situ arc, and some models (e.g., Gray and Foster, 2004), do invoke an east-west arc at this time (Figure 28).

Tectonic complexities

Although eastern Australia records a relatively simple passive margin to deep marine environment and an oceanic arc environment during the Benambran cycle, in detail the situation is more complex and controversy exists over the position of terranes, number and location of subduction zones and mechanisms of terrane accretion. The situation is apparently simpler in northeastern Australia at this time, although the actual position of any arc is uncertain and may be represented in part by granites in the Charters Towers region (northern Thomson) and/or by an oceanic arc (remnants of which are now accreted within the Broken River region and within the Anakie Inlier (Figure 33). The extent and orientation of this arc to the south, for example, in the southern Thomson Orogen, is more speculative. Champion et al. (2009) suggested a model (Figure 33) which invoked a subduction zone and arc south of the Thomson Orogen, which linked through to the Larapinta Seaway via a (failed?) triple point junction (as also suggested by Gray and Foster, 2004). This arc may join with those suggested for the eastern Thomson Orogen and North Queensland. The latter, however, may relate more to the Macquarie Arc and reflect accretion associated during the Benambran Orogeny.

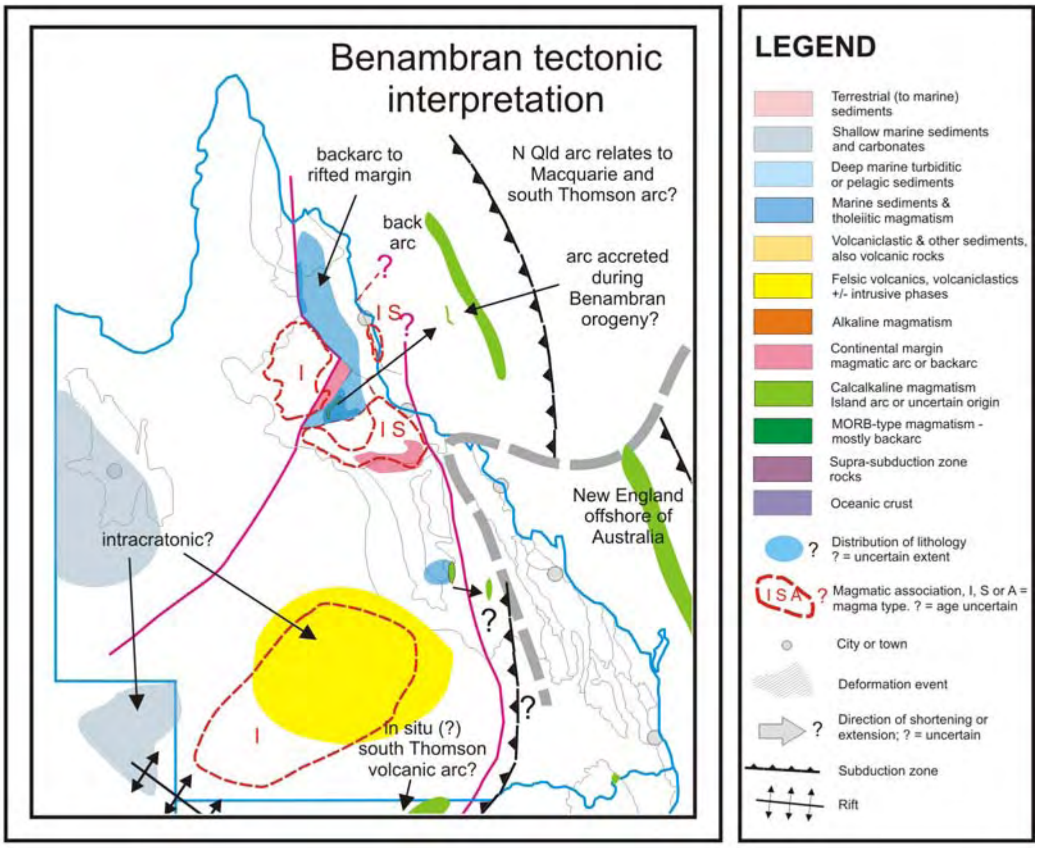

Figure 33 . Interpreted tectonic model for the Benambran cycle (ca. 490 Ma – ca. 430 Ma) of Queensland. Refer to text for detailed discussion.

2.6. Silurian to Middle to early Late Devonian

Post-Benambran to Tabberabberan Orogeny: ca. 430 to 380 Ma

Overview

The Tabberabberan Cycle (Post-Benambran to Tabberabberan Orogeny) in eastern Australia is marked by widespread extensional episodes, with accompanying basin formation and very widely distributed and voluminous extrusive and intrusive magmatism. The extension is probably related to significant subduction zone rollback after the Benambran Orogeny (e.g., Glen et al., 2004; Spaggiari et al., 2004). Two orogenies – the Bindian (ca. 420-400 Ma) and Tabberabberan (ca. 390-380 Ma) - break the extension within the Tabberabberan Cycle into two episodes. Both orogenies are recorded in most regions.

Like the Benambran cycle (ca. 490 to 430 Ma), it is evident that the Tabberabberan cycle (ca. 430 to 380 Ma) within eastern Australia records a relatively simple overall backarc environment behind a subduction zone to the east within the New England Orogen (e.g., Gray, 1997; Glen et al., 1998; Cayley et al., 2002; Gray and Foster, 2004; Glen, 2005; Collins and Richards, 2008; Figure 28). Significant accretion and amalgamation is inferred to have occurred during the Tabberabberan Orogeny.

Northern Australia

The Tabberabberan Cycle in North Queensland is characterised by extensive marine sedimentation in the Hodgkinson and Broken River regions (along the eastern and southeastern margins of the Proterozoic Georgetown block (Bultitude et al., 1997; Withnall et al., 1997b), as well as post-Bindian Orogeny terrestrial to shallow marine sedimentation in the Burdekin Basin (Charters Towers region; Hutton et al., 1997), and minor pre-Bindian Orogeny sedimentation in the Georgetown region (Withnall et al., 1997a; Figures 12, 36). Sedimentation in these regions includes marine siliciclastic sediments and carbonates, and, locally abundant, pre-Bindian tholeiitic mafic volcanism (Arnold and Fawckner, 1980). Sediment provenance is dominantly cratonic (e.g., Bultitude et al., 1997) but does include volcaniclastic material, some of which is older. For example, Garrad and Bultitude (1999) record ages of 465 Ma for dacitic clasts present within conglomeratic units in the Hodgkinson region.

Contemporaneous with sedimentation in the Broken River and Hodgkinson Provinces was emplacement of widespread and voluminous Silurian and Devonian I- and S-type felsic, and lesser mantle-derived mafic, magmatism (ca. 430 to 380 Ma) of the Pama Association (Bain and Draper, 1997). The Pama Association forms an extensive quasi-continuous belt around the Hodgkinson and Broken River Provinces, from Charters Towers in the south, north to Cape York. Pama Association magmatism in the region is diachronous. It ranges from ca. 430 Ma (syn-Benambran) in the Georgetown region, to ca. 425 to 405 Ma (and younger) in the Charters Towers region, and ca. 410 to 395 Ma in the Coen region.

Sedimentation and associated extrusive and intrusive magmatism in the Thomson Orogen and Koonenberry region also occurred within two episodes, largely in response to extension following the Benambran and Bindian orogenies (e.g., Olgers, 1972; Neef and Bottrill, 1991; Murray, 1994, 1997a; McKillop et al., 2005; Withnall et al., 1995; Gilmore et al., 2007). Post-Benambran, Late Silurian to Early Devonian marine and terrestrial sediments, of cratonic and/or volcanic provenance, are also recorded in the Koonenberry region (Neef and Bottrill, 1991), and in the Thomson Orogen (Olgers, 1972; Murray, 1994; 1997; Withnall et al., 1995; Figures 12, 36). These are associated with mafic and felsic volcanic rocks in the Koonenberry region (Neef and Bottrill, 1991) and the Anakie Inlier (Withnall et al., 1995), and felsic intrusives in the basement of the Thomson Orogen (e.g., Murray, 1994) and Koonenberry region (Gilmore et al., 2007; Figure 36). Both Murray (1994) and Thalhammer et al. (1998) have suggested continental settings. Renewed extension, following the Bindian Orogeny, produced the Early to Late Devonian, terrestrial to shallow marine Adavale Basin overlying the central Thomson Orogen (McKillop et al., 2005), the Early to Late Devonian non-marine sedimentation in the Georgina Basin (Haines et al., 2001), and Early to Middle Devonian quartz-rich sedimentation in the Koonenberry region (Neef, 2004). Haines et al. (2001) suggested that deposition of this age in the Georgina Basin (and Wiso, Ngalia, and Amadeus Basins) was synorogenic, related to the Alice Springs Orogeny. The Adavale Basin, in contrast, is considered to have formed in a continental setting possibly as an intracontinental volcanic rift (Murray, 1994; McKillop et al., 2005). Felsic intrusive magmatism accompanied extension in the Thomson Orogen (e.g., Murray, 1994; Evans et al., 1990; Hutton et al., 1997). McKillop et al. (2005) suggest that extension may have been the result of far field events, such as subduction further to the east (in the New England Orogen).

Bindian Orogeny

The Bindian Orogeny (ca. 420-400 Ma), although largely poorly defined and variably developed, appears to be present within the Lachlan, Delamerian, Thomson and North Queensland orogens, but not the New England Orogen (Figure 34). The orogeny is most evident in the Central and Eastern Lachlan in Victoria and New South Wales, where basins were inverted during the latest Silurian (-Earliest Devonian) (ca. 420-410 Ma; e.g., Gray et al., 2003). Bindian-aged deformation - ca. 410-400 Ma – in North Queensland is recorded in the Georgetown, Coen and Charters Towers regions, where it coincides with part of the extensive Pama Association magmatism (Figure 34). Bultitude et al. (1997) record a change in sedimentation in the Hodgkinson Province in the Late Lochkovian (ca. 412 Ma), and Withnall et al. (1997b) record a hiatus in sedimentation at this time in the Graveyard Creek Subprovince. Both authors suggested that these changes were related to hinterland uplift (due to Bindian Orogeny?). Sedimentation also appears to recommence at this time in the Charters Towers region. Local folding and metamorphism, probably with associated felsic magmatism, took place in the Koonenberry region and the Thomson Orogen during the Bindian Orogeny (e.g., Thalhammer et al., 1998; Figure 34). The orogeny may have been diachronous. Deformation in the Koonenberry region is recorded as Late Silurian to Early Devonian (Gilmore et al., 2007), while it appears to be late Early Devonian in the Thomson Orogen, constrained by ages of ca. 408 and 402 Ma in overlying volcanic rocks in the post-Bindian Adavale Basin (McKillop et al., 2005). A slightly younger, significant early Middle Devonian unconformity in the Adavale Basin (McKillop et al., 2005) could, however, also relate to the Bindian Orogeny.

Tabberabberan Orogeny

Deformations around this age in North Queensland are best represented in the Broken River and Hodgkinson regions and also in the Charters Towers region, where they include time breaks and slight angular unconformities (Withnall and Lang, 1993; Bultitude et al., 1997; Figure 35). Henderson (1987) suggested that this event resulted in the cessation of deep-marine sedimentation in the Camel Creek Subprovince, and produced the Middle Devonian angular unconformity observed in the Graveyard Creek Subprovince. Garrad and Bultitude (1999) recorded east to north-east directed thrusting and north-northwest-trending shear zones in the Hodgkinson Province, which they suggested were of Late Devonian age, possibly related to basin inversion (though possibly also related to development of an accretionary wedge). Although apparently slightly younger, the latter events probably equate with the Tabberabberan Orogeny, especially given the strong commonalities between the Broken River and Hodgkinson Provinces, that is, deep-water marine sedimentation probably ceased simultaneously in both.

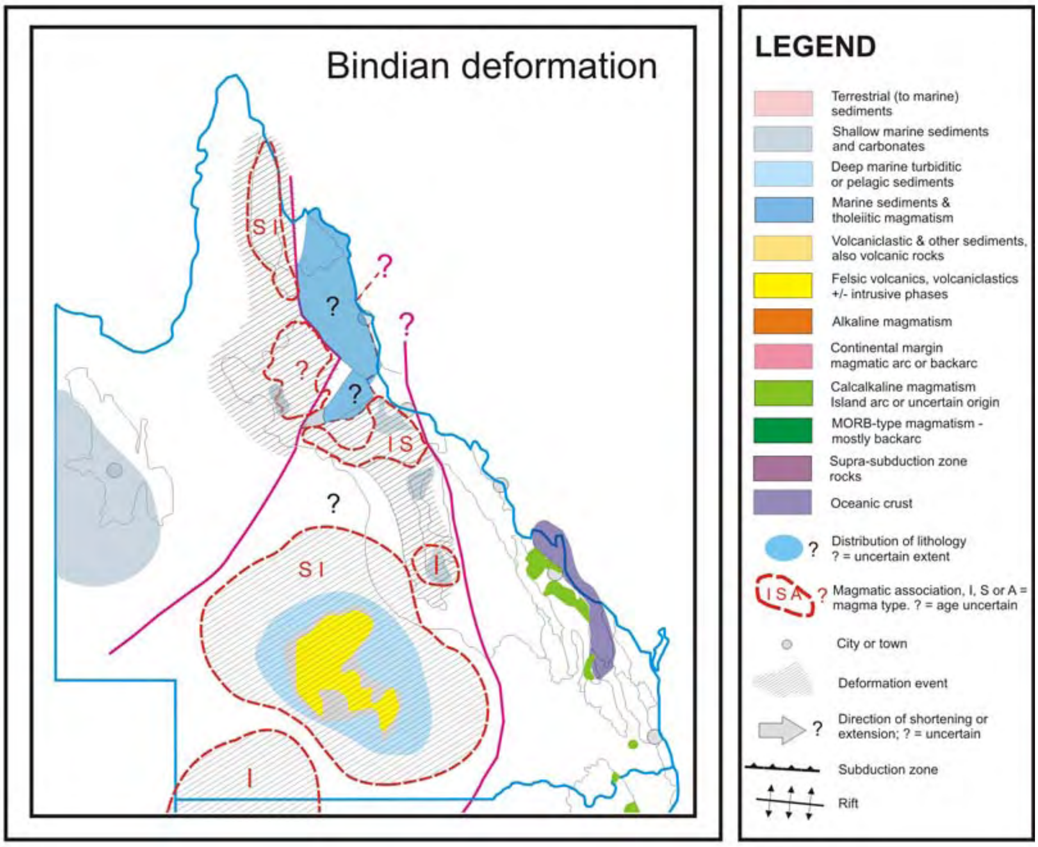

Figure 34. The generalized (approximate) distribution of deformation during the Bindian Orogeny deformation (ca. 420 to 400 Ma) as defined by outcrop and drill hole information – actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. See text for data sources. Refer to Figure 12 for additional geological explanations.

Deformation of this age in the Thomson Orogen (often called the Alice Springs Orogeny (2)) is either poorly developed or difficult to distinguish from other events (Withnall et al., 1995; Hutton et al., 1997). In the Adavale Basin, the orogeny appears to have produced an unconformity between terrestrial and overlying shallow marine sedimentary rocks, and a possible change to restricted basin conditions in the late Middle Devonian (McKillop et al., 2005). The Tabberabberan Orogeny in the Koonenberry region resulted in east-northeast – west-southwest contractional deformation at ca. 395 Ma (Mills and David, 2004; Neef, 2004).

Tectonic complexities

The geodynamic setting for sedimentation and magmatism in North Queensland during the Tabberabberan cycle is controversial. Geodynamic models for the Hodgkinson and Broken River provinces, where the great bulk of Tabberabberan sedimentation is concentrated, include both backarc, forearc/accretionary wedge, and rifted continental margin interpretations (see summaries in Arnold and Fawckner (1980), Withnall et al. (1997c) and Garrad and Bultitude (1999)). Arnold (in Arnold and Fawckner, 1980), and Henderson (1987), amongst others, suggested that the Hodgkinson and Broken River Province sedimentation was part of a forearc basin and accretionary wedge. This model has difficulties explaining the tholeiitic volcanism, which is locally abundant in the western part of the Hodgkinson Province. Tholeiitic magmatism is more consistent with rift or backarc models (e.g., Fawckner in Arnold and Fawckner, 1980; Bultitude et al., 1997), although it could possibly represent either accreted ocean floor basaltic magmatism or forearc magmatism (although the latter is often associated with boninitic, high-Mg andesitic or alkaline magmatism, e.g., McCarron and Smellie (1998), Madsen et al. (2006)). Resolution of the geodynamic setting in the region is critical to understanding the origins of the widespread Pama Association magmatism. The latter forms an extensive quasi-continuous belt around the Hodgkinson and Broken River Provinces, from Charters Towers in the south, north to Cape York, and at least superficially, resembles the roots of a magmatic arc. Pama Association magmatism in the region is diachronous. It ranges from ca. 430-420 Ma felsic I-type magmatism (syn-Benambran) in the Georgetown region, to ca. 425 to 405 Ma (and younger) dominantly I-type felsic magmatism in the Charters Towers region, to ca. 410 to 395 Ma I- and S-type magmatism in the Coen region. As pointed out by Champion and Bultitude (2003), these age differences are also matched by changes in geochemical signature, and the early Pama magmatism (in the Georgetown region) has a geochemical signature consistent with arc magmatism. Overall, however, the geochemical and isotopic signatures of this felsic magmatic association are dominated by a strong crustal input (e.g., Champion and Bultitude, 2003) making geodynamic interpretation equivocal.

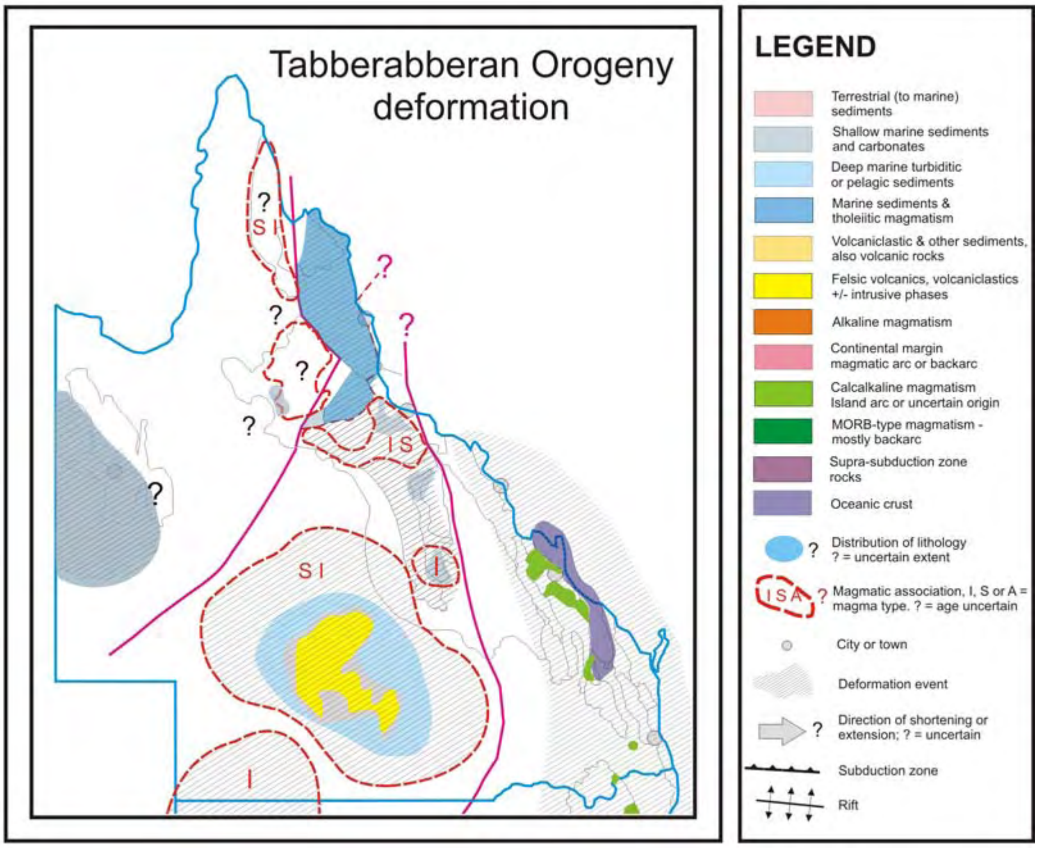

Figure 35 . The generalized (approximate) distribution of deformation during the Tabberabberan Orogeny (ca. 390 to 380 Ma) as defined by outcrop and drill hole information – actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. See text for data sources. Refer to Figure 12 for additional geological explanations.

The Pama Association magmatism in North Queensland forms part of the extensive belt of magmatism that runs from Tasmania to North Queensland. The large areal distribution of this magmatism in eastern Australia during the Tabberabberan cycle (Figures 12, 36) is problematical and has led many authors to speculate on various tectonic scenarios. This is especially so for the Lachlan Orogen, where the Silurian-Devonian magmatism occupies some 650 km east-west extent. Suggested tectonic environments for the Lachlan during the Tabberabberan cycle include multiple subduction zones (e.g., Collins and Hobbs, 2001; Soesoo et al., 1997; Gray and Foster, 1997), delamination (Collins and Vernon, 1994), mantle plumes (e.g., Cas et al., 2003), and backarc extension and episodic contraction related to variable subduction zone rollback (VandenBerg, 2003). The multiple subduction models, especially the divergent double subduction model of Soesoo et al. (1997), have the advantage of potentially explaining the distribution of, and the observed diachronous trends shown by, the Lachlan granites, especially in the western and central Lachlan. It is noted, however, that magmatism of this age in the Thomson Orogen and Koonenberry region (Figure 36), although poorly understood and with little geochronological control, appears to occupy a somewhat similar east-west extent to the Lachlan Orogen, suggesting that backarc to behind-arc processes (not multiple subduction zones) are sufficient to explain the width of magmatism in eastern Australia. As already discussed, differing tectonic models also exist for the widespread Pama Association magmatism in North Queensland and Charters Towers (Figures 12, 36), that is, magmatic arc ± backarc versus backarc. This situation mirrors, to some extent, the controversy within the New England Orogen concerning the nature of the Calliope-Gamilaroi Arc, which has, on the basis of geology, geochemistry and isotope data, variously been interpreted as oceanic arc, continental margin arc, rifted arc, or back-arc (e.g., Flood and Aitchinson, 1992; Leitch et al., 1992; Morand, 1993a, b; Aitchinson and Flood, 1995; Bryan et al., 2003; Murray et al., 2003; Murray, 2007; Murray and Blake, 2005; see discussion in Glen, 2004). As shown by Murray (2007) and Aitchinson and Flood (1995), the true picture may have been significantly more complex, for example, subduction polarity flips. Given the general dynamic variability of arc environments (e.g., Hamilton, 1995) such complexity is probably to be expected. In this regard, the diachronous nature of the Pama Association magmatism and the corresponding changes in geochemical signature (e.g., Champion and Bultitude, 2003), could be interpreted as a switch from an early arc-forearc environment (ca. 430 Ma) evolving to a backarc environment (ca. 420-400 Ma and younger?), similar to the model of Collins and Richards (2008) for the Lachlan Orogen.

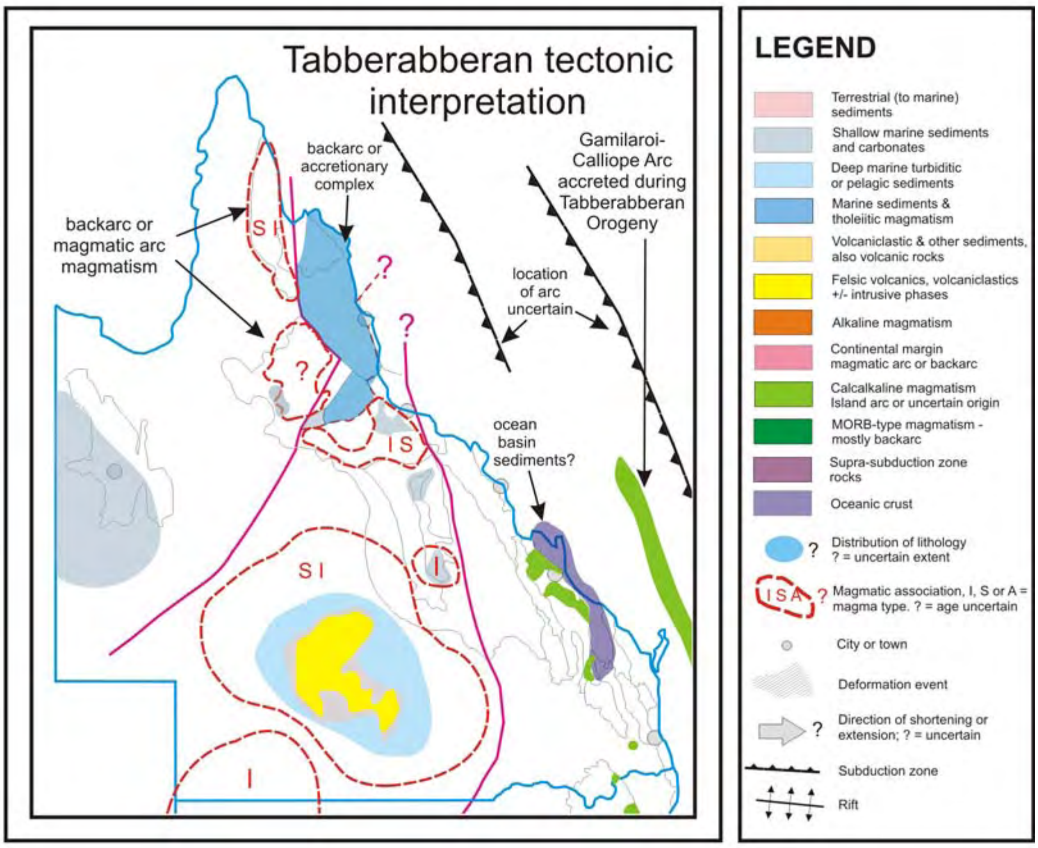

Figure 36. Interpreted tectonic model for the Tabberabberan cycle (ca. 440 to 380 Ma) of Queensland. Refer to text for detailed discussion.

2.7. Late Devonian to Early Carboniferous

Post-Tabberabberan to Kanimblan Orogeny: ca. 380 Ma - 350 Ma

Overview

During the Kanimblan cycle, the now largely cratonic Lachlan, Delamerian, Thomson and North Queensland Orogens were marked by widespread extension, rifting and accompanying basin formation, as well as significant extrusive and intrusive magmatism (e.g., VandenBerg et al., 2000; Lyons et al., 2000; Glen, 2005). Like earlier orogenic cycles, this extension is thought to reflect behind-arc processes, including a backarc basin in the north, related to renewed rollback of the subduction zone within the New England Orogen (e.g., Glen, 2005; Collins and Richards, 2008). This extension ended with the Kanimblan Orogeny (ca. 350 Ma).

North Queensland region

The Kanimblan cycle in North Queensland consists of largely non-volcanic (cratonic provenance), terrestrial and lesser marine sedimentation across all regions, best preserved in the lower successions of the Bundock, Clarke River and Burdekin basins of the Broken River and Charters Towers regions. These successions also include Late Devonian red bed units, partly contemporaneous with those in the Lachlan Orogen. Minor andesitic volcanism is recorded in the Georgetown region (Withnall et al., 1997a), and minor volcaniclastic input is recorded in sediments in several of the regions, possibly consistent, at least in part, with a backarc environment (e.g., Draper and Bain, 1997). Similarly, terrestrial (including red bed units) and marine sedimentation, often with accompanying volcanism, occurred in the Thomson Orogen, in the Adavale Basin and in the Koonenberry region, during this cycle. These also appear to have been deposited largely in response to intracratonic extension following the Tabberabberan Orogeny, but also in response to backarc extension behind the arc in the New England Orogen (e.g., Evans et al., 1990; Neef and Bottrill, 1991; Murray, 1994; Withnall et al., 1995; Henderson et al., 1998; Draper et al., 2004; McKillop et al., 2005; Gilmore et al., 2007).

Backarc extension also resulted in initiation of the Drummond Basin in the Late Devonian (Henderson et al., 1998). The Drummond Basin contains a thick succession of continental and lesser marine sediments and volcanic rocks (Olgers, 1972; Hutton et al., 1998; Henderson et al., 1998), with the lowermost units being Late Devonian to Early Carboniferous syn-rift related volcanics rocks and associated marine to terrestrial volcaniclastic sediments (Olgers, 1972; Henderson et al., 1998). In the Thomson Orogen, felsic and lesser intermediate and mafic magmatism accompanied extension episodically throughout this cycle. This includes intrusive and related extrusive magmatism in the Anakie Inlier prior to Drummond Basin formation, regionally extensive Late Devonian to Early Carboniferous, felsic magmatism in the Thomson Orogen, including within the Drummond Basin (e.g., Olgers, 1972; Murray, 1994), and Early Carboniferous granites in the basement to the Thomson Orogen and intruding the Warburton Basin (e.g., Murray, 1994). The Late Devonian-Early Carboniferous backarc silicic magmatism in the Drummond Basin at this time may be related to episodes of silicic magmatism in the New England Orogen (e.g., Bryan et al., 2004).

Kanimblan Orogeny

Extension in eastern Australia was ended by the Early Carboniferous (ca. 360-340 Ma) contractional east-west Kanimblan Orogeny (e.g., Gray, 1997; Meakin and Morgan, 1999; VandenBerg et al., 2000; Gray et al., 2003; Glen, 2005), which variably affected most of eastern Australia. Kanimblan deformation in North Queensland was generally minor in nearly all areas, and typically poorly constrained temporally, for example, minor deformation in sediments of the Pascoe Basin in the Coen region. The major exception is the Hodgkinson Province, where significant east-west shortening and further basin inversion occurred (Garrad and Bultitude, 1997). Little evidence for this deformation, however, is recorded in the nearby Broken River Province, though it may correspond to recorded breaks in sedimentation. Like the bulk of the North Queensland region, however, the Broken River Province records a major switch to long-lived, voluminous and widespread, extrusive (and intrusive magmatism) of the Kennedy Association, at or just after, the inferred timing of the Kanimblan Orogeny.

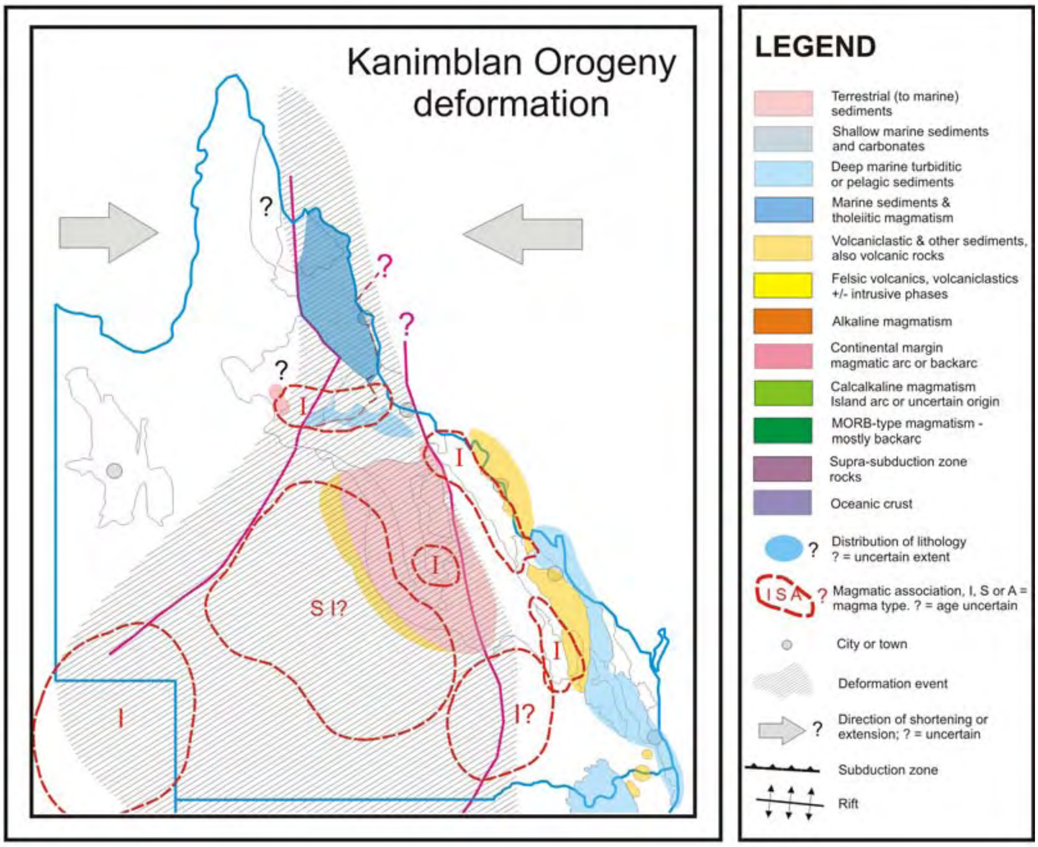

Figure 37. Generalised (approximate) distribution of deformation within the Kanimblan Orogeny (ca. 360 to 350 Ma) as defined by outcrop and drill hole information – actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. See text for data sources. Refer to Figure 13 for additional geological explanations.

The Early to ?Middle Carboniferous Kanimblan Orogeny, or Alice Springs Orogeny (3) as it is also been called in the Thomson Orogen, (also referred to as the Quilpie Orogeny in the Devonian basins of Queensland; Finlayson et al., 1990), produced a major episode of faulting and deformation in the Koonenberry Belt, slight contraction in the Drummond Basin and regional-scale folding and subsequent erosion in the Adavale Basin (e.g., Olgers, 1972; Neef, 2004; Gilmore et al., 2007). Deformation in the Drummond Basin is recorded by an unconformity between the Drummond and overlying strata in the Galilee Basin (Scott et al., in prep).

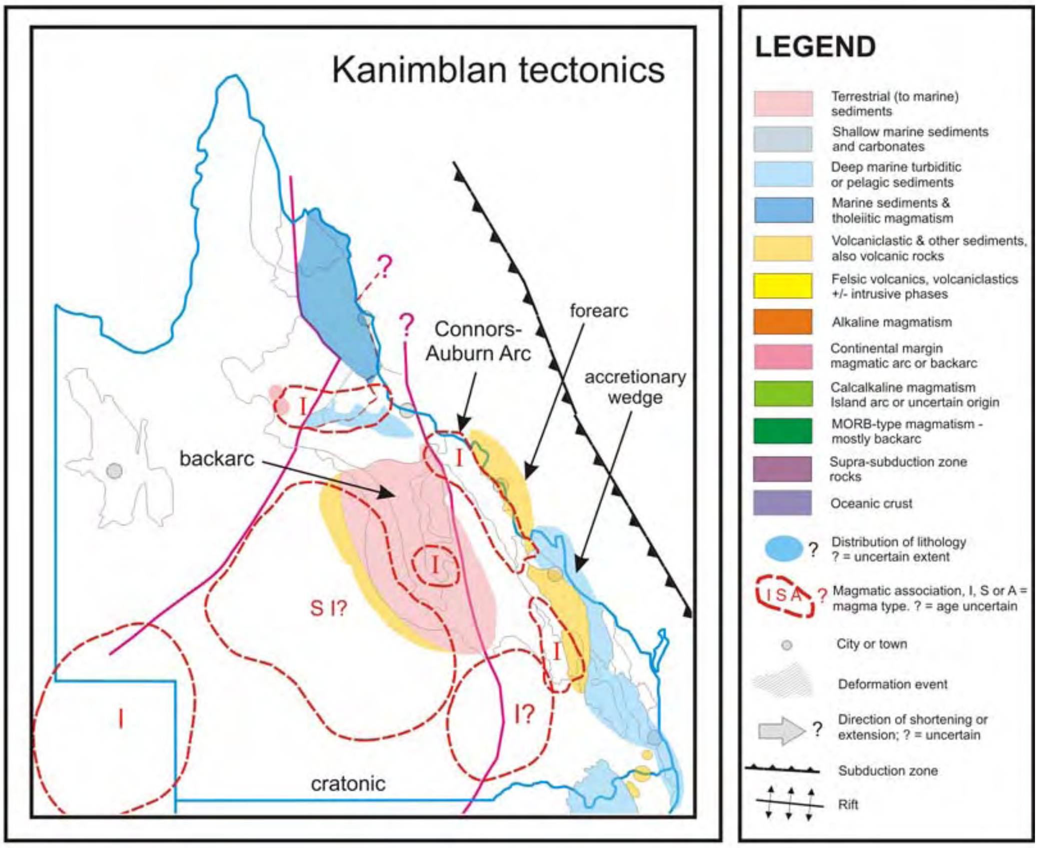

Figure 38. Interpreted tectonic model for the Kanimblan cycle (ca. 380 to 350 Ma) of Queensland. Refer to text for detailed discussion.

2.8. Middle Carboniferous to Middle Triassic

Post-Kanimblan to Hunter-Bowen Orogeny: ca. 350 Ma to ca. 230 Ma

Overview

The Hunter-Bowen cycle is largely defined on the tectonic evolution of the New England Orogen, although in detail the New England Orogen records an event history distinct from the remainder of the Tasmanides (e.g., Glen, 2005).

This period in North Queensland and in the northern Thomson Orogen (Charters Towers region and northern Drummond Basin) is characterised by the commencement of the widespread and voluminous extrusive and intrusive Kennedy Association magmatism, plus associated, mostly minor sedimentation (Figures 14, 40). As documented by Richards et al. (1966) and Champion and Bultitude (2003), this magmatism is crudely diachronous, commencing earlier in the Georgetown, Broken River and Charters Towers regions (ca. 340-335 Ma), and younging to mid to Late Permian in the Hodgkinson Province. There are also accompanying changes in geochemistry. Magmatism in the mid to Late Carboniferous is almost exclusively I-type, along with some mantle-derived magmatism. In the Early Permian, magmatism switched to A- and I-type in the Georgetown and western Hodgkinson regions, and to S- and I-type in the central and eastern Hodgkinson region (Champion and Bultitude, 2003). The tectonic regime for this magmatism is not well understood. Despite the strong crustal input into the magmatism, it is generally thought to be broadly arc-related (e.g., Champion and Bultitude, 2003, though cf.

Murray et al., 1987), probably in an extensional backarc position relative to the continental magmatic arc in the New England Orogen (Figure 40). This is consistent with the younging of magmatism to the east, matching the inferred migration of the Connors-Auburn Arc eastwards at this time (Holcombe et al., 1997a; Jenkins et al., 2002; Roberts et al., 2004).

Hunter-Bowen Orogeny and other deformation

In the Early Permian, oroclinal bending of the forearc and accretionary wedge successions of the New England orogen produced the Texas and Coffs Harbour Oroclines (Korsch and Harrington, 1987; Murray et al., 1987). Drivers for the oroclinal folding are controversial, for example, transform faulting, transtension and transpression (Korsch and Harrington, 1987; Murray et al., 1987; Fergusson and Leitch, 1993; Korsch et al., 1990; Offler and Foster, 2008) although, as summarised by Offler and Foster (2008), most models invoke dextral movement. The timing of oroclinal bending has also been the subject of much debate (e.g., see Murray et al., 1987; Fergusson and Leitch 1993; Korsch and Harrington, 1987; Donchak et al., 2007; Offler and Foster, 2008). Recent work by Offler and Foster (2008) suggests orocline deformation commenced at ca. 276 Ma, although it is noted that this is possibly contradicted by recent age dates of ca. 280-290 Ma for undeformed granites in southern Queensland (e.g., Donchak et al., 2007). What effects this orocline formation had on northern Queensland is also uncertain.

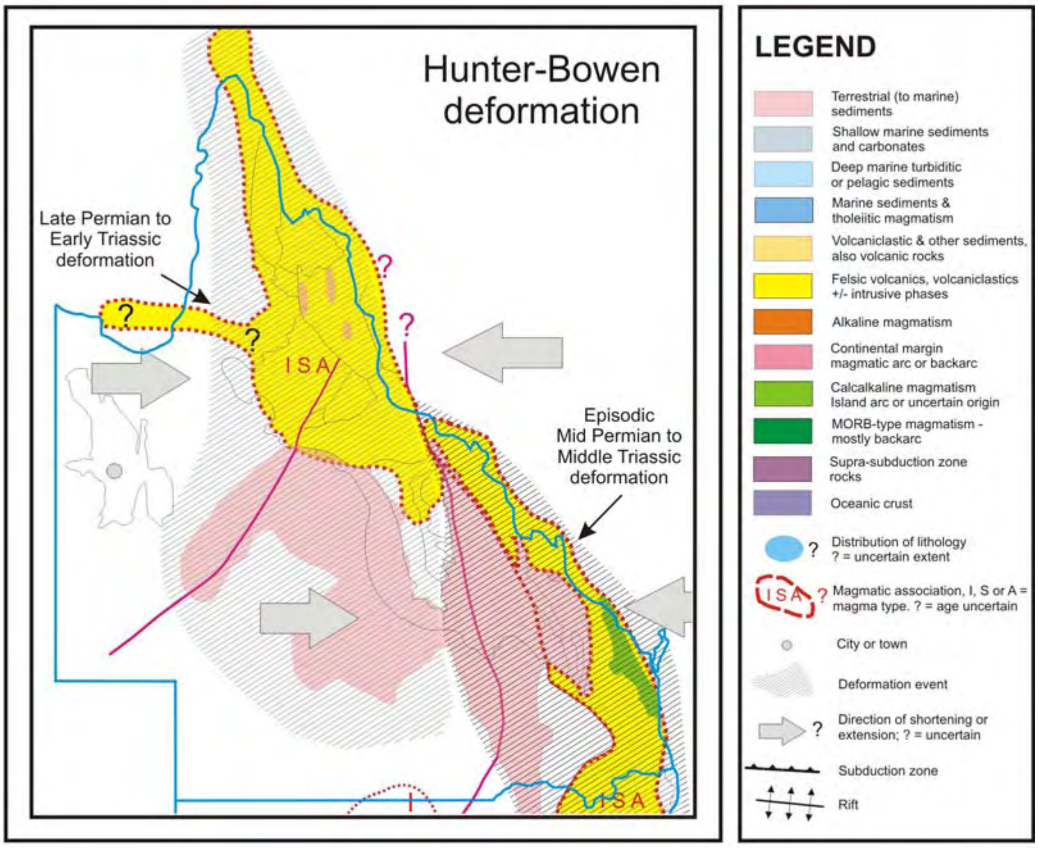

Figure 39. Generalised (approximate) distribution of deformation within the Hunter-Bowen Orogeny (~265-230 Ma) as defined by outcrop – actual extent of deformation may be greater and more continuous. The intensity of deformation is variable within the areas indicated. See text for data sources.

Deformation in North Queensland appears to have occurred at least twice during this cycle. There is a widespread but minor north-south contraction, thought to be mid to Late Carboniferous in age, commonly equated with the Alice Springs Orogeny, observed in the Broken River, Hodgkinson and Georgetown regions (Withnall et al., 1997a, b; Bultitude et al., 1997). In addition, there is a more significant deformation in the Early Permian, possibly related to an early phase of the Hunter-Bowen Orogeny. This penetrative east-west shortening deformation is best documented in the Hodgkinson Province (e.g., Davis, 1994; Davis et al., 1996; Garrad and Bultitude, 1999).

From the Late Carboniferous to Early Permian, extension initiated extensive basin formation in eastern Australia. Although the extension was dominantly located on the continental margin (New England Orogen), basins such as the Galilee and Cooper formed on the craton further west during the latest Carboniferous to Permian (Bain and Draper, 1997; Draper and McKellar, 2002; Figures 14, 40). These basins contain widespread terrestrial and glacial sediments, including coal measures (e.g., Scott et al., 1995; Draper, 2002a, b, 2004; Gray and McKellar, 2002). A connection between the Cooper and Galilee basins meant the two basins experienced related sediment deposition (Scott et al., 1995).

The onset of the Hunter-Bowen Orogeny and the resultant change from extensional to contractional tectonism in the latest Early to mid Permian, is marked by a well-developed mid Permian unconformity in the backarc Bowen Basin and intracratonic Galilee and Cooper basins (e.g., Stephens et al., 1996; Korsch et al., 1998). The switch to contraction resulted in the transition of the Bowen-Gunnedah-Sydney basin system from backarc extensional basins to foreland basins in a backarc setting (Roberts et al., 1996; Korsch et al., 2009b). The Bowen-Gunnedah-Sydney basin system retained this foreland basin setting until the Middle or Late Triassic (e.g., Harrington and Korsch, 1985; Korsch and Totterdell, 1995; Korsch et al., 2009a). Foreland basin sedimentation is also recorded in the New England Orogen, e.g., Yarrol Terrane, and Gympie Terrane. Related forearc and accretionary wedge sedimentation in the New England Orogen is thought to be located further east (now offshore, e.g., Korsch, pers. comm., 2008; Figure 40).

Terrestrial and marine sedimentation in the foreland (e.g., Bowen-Gunnedah-Sydney basins), and intracratonic basins (e.g., Cooper and Galilee basins), continued throughout the Permian and up to the Middle Triassic. Fluvial and lacustrine systems were associated with extensive peat swamps (coal measures) in the Cooper and Galilee basins (Gray and McKellar, 2002; Scott et al., 1995; Cowley, 2007; Figure 40). In the Late Permian, swamps also formed in the subsiding Bowen Basin, leading to an accumulation of extensive coal deposits (Shaw, 2002). Local, possibly originally more extensive, exposed and concealed, Late Permian, largely terrestrial sediments and coal measures occur in the Coen region and in the Hodgkinson Province (McConachie et al., 1997; Garrad and Bultitude, 1999; Figure 40).

Widespread Middle to Late Permian intrusive and extrusive magmatism (and minor sediments) is also recorded in north Queensland, where it represents the youngest component of the voluminous Carboniferous-Permian Kennedy Association magmatism (Bain and Draper, 1997; Figure 40). Late Permian Kennedy Association magmatism is largely confined to the eastern Hodgkinson Province (dominantly S-type; Bultitude et al., 1997; Garrad and Bultitude, 1999) and the Charters Towers region (I-type and mantle-derived; Hutton et al., 1997), but also includes A-, I- and mantle-derived extrusive and intrusive magmatism in the Coen, Georgetown and western Hodgkinson regions (Figure 40). It is generally thought to be broadly arc-related (e.g., Champion and Bultitude, 2003), probably in an extensional backarc or behind arc position relative to the continental arc in the New England Orogen (Figure 40). Unlike the New England Orogen, magmatism in north Queensland ceased by the end of the Permian and no Early Triassic magmatism is recorded. West of the New England Orogen, restricted Triassic magmatic activity is recorded in the Cooper Basin (Murray, 1994; Draper, 2002a, b) and in the Bourke-Louth region (Burton et al., 2008). These magmatic events suggest that tectonism on the eastern continental margin may have influenced the craton further west, for example, Burton et al.

(2008) suggest that the intrusives east of Bourke, NSW, indicate a more spatially widespread Middle Triassic magmatic pulse than is currently recognised.

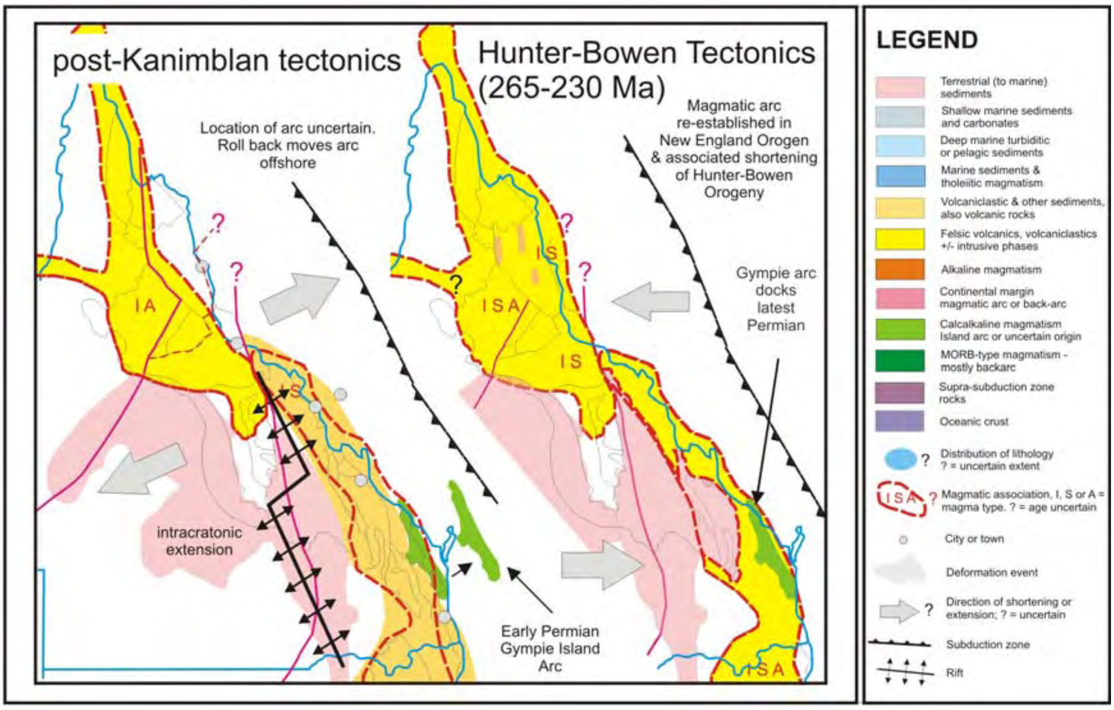

Figure 40. Interpreted tectonic models for the Early Carboniferous to mid Permian and early Late Permian to Middle-Late Triassic of the Hunter-Bowen cycle of Queensland. Refer to text for detailed discussion.

The Hunter-Bowen Orogeny covers a period of about 35 m.y. from ~265 Ma to ~230 Ma, (Murray, 1997; Holcombe et al., 1997b; Korsch et al., 2009b; Figure 39) and encompasses all of the Hunter-Bowen cycle. In the New England Orogen, deformation is characterised by retrothrusting driven by subduction further to the east. This major west-directed thrusting led to the formation of a retroforeland fold-thrust belt (Korsch et al., 1990; 1997; Fergusson, 1991; Holcombe et al., 1997; Korsch, 2004). Subsidence of the Bowen and Gunnedah basins during the foreland basin phase was driven by thrust loading related to these westward-propagating thrust sheets (Korsch et al., 2009b). The foreland basin phase of sedimentation associated with the Hunter-Bowen Orogeny was punctuated by a series of discrete contractional events (Korsch et al., 2009b) during the Permian and Triassic.

Recent detrital zircon age data suggest that the island arc component of the Gympie Terrane came into contact with the mainland New England Orogen (i.e., continent-island arc collision) prior to ~250 Ma (Permian-Triassic boundary; Korsch et al., 2009e; Figure 40). Approximately similar timing is recorded in north Queensland, where Late Permian east-west deformation, equated with the Hunter-Bowen Orogeny, is best developed in the Hodgkinson and Barnard provinces (Garrad and Bultitude, 1999; Figure 39). Contractional events of the Hunter-Bowen Orogeny also appear to have thrust the Tamworth Belt westwards over the eastern edge of the Sydney-Gunnedah Basin and Lachlan Orogen (Korsch et al., 1997; Roberts et al., 2004) around this time in the Late Permian and earliest Triassic.

In the late Middle to Late Triassic, regional contraction resulted in uplift and erosion, and cessation of deposition in the Galilee, Cooper and Bowen basins (Apak et al., 1997; Bain and Draper, 1997; Green et al., 1997; Korsch et al., 1998), as well as east-west deformation and uplift in the Drummond Basin (Olgers, 1972; Fenton and Jackson, 1989; Murray, 1990; Johnson and Henderson, 1991; Figure 39).

The Hunter-Bowen cycle marks the timing of effective cratonisation of eastern Australia. Following this cycle, there was a switch in geodynamics back to an extensional, probably backarc environment (e.g., Holcombe et al., 1997b). This resulted in a change in plutonism (A-type granites), felsic and/or bimodal volcanism (Stephens et al., 1996; Holcombe et al., 1997b) and development of extensional basins with coal-bearing successions (Holcombe et al., 1997b; Shaw, 2002). The change from backarc contraction and thrust loading to backarc extension was probably at ~230 Ma (R.J. Korsch, pers. comm. 2008).

2.9. Mesozoic basin development and Late Mesozoic magmatism

Overview

The evolution of eastern Australia from the Paleozoic into the Mesozoic – up to the end of the Hunter-Bowen Orogeny - was dominated by convergent plate margin processes, including episodes of extension, which were mainly operating in a backarc setting inboard of the active subduction system (e.g., Korsch, 1996; Veevers, 2004). This geodynamic regime is largely thought to have continued from the Early Jurassic to the Early Cretaceous, that is, eastern Australia still formed part of the eastern convergent margin of Gondwana (e.g., Norvick et al., 2001; Veevers, 2004; Raza et al., 2009). Unlike previous orogenic cycles, however, this was most probably all within a backarc setting, that is, with the arc well offshore (up to several hundred kilometres, e.g., Gurnis et al., 1998). Importantly, however, this period also coincides with the initial and on-going breakup of Pangaea (Veevers, 2004) and so some of the extension in eastern Australia may be related to this (e.g., Bryan et al., 1997, 2000). Associated sedimentation and episodic volcanism (e.g., Reid et al., 2009) continued until about ca. 95 Ma (Korsch et al., 1998; 2009; Waschbusch et al., 2009). At this time there was a hiatus (Schellart et al., 2006; Raza et al., 2009) related to a major contractional event (ca. 95-90 Ma) – called the Moonie Event by Korsch et al. (1998). This effectively ended sedimentation in a number of basins, and much of eastern Australia at this time appears to have undergone exhumation and denudation (Raza et al., 2009). Subsequent continuing extension resulted in the opening of the Tasman Sea at ca. 85 Ma (e.g., Gaina et al., 1998) and rifting of continental fragments from mainland Australia (e.g., Lord Howe Rise, New Caledonia; Gaina et al., 1998; Norvick et al., 2008; Korsch et al., 2009a, b). Northward-propagating sea floor spreading of the Tasman Sea, and subsequently the Coral Sea (ca. 62 Ma), continued into the Tertiary (ca. 52 Ma, e.g., Gaina et al., 1998).

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Much of northern Queensland underwent a depositional hiatus between the Middle Triassic and Early Jurassic (Draper and Bain, 1997) following the end of the Hunter-Bowen Cycle. The first significant event in most of North Queensland after the Hunter-Bowen Cycle was formation of the Early Jurassic to mid Cretaceous Carpentaria, Eromanga and Laura basins (Draper and Bain, 1997; McConachie et al., 1997a, 1997b; Figures 15, 42). These basins form a very widely distributed succession of Early Jurassic to mid Cretaceous fluvial and marine sedimentation (Norvick et al., 2008) in a number of component basins (also including the Nambour, Clarence-Moreton, Maryborough, and Surat Basins in Queensland; Garrad et al., 2000). Korsch et al. (1998), Korsch and Totterdell (2009) and Waschbusch et al. (2009) propose subsidence and deposition within the Surat and Eromanga basins was being driven by dynamic platform tilting due to west-dipping subduction (and corner flow coupling) in the east of Australia. The basins record episodic influxes of volcanic detritus in the Jurassic and Cretaceous (Draper, 2002), which Reid et al. (2009) suggested were related to the magmatic arc off eastern Australia. The largest volcanic influx is in the Early Cretaceous, thought to be related to the voluminous Whitsunday Volcanic Province, and their ages coincide with a period of subsidence (Draper and Bain, 1997). Although possibly as old as ca. 138 Ma, the Whitsunday Volcanic Province largely consists of ca. 125 to 95 Ma intermediate to rhyolitic calcalkaline volcanic rocks and contemporaneous intrusives (Ewart et al., 1992; Allen and Chappell, 1996; Bryan et al., 1996, 1997, 2000; Figures 15, 42). They form the northern part of an extensive, north-south belt of, largely extrusive, magmatism and associated volcaniclastic rocks of this age (e.g., Gippsland Basin) that extends along eastern Australia down to the Challenger Plateau and also New Zealand (Bryan et al., 1996, 1997, 2000; Power et al., 2001; Norvick et al., 2001, 2008). Most workers suggest an extensional geodynamic regime for this magmatism and sedimentation (Ewart et al., 1992; Bryan et al., 1996, 1997, 2000; Korsch et al., 1998, 2009; Schellart et al., 2006; Norvick et al., 2001, 2008; Crawford et al., 2003; Raza et al., 2009), although both backarc rifting and, possibly plume-related, intraplate extension have been suggested as geodynamic drivers. This is, to some extent, a semantic argument, as an arc was most likely present at this time well offshore (e.g., Crawford et al., 2003; Schellart et al., 2006), at the same time as the eastern margin of Australia [and associated pre-rifted fragments (cf. Gaina et al. 1998)] was undergoing significant extension (e.g., Korsch et al., 1998; Norvick et al., 2001, 2008; Schellart et al., 2006), possibly as a precursor to initiation of the Tasman Sea (e.g., Bryan et al., 1997; Korsch et al., 1998). Also, as indicated above, subsidence in contemporaneous basins, such as the Surat and other related basins, can be reasonably explained by dynamic platform tilting behind an arc (e.g., Russell and Gurnis, 1994; Waschbusch et al., 2009). Crawford et al. (2003) suggested that the widely distributed rifting along the eastern Gondwana margin at this time most likely resulted from rapid easterly rollback of a subduction zone to the east; Schellart et al. (2006) show a similar interpretation.

Extension, and associated deposition in eastern Australia, underwent a hiatus in the early Late Cretaceous (Schellart et al., 2006; Raza et al., 2009) related to a major contractional event (ca. 95-90 Ma) – called the Moonie Event by Korsch et al. (1998) (Figure 41). The effects of this contraction in northern Queensland are not obvious. McConachie et al. (1997a, 1997b) indicate that the Laura Basin is little deformed, and suggested that the dominant deformation recorded in the Carpentaria Basin is related to formation of the Coral Sea at ca. 65 Ma. Regardless, it seems that the youngest known rocks in the Carpentaria Basin are ca. 95 Ma (McConachie et al., 1997a, b). This is more consistent with the effects of the Moonie Event elsewhere, which effectively ended sedimentation in the Eromanga and Carpentaria basins, and resulted in basin inversion and subsequent erosion (Draper, in Withnall et al. 1997c; Korsch et al., 2009a, b). At this time, much of eastern and southeastern Australia appears to have undergone exhumation and denudation (e.g., Duddy, 2003; Raza et al., 2009; Figure 41). Volcanism also apparently ceased at this time (ca. 95 Ma., e.g., Raza et al., 2009), although, as noted by Bryan et al. (1997), the main phase of volcanism in the Whitsunday Volcanic Province was over by ca. 105 Ma, consistent with detrital zircon ages in eastern Australia which rapidly decrease in volume post 105 Ma (see compilation in Reid et al., 2009). Korsch et al. (1998) indicated that this contraction took place in an overall extensional environment and, with others (e.g., Gurnis et al., 1998; Raza et al., 2009), suggested contraction was caused by regional uplift of a passive margin associated with the start of sea floor spreading. Along similar lines, Norvick et al. (2001, 2008) and Korsch and Totterdell (2009) suggested that subduction either ceased at this time or jumped eastwards, and that the early Late Cretaceous uplift reflected rebound after the widespread subduction along the eastern Australia margin. Russell and Gurnis (1994) also related changes in sedimentation within the Eromanga and Surat basins to the changes in, and cessation of, subduction offshore.

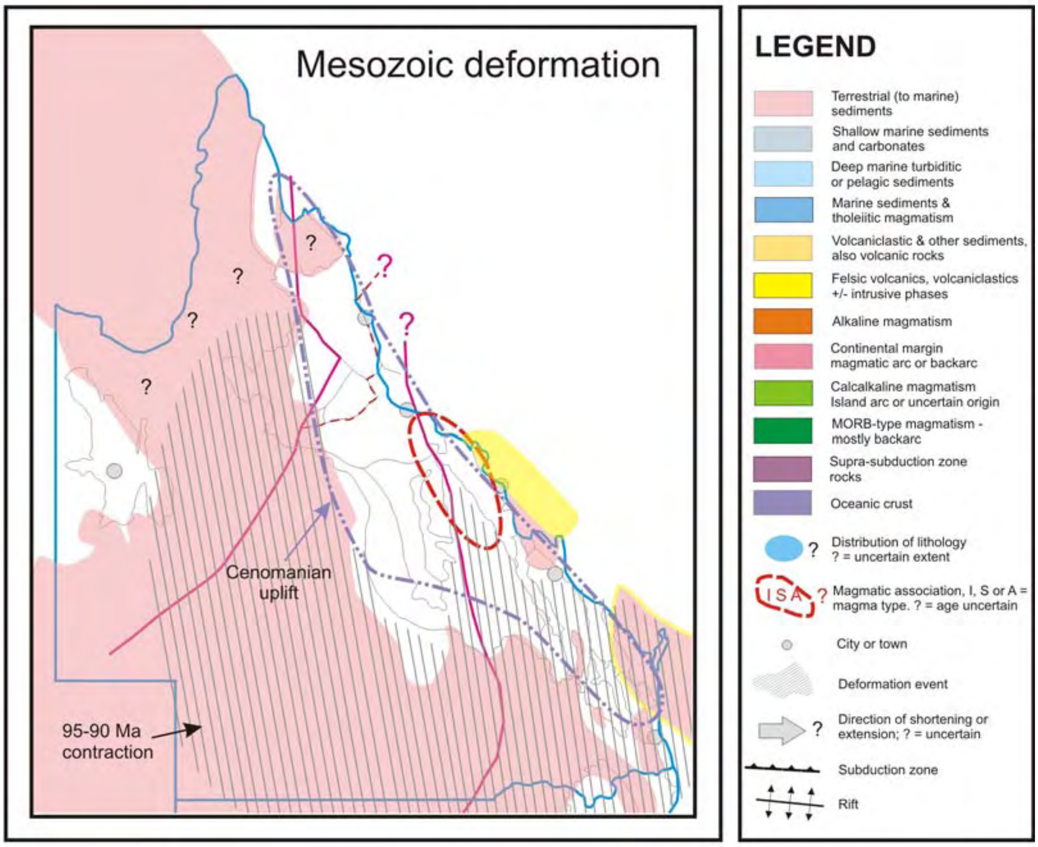

Figure 41. General distribution of Mesozoic deformation in North Queensland. Refer to Figure 15 and text for discussion.

Extension continued (or resumed, e.g., Norvick et al., 2008) after the Moonie event, most likely related to further extensive rollback of the subduction zone to the east (e.g., Schellart et al., 2006), eventually resulting in the start of seafloor spreading in southeastern Australia at ca. 85 Ma with the opening of the Tasman Sea (e.g., Gaina et al., 1998; Figures 42, 43). The Tasman Sea opened gradually northward, and resulted in rifting off and formation of continental fragments, for example, Lord Howe Rise, New Caledonia, New Zealand from Australia (Gaina et al., 1998; Norvick et al., 2008; Korsch et al., 2009a, b). Notably, there is little recorded sedimentation and magmatism within onshore North Queensland during the Late Cretaceous (post 95 Ma), although, for example, deposition, including rift-related successions, continued on the continental margin and other continental fragments now offshore (e.g., Wellman et al., 1997; Duddy, 2003; Norvick et al., 2001, 2008). Seafloor spreading of the Tasman and Coral Seas (commencing ca. 62 Ma) continued into the Tertiary (ca. 52 Ma, e.g., Gaina et al., 1998; Figures 42, 43). As suggested by McConachie et al. (1997a), the opening of the Coral Sea in North Queensland (ca. 65 Ma) may have had related uplift and erosional effects on the north Queensland mainland at that time.

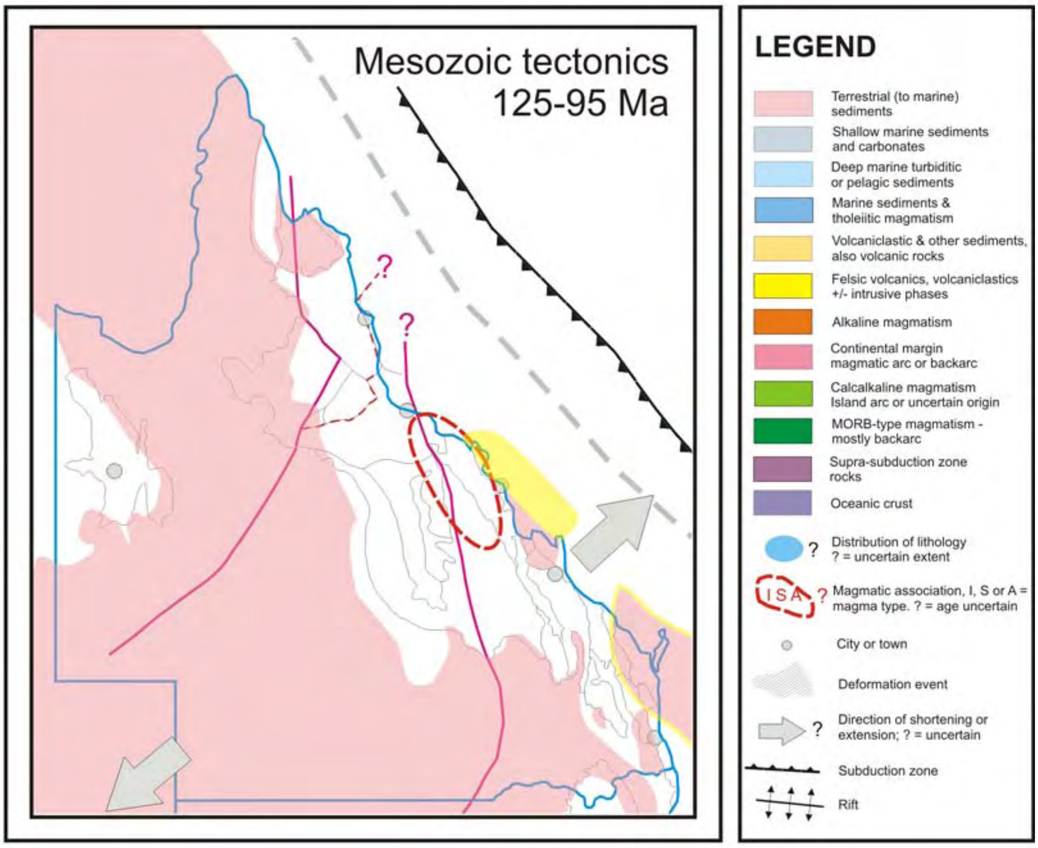

Figure 42. Interpreted tectonic model for the Mesozoic period 125-95 Ma in North Queensland. Refer to text for detailed discussion.

2.10. Cenozoic basins and within-plate magmatism (± hotspot activity)

Overview

The Cenozoic period in eastern Australia consists of two dominant geodynamic regimes. Firstly, there was a continuation of the rifting and associated seafloor spreading in southern and eastern Australia that commenced in the Mesozoic (e.g., Veevers, 2004); in particular the continuing northward opening of the Tasman Sea and opening of the Coral Sea (Gaina et al., 1998). Secondly, widespread basaltic intraplate magmatism of the Eastern Australian Volcanic Province occurred along eastern Australia at this time (~95 to 55 Ma) possibly related to both hotspot migration and more enigmatic far-field effects (see discussion in Johnson et al., 1989). Continuing offshore and onshore sedimentation, largely associated with rifting and magmatism (e.g., Grimes, 1980), also occurred through the Cenozoic. The period was also a time of significant weathering and erosion (e.g., Grimes, 1980).

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The Tasman Sea, which initiated in the Mesozoic, continued opening northward, with further spreading of continental fragments from mainland Australia, e.g., Lord Howe Rise, New Caledonia, New Zealand (Gaina et al., 1998; Norvick et al., 2008; Korsch et al., 2009a, b). In the North Queensland region this continued extension resulted in opening of the Coral Sea (ca. 62 Ma; Gaina et al., 1998) with probable associated rift-related sedimentation of similar age (e.g., Norvick et al., 2001). Spreading in the Tasman and Coral Seas, and associated rifting of the Lord Howe Rise from Australia, appears to have ceased ca. 52 Ma (e.g., Gaina et al., 1998), which may reflect a switch to east-dipping subduction at this time (ca. 55-50 Ma, e.g., Crawford et al., 2003; Schellart et al., 2006). In the North Queensland region there is only minor preserved evidence for onshore sedimentation during this period, for example, in the Charters Towers region (Withnall et al., 1997c). The main basins in this region are either significantly younger (Karumba Basin) or poorly age-constrained (Kalpowar Basin) (e.g., McConachie et al., 1997a, b; Figures 15, 41-43).

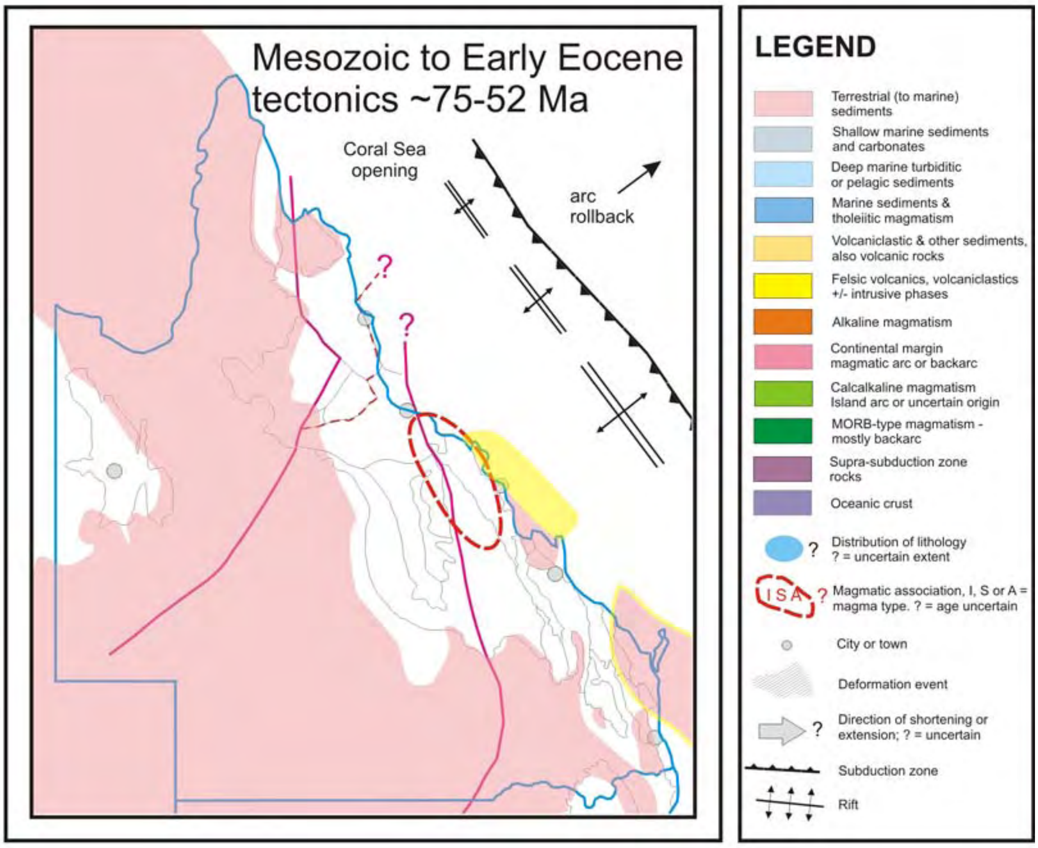


Figure 43. Interpreted tectonic model for the Mesozoic period ~75-52 Ma of North Queensland. Refer to text for detailed discussion.

Basaltic magmatism (and local associated sedimentation) has been widespread in eastern Australia during the last 70 million years (Wellman and McDougall, 1974; Stephenson et al., 1980; Stephenson, 1989; Johnson et al., 1989; Sutherland 1991; Zhang et al., 2001; Veevers 2000; Figure 19). Basaltic provinces stretch nearly 4000 km north-south in a belt from North Queensland to Tasmania (the Eastern Australian Volcanic Province - EAVP), mainly within 200 km of the eastern and southern Australian coast (Johnson et al., 1989). The EAVP in North Queensland includes two main types of volcanic fields, as recognised by Wellman and McDougall (1974): sporadic central volcanic fields and prevalent basaltic lava fields.

Central-volcano type magmatism began ~40-35 million years ago in Central Queensland, and the style shows a remarkable variation in age relative to latitude (Wellman and McDougall, 1974). Wellman and McDougall (1974) showed that from the Hillsborough Province (~40 Ma), there is a progressive decrease in age southwards to the youngest, the Macedon Province in Victoria (6 Ma). Australian plate motion calculations were used by Sutherland (1998) to predict past volcanism along thermal anomaly paths from Bass Strait to North Queensland, and the predicted ages of 30-36 Ma for Nebo, 33-39 Ma for Hillsborough, 35-41 Ma for Mingela and 42-43 Ma for West Atherton fields generally match observed ages (Sutherland, 1998). This time progression of the central-volcano magmatism reflects northward Australian plate motion over an asthenospheric plume system (hotspot), now affecting the Bass Strait-West Tasman Sea region (Wellman and McDougall 1974), referred to as the East Australian Plume System (Sutherland, 2003). The central-volcano activity implies a hotter mantle under the eastern Australian margin south of Central Queensland at this time (~40-35 Ma; Wellman and McDougall, 1974; O'Reilly and Griffin 1985), possibly a residue of a mantle anomaly that resulted in late Mesozoic and early Tertiary seafloor spreading in the Tasman and Coral Seas (Johnson et al., 1989; Sutherland, 1998).

The older occurrences in North Queensland (i.e., 44-25 Ma; Mingela, Pentland; Figure 19) are contemporaneous with the plume-related, central volcano basalts at Nebo, Peak Range and Springsure (33-24 Ma) and lava-field basalts from Anakie (31-19 Ma), some ~300-500 km to the south (Zhang et al., 2001). The data of O'Reilly and Zhang (1995) and Zhang et al. (1997, 2001) show that the Mingela basalts have incompatible element patterns and Sr-Nd isotope ratios similar to the primitive central Queensland plume-related basalts. These data may indicate a genetic link between the two contemporaneous basalt provinces, and highlight the possibility that the Australian plume may have contributed to the early Mingela basalts (Zhang et al., 1997, 2001).

The lava-field provinces of North Queensland are composed predominantly of small volume alkaline basalts (bearing abundant mantle xenoliths) occurring as dykes, pipes, diatremes, maars and long lava flows (Stephenson et al., 1989). The origin of this younger magmatism (i.e., 8.0 Ma to 10 ka) is problematical (Stephenson et al., 1989). The spatial distribution of the lava field basalts does not provide any evidence for the migration of the locus of volcanism with time (Wellman and McDougall, 1974; Stephenson et al., 1980), as predicted by conventional hotspot models, and as shown by the Australian central-volcano provinces. In New South Wales and Victoria, most of the lava field basalts are either older or approximately the same age as the central volcano basalts located at the same latitude, whereas in North Queensland, the main lava field basalts are much younger than the central-volcano basalts in the same region (Zhang et al., 2001). Geological and geophysical data do not support the presence of a plume as a mantle source for lava field magmatism in North Queensland during the last 10 million years (O'Reilly and Zhang, 1995; Zhang et al. 1997; 2001).

A number of origins for the lava field magmatism have been proposed. O'Reilly and Zhang (1995) related basaltic lava field activity to irregular small mantle plume upwellings. Zhang et al. (2001) suggested that generation of the North Queensland basalts could be induced by upwelling asthenospheric diapir(s) responding to regional extension and/or stress release. Sun et al. (1989) attributed low abundances of incompatible elements in the tholeiitic basalts to derivation from a hot and deep asthenospheric source with no apparent connection to plume activity. Several of the provinces are located close to the intersection of two major tectonic blocks, which led Johnson et al. (1989) to suggest that readjustment of these blocks might be expected to cause rifting and the possible opening of deep crust-mantle fractures, resulting in the generation of deeply sourced basaltic magmas. Whitehead et al. (2007) suggested that the volcanism may have been triggered by changes in the stress regime for North Queensland, which allowed the ascent of magma from a region of anomalously hot mantle. Changes in North Queensland lithospheric stresses, caused by far field effects such as the docking of the Ontong Java Plateau, and the subsequent development of northward subduction (San Cristobal Trench), may have allowed magma ascent from deep mantle levels (Whitehead et al., 2007).

As noted above, there is little suggestion of migration of eruption centres with age in any of the lava field provinces in North Queensland (Wellman and McDougall, 1974). This might suggest the existence of potentially eruptive basaltic magma in the asthenosphere, which intermittently establishes pathways to the surface over some period of time, maintaining the same structurally-located province. In this case, the age-position patterns of the basaltic provinces could be random, their activity being determined by favourable circumstances of stress for melt segregation and penetration of the buoyant magmas through the lithosphere. It appears likely that the localisation of the basaltic lava field provinces was controlled by structures in the lower crust or deep lithosphere (Stephenson et al., 1980).

The youngest North Queensland basalts show distinctive high $^{87}Sr/^{86}Sr$ ratios, typical of basaltic rocks from arc environments (O'Reilly and Zhang, 1995). They are also enriched in $^{207}Pb/^{204}Pb$, possibly the result of incorporation of Pacific sediments through subduction into the mantle wedge (O'Reilly and Zhang, 1995; Zhang et al., 2001). Nevertheless, North Queensland was not in a continental arc setting at the time of eruption of the basalts. The arc signatures, therefore, probably indicate a role for lithospheric mantle modified by previous (Mesozoic?) subduction. The basalt chemistry requires mixing of at least two components, namely an Indian Ocean MORB-type asthenosphere component and an enriched subcontinental lithospheric mantle component (Zhang et al., 1997).

SECTION 3. NORTH QUEENSLAND MINERALISATION

Introduction

The previous section provided an overview of the geology of the North Queensland region from the Palaeoproterozoic through to the present and developed a framework for the geodynamic evolution of this region. In this section, we place metallogenic events into this framework and use these relationships and general relationships between metallogeny and geodynamics to predict mineral potential for the North Queensland region.

To provide an indication of this potential, basic data, including the age, size, geological characteristics and likely deposit type, are provided for all major deposits and many important prospects in the North Queensland region. The deposits were grouped by age into a series of mineralising events. Following the methodology of the previous section, descriptions of known Proterozoic and Phanerozoic mineralising events are grouped according to the following time intervals:

1. Palaeoproterozoic to Neoproterozoic (1750-600 Ma)
2. Delamerian cycle: Late Neoproterozoic to Late Cambrian (600-490 Ma)
3. Benambran cycle: Late Cambrian to Earliest Silurian (490-430 Ma)
4. Tabberabberan cycle: Middle Silurian to Late Devonian (430-380 Ma)
5. Kanimblan cycle: Late Devonian to Late Devonian-Early Carboniferous (380-350 Ma)
6. Hunter-Bowen cycle: 350 Ma to 230 Ma
7. Mesozoic (250-65 Ma)
8. Cenozoic (65 Ma- present)

For each of these cycles, mineral potential analysis was undertaken using the distribution of known deposits and prospects and the predicted distribution of deposit groups based on the geodynamic framework described in Section 2.

3.1. Paleoproterozoic to Mesoproterozoic (ca. 1750 Ma to 600 Ma)

The Mount Isa Province, located in northwestern Queensland, is one of the most richly mineralised provinces known in the world, containing five world class Zn-Pb-Ag deposits (Mount Isa Zn-Pb-Ag, Hilton-George Fisher, Century, Dugald River and Cannington), a world class Cu deposit (Mount Isa Cu), and numerous smaller Zn-Pb-Ag, Cu and U deposits. This province, along with the Etheridge Province, forms the eastern margin of the North Australian Craton, one of three cratons that constitute the Archean to Proterozoic core of the current Australian continent. Although the oldest known deposit in the North Australian Craton, the Namoona prospect, has a lead isotope model age of ~2000 Ma (using the North Australia model of Sun et al., 1996), the main period of Proterozoic Zn-Pb-Ag deposition in the North Australian Craton was between 1690 and 1575 Ma. Mineralisation was pulsed and produced the North Australian Zinc Belt (Figure 44), which includes deposits of both the Mount Isa- and Broken Hill-type classes (Table 1). This zinc belt contains pre-mining resources of nearly 120 Mt Zn and Pb (over 52% of Australia's pre-mining Zn and Pb resources: Huston et al., 2006), most of which was produced from the Mount Isa Province. Copper (e.g., Mount Isa copper) and uranium (e.g., Valhalla) mineralisation in the Mount Isa Province, for the most part, post-dates Zn-Pb-Ag mineralisation and is temporally associated with the 1620-1520 Ma Isan Orogeny.

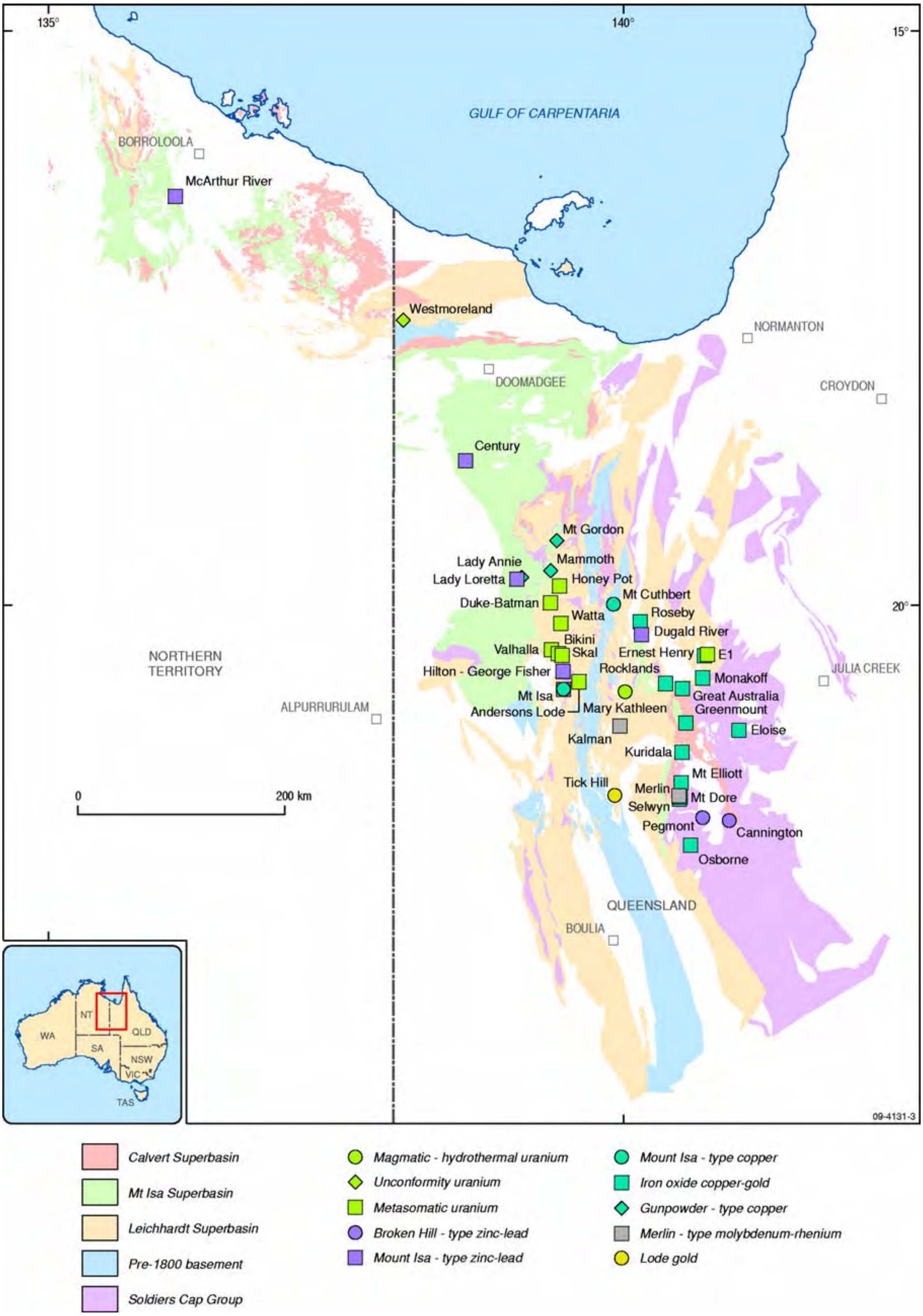


Figure 44 . Geological map of the North Australian Basin system showing the distribution of superbasins, basement and deposits discussed in the text.

Table 1. Production and resources of selected mineral deposits in the Mount Isa and Etheridge Provinces (listed in order of discussion in text).

Deposit	Production and resource	Reference
Mary Kathleen	10.1 kt U3O8 (production and remnant ore)	Miezitis and McKay (2001)
Cannington	43.8 Mt @ 4.4% Zn, 11.6% Pb and 538 g/t Ag	Huston et al. (2006)
Pegmont	8.6 Mt @ 3.5% Zn, 7.8% Pb and 10 g/t Ag	Huston et al. (2006)
Dugald River	50 Mt @ 12.1% Zn, 1.9% Pb and 41 g/t Ag	Huston et al. (2006)
Mount Isa Zn-Pb	150 Mt @ 7.0% Zn, 6.0% Pb and 150 g/t Ag	Huston et al. (2006)
Hilton-George Fisher	228 Mt @10.8% Zn, 5.5% Pb and 97 g/t Ag	Huston et al. (2006)
Lady Loretta	13.6 Mt @ 17.1% Zn, 5.9% Pb and 97 g/t Ag	Huston et al. (2006)
Century	105 Mt @ 12.1% Zn, 1.8% Pb and 46 g/t Ag	Huston et al. (2006)
Westmoreland	24.0 Mt @ 0.092 % U_3O_8 (NI43-101-compliant total resource)	www.laramide.com
Valhalla	35.1 Mt @ 0.0872% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Skal	7.6 Mt @ 0.0508% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Bikini	10.1 Mt @ 0.0517% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Duke-Batman	2.11 Mt@ 0.0666% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Honey Pot	2.56 Mt @ 0.0700% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Andersons	2.0 Mt @ 0.101% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Watta	4.2 Mt @ 0.0410% U_3O_8 (JORC-compliant total resource)	www.summitresources.com.au
Mount Isa Cu	255 Mt @ 3.3% Cu and 0.1 g/t Au (pre-mine resource)	Williams (1998)
Ernest Henry	167 Mt @ 1.1% Cu and 0.54 g/t Au (pre-mining resource)	
E1	38.5 Mt @ 0.81% Cu and 0.23 g/t Au	www.excoresources.com.au
Roseby	128.5 Mt @ 0.68% Cu and 0.06 g/t Au (JORC-compliant total resource)	www.universalresources.com.au
Rocklands	25 Mt @ 2.% Cu equivalent	www.cudeco.com.au
Kuridala	3.5 Mt @ 1.3% Cu (JORC-compliant total resource)	www.matrixmetals.com.au
Starra (Selwyn)	7.4 Mt @ 1.88% Cu and 3.8 g/t Au (pre-mining resource)	Williams et al. (2005)

Starra (continued)	30 Mt @ 0.9% Cu and 0.8 g/t Au (JORC-compliant total resource from remnant and new ore zones [2009])	www.ivanhoeaustralia.com
Osborne	11.2 Mt @ 3.51% Cu and 1.49 g/t Au	Williams et al. (2005)
Monakoff	1.902 Mt @ 1.58% Cu and 0.48 g/t Au (JORC-compliant total resource)	www.excoresources.com.au
Great Australia	2.134 Mt @ 1.54% Cu and 0.13 g/t Au (JORC-compliant total resource)	www.excoresources.com.au
Eloise	3.5 Mt @ 3.1% Cu, 10 g/t Ag and 0.8 g/t Au (JORC-compliant total resource)	www.breakawawayresources.com.au
Mount Elliott	3.3 Mt @ 3.6% Cu and 1.8 g/t Au (original resource) 475 Mt @ 0.5% Cu and 0.3 g/t Au (JORC-compliant total resource from remnant and new ore zones [2009])	Williams and Pollard (2001) www.ivanhoeaustralia.com
Greenmount	7.97 Mt @ 1.0% Cu (JORC-compliant total resource)	www.matrixmetals.com.au
Mount Dore	80 Mt @ 0.6% Cu (JORC-compliant total resource)	www.ivanhoeaustralia.com
Merlin	13 Mt @ 0.8% Mo, 14 g/t Re, 0.2% Cu and 4.8 g/t Ag (JORC-compliant total resource)	www.ivanhoeaustralia.com
Kalman	61 Mt @ 0.05% Mo, 1.2 g/t Re, 0.32%Cu and 0.15 g/t Au	Leahy (2009)
Mount Cuthbert	8.33 Mt @ 1.0% Cu (JORC-compliant total resource)	www.matrixmetals.com
Gunpowder/Mount Gordon	16 Mt @ 4.1% Cu	http://www.miningnews.net/ storyview.asp?storyid=61135
Lady Annie	4.4 Mt @ 1.8% Cu	http://www.miningnews.net/ storyview.asp?storyid=61135
Tick Hill	0.706 Mt @ 22.5 g/t Au (production)	Forrestal et al. (1998)
Chloe-Jackson-Stella	4.6 Mt @ 4.8% Zn, 2.0 % Pb, 0.2% Cu and 51 g/t Ag (JORC-compliant total resource)	www.copperstrike.com.au
Railway Flat	0.9 Mt @ 3.4% Zn, 0.9% Pb, 0.2% Cu and 16 g/t Ag (JORC-compliant total resource)	www.copperstrike.com.au
Kaiser Bill	15.6 Mt @ 0.88% Cu, 8 g/t Ag and 0.12 g/t Au (JORC-compliant total resource)	www.copperstrike.com.au
Einasleigh	(production) 1.1 Mt @ 2.9% Cu, 13 g/t Ag and 0.15 g/t Au (JORC-compliant total resource)	www.copperstrike.com.au

In contrast, mineralisation in the Etheridge Province is much more restricted, both in timing and in size, although a more extensive range of commodities are involved. Probable Proterozoic deposits in the Etheridge Province include Broken Hill-type Zn-Pb-Ag (Table 1), Cu-Au deposits of uncertain, though probably epigenetic, origin (e.g., Einasleigh), lode gold deposits, and polymetallic (Sn-Zn-Pb-Cu) vein deposits most likely associated with Esmeralda-suite (~1560 Ma) granites. As the lode gold deposits in the Etheridge Province are thought to be Middle or upper Paleozoic in age (Garrad et al., 2000), they are described in a later section. No significant mineralisation is recorded for the Yambo Subprovince of the Etheridge Province (Garrad et al., 2000). Resource assessment reports on both the Georgetown-Croydon and Coen regions of the Etheridge Province have been produced by Denaro et al. (1997) and Denaro and Ewers (1995). These include detail on minor Proterozoic mineralisation.

3.1.1. Geology, geodynamic evolution and metallogenesis of the Mount Isa Province

As the host rocks to most major deposits in the Mount Isa Province appear to correlate with rocks in the McArthur Basin and the Lawn Hill Platform (Page et al., 2000; Neumann, 2007), we consider this basin system as a whole, including the westward extension of the basin into the Northern Territory. The geodynamic evolution of Paleo- to Mesoproterozoic sequences in the North Australian Craton and, more particularly, the Mount Isa Province, has long been contentious, although recent geochronological data (Page et al., 2000; Bierlein et al., 2008; Neumann et al., 2006, 2009) are providing tighter constraints on the geologic setting and, thereby, the geodynamic history of this craton. In the 1970s and 1980s, regional mapping in the Mount Isa Province, identified three successions that overlie polydeformed basement of the Kalkadoon-Leichhardt Belt (Blake and Stewart, 1992). This basement block has been intruded by ~1860-1850 Ma granites (Bierlein et al., 2008).

Subsequent work using sequence stratigraphic principals on the successions has identified three superbasins overlying the polydeformed basement (Figure 44). The oldest superbasin, the Leichhardt Superbasin, was deposited between ~1800 Ma and 1750 Ma (Page et al., 2000) and contains a rift fill dominated by a thick pile of continental tholeiites (Eastern Creek Volcanics) and fluvial to lacustrine siliciclastic and lesser carbonate rocks (Jackson et al., 2000). Gibson et al. (2008) inferred that this basin formed as a result of ENE-WSW-directed extension (see also Betts et al., 2006). Recently acquired seismic data (Gibson et al., in prep.) in the western Mount Isa Province indicates that this extensional geometry has largely been preserved, with thickening of the rift fill in the Leichhardt River Fault Trough controlled by original extensional faults that were inverted during the Isan Orogeny. The Leichhardt Superbasin thins in the Century area , but appears to thicken westward into the Northern Territory, where the Seigal Volcanics are inferred to be equivalent to the Eastern Creek Volcanics (Neumann, 2007), although precise correlations are uncertain.

In the western part of the Mount Isa Province (mostly to the west of the Kalkadoon-Leichhardt Belt) and in the McArthur Basin, the Calvert Superbasin, which overlies the Leichhardt Superbasin, was deposited between 1730 Ma and 1695 Ma (Page et al., 2000). In the Northern Territory, the 'mid Tawwallah contraction event' occurs between the Leichhardt and Calvert Superbasin times, but this event is not mapped in the Mount Isa Inlier. The superbasin consists of continental to shallow marine siliciclastic and carbonate rocks, including red beds, that are interlayered with intrusive and extrusive felsic and mafic volcanic rocks that were deposited in a rift environment (Jackson et al., 2000). The volcanic rocks are erupted over an extended time range from ~1730-1720Ma in the Peters Creek Volcanics to ~1709 Ma for the Fiery Creek Volcanics. Gibson et al. (2008) inferred that this basin formed as a consequence of a NE-SW to ENE-WSW extension direction, possibly initiating with the Wonga extensional event that was accompanied by the emplacement of ~1740 Ma syn-kinematic granites (Holcombe et al., 1991; Gibson et al., 2008). Betts et al. (1999) infer a north-west to south-east extension during Calvert time in the Fiery Creek Dome. Although not known to contain significant

Zn-Pb-Ag deposits, some parts of the Calvert stratigraphy were extensively K-feldspar-hematite altered at ~1640 Ma (Cooke et al., 1998). During this alteration, both Zn and Pb were lost, suggesting that this part of the Calvert Superbasin may have been an important source of metals to Zn-Pb-Ag deposits in the overlying Isa Superbasin.

However, the relationship of rocks in the eastern part of the Mount Isa Province to the Calvert Superbasin during Calvert-time is more complex. Rocks in this area, although generally included in the Calvert Superbasin (Murphy et al., 2008), are dominated by deep water turbidites that contain mafic intrusive and extrusive igneous rocks and minor felsic volcanic rocks (Beardsmore et al., 1988). These rocks, which form the Soldiers Cap Group, are, at ~1676 Ma (Page and Sun, 1998), younger than the shallow marine part of the Calvert Superbasin to the west and correspond in time with development of the Gun unconformity and the emplacement of the Sybella and related granites in the western Mount Isa Province (Neumann et al., 2009). Emplacement of the Sybella Granite was accompanied by development of high grade shear zones and amphibolite grade metamorphism (Rubenach, 2008). This unconformity, the coeval magmatism and change in style of sedimentation suggests opening of the rift basin to the east. The oldest Zn-Pb-Ag deposits, the Broken Hill-type Cannington and Pegmont deposits, are hosted by turbiditic rocks of the Soldiers Cap Group.

The third superbasin, the 1665-1595 Ma Isa Superbasin (Page et al., 2000; Neumann et al., 2008), overlies the Calvert Superbasin and rocks of the Soldiers Cap Group. The older part of the basin contains fluviatile to shallow marine sandstone, siltstone and dolomite with subordinate black shale and minor felsic volcanism ("pinkites": tuffs and peperites), whereas the younger part of the superbasin comprises up to 8 km of turbidites, carbonaceous shales and stromatolitic dolostones deposited in a shallow to deep marine environment (Hutton and Sweet, 1982; Southgate et al., 2000; Betts et al., 2006). Gibson et al. (2008) suggest that the older part of the Isa Superbasin may be a younger continuation of the syn-rift Calvert Superbasin as it has similar thickening and facies patterns. However, Betts et al. (1999) record northwest-southeast extension during Calvert and Isa Superbasin times in the Fiery Creek Dome adjacent to the Lawn Hill Platform. The Lawn Hill Platform also records northwest-southeast directed shortening as the main deformational phase, swinging around to north-south compression in the Murphy Tectonic ridge. The timing of the north-south oriented compression is unclear as it clearly postdates cessation of deposition of the Lawn Hill Formation (~1590Ma), and hence D_1. The timing correlates more with D_2 to the south. This paradox is unresolved. It quite clearly indicates a different geodynamic history on the Lawn Hill Platform to that in the Leichhardt River Fault Trough and central and southern parts of the Mount Isa Inlier.

Although consensus exists that the Leichhardt and Calvert Superbasins and the Soldiers Cap Group infilled rifts in an overall extensional environment (Jackson et al., 2000; Giles et al., 2003; Gibson et al., 2008), opinion of the geodynamic setting of the Isa Superbasin differs. Historically, deposition of the Isa Superbasin has been considered the consequence of post-rift thermal sag (Etheridge and Wall, 1994; Betts et al., 2003, 2006). More recently, alternative geodynamic scenarios have been presented. For instance, Southgate et al. (2000) suggested a model whereby deposition of the Isa Superbasin was controlled by the development of pull-apart basins associated with dilational jogs related to north-northeast-trending sinistral faults. These basins were interpreted to have formed on a southeast-facing ramp. Alternatively, Gibson et al. (2008) indicates that the Mount Isa Superbasin consists of two parts, an extensional older succession, deposited between 1665 Ma and 1640 Ma, and a post-extensional younger succession, deposited between 1640 Ma and 1595 Ma. The Mount Isa Group in the Isa valley includes only the older of these two parts. The upper part is restricted to the Lawn Hill Platform to the west and north-west. Rocks equivalent in age to the upper part of the Isa superbasin are now recorded form the eastern succession in the Tommy Creek Block. The boundary of between these packages corresponds to initiation of D_1 (using the structural timing nomenclature of Murphy et al., 2008) of the Isan Orogeny, which is characterised by east-west trending folds, implying north-directed, thin-skinned thrusting (Murphy et al., 2008). In this model, the early phase of the basin formed through continuation of rifting with a NE-SW extension direction, initiated during Calvert time. However, the later part of the basin is interpreted as post-rift (Gibson et al., 2008), developed upon a platform with a margin to the northeast (Gibson et al., 2008), or possibly as a foreland basin associated with orogeny to the south. A change in the depositional geometry is recorded at the base of the River Supersequence on the Lawn Hill Platform (Krassay, & others, 2000). The age of this event is uncertain but may equate to ~1650Ma (Page et al., 2000). However there are growth faults recognized within the Pmh4 sequence in the Century Mine, suggesting that extension, even if only on a small scale, acted during deposition of the upper Mount Isa superbasin in this region.(I don't have a reference for this it was told to us by a mine geo at Century this year) The ~1640 Ma internal boundary within the Isa Superbasin corresponds to the initiation of the Leibig Orogeny along the southern margin of the North Australian Craton, which records the docking of the Warumpi Province (Scrimgeour et al., 2005).

Additional constraints on the geodynamic evolution of the North Australian Basin System are provided by the Paleo- to Mesoproterozoic apparent polar wander path (APWP) for the North Australia Craton documented by Idnurm (2000), who identified a series of bends in the north Australian APWP, which most likely respond to plate reorganisation. Although the earliest bends predate deposition of the Mount Isa Superbasin, major flexures at ~1655 Ma (B_3) and ~1590 Ma (B_5) and a major U-turn at ~1640 Ma (B_4) overlap the evolution of the Mount Isa Superbasin. The ~1655 Ma bend and the ~1640 Ma U-turn correspond to major periods of Mount Isa-type Zn-Pb mineralisation, and a sharp bend at ~1680 Ma (B_2) corresponds to Broken Hill-type mineralisation in the Soldiers Cap Group (see below). Although the bend at ~1655 Ma cannot be correlated with known geodynamic events, the bend at ~1590 Ma corresponds in time with cessation of deposition in the Isa Superbasin and initiation of the second, major phase of the Isan Orogeny, which involved east-west contraction (Murphy et al., 2008). It also may be related to the mineralization at Century which has been dated at ~1585 Ma (Broadbent et al., 1998).

The U-turn at ~1640 Ma corresponds to the 1640-1635 Ma Liebig Orogeny, which is interpreted to be the consequence of the oblique accretion (from the southwest) of the Warumpi Province along the southern margin of the North Australian Craton (Scrimgeour et al., 2005). Although the effects of the Liebig Orogeny are most extensively developed along this margin, involving high pressure, amphibolite to granulite grade metamorphism, the effects appear to be more extensively developed: for instance, paleomagnetic and geochronological data constrain formation of a syncline at the HYC deposit, 800 km to the north of the craton margin, to between ~1639 Ma and 1636 Ma (Symons, 2007; see also below). The temporal coincidence of the Leibig Orogeny and the change in style of sedimentation in the Isa Superbasin (cf. Gibson et al., 2008) may suggest that the upper part of this superbasin may have been deposited in a foreland basin environment. However, Selway et al. (2009) suggest that the Liebig Orogeny records southward movement with the North Australia Craton being subducted beneath the Warumpi Province. This suggests that the development of the upper part of the Isa Superbasin sequence may not have been deposited as a foreland basin resulting from northward directed thrusting.

Consensus exists that the Leichhardt and Calvert Superbasins, as well as the Soldiers Cap Group, formed in extensional, or rift, environments. Although disagreement exists about the early part of the Isa Superbasin, most workers concur that the later part (<1640 Ma) of this superbasin was formed as a post-rift thermal subsidence phase, with some workers suggesting a foreland basin associated with collision of the Warumpi Province. The early part of this basin is variably interpreted as a post-rift thermal subsidence phase or as a continuation of the rift-related Calvert Superbasin. This analysis suggests that Broken Hill-type deposits hosted by the Soldiers Cap Group were deposited in a rift environment, whereas Mount Isa-type deposits hosted by the Isa Superbasin were formed in a post-rift environment, either in a thermal subsidence or foreland basin environment.

Rocks of the Mount Isa Province were subjected to four phases of deformation associated with the 1640-1500 Ma Isan Orogeny. The earliest deformation began at ~1640 Ma and involved north-directed thin-skinned thrusting, possibly associated with the accretion of the Warumpi Province to the south, as discussed above. The main period of deformation (D_2) began at 1600 Ma, and extended to 1565 Ma (Connors and Page, 1995; Giles and Nutman, 2002; Hand and Rubatto, 2002; Rubenach, 2008). This event was characterised by thrust development within an east-west contractional regime (Murphy et al., 2008). This was followed by brittle D_3 structures formed under southeast-northwest contraction at ~1550 Ma (though poorly dated: Connors and Page, 1995; Hand and Rubatto, 2002; Betts et al., 2006) and then by localised D4 deformation associated with the emplacement of the Naruku-Williams Granite Suite between 1530 and 1500 Ma (Rubenach, 2008).

3.1.1.1. Mary Kathleen uranium deposit (with contributions by A Schofield)

The Mary Kathleen U-REE deposit, which was located in the Kalkadoon-Leichhardt Belt, is classified as a metamorphic-related deposit (McKay and Miezitis, 2001). The deposit was discovered in 1954, and by closure of the mine in 1982, had produced 8.882 kt U_3O_8 (McKay and Miezitis, 2001). Numerous small U prospects and occurrences are located near to the Mary Kathleen deposit (Brooks, 1975), which is hosted by metasediments of the ~1780-1760 Ma Corella Formation. This unit comprises calc-silicate rocks, scapolitic metasediments, and slates that were deposited in a mixed clastic-carbonate shoreline and near-shore environment (Brooks, 1975; Hawkins, 1975; Oliver et al. 1999).

This sequence was intruded by the ~1740 Ma (Page, 1983) Wonga Granite, which was accompanied by the development of a large (~1.5 × 4 km) body of skarn along its western margin (Oliver et al., 1999). This skarn consists of two types: banded garnet-pyroxene skarn and massive garnet skarn. The uranium deposit itself is associated with smaller bodies of skarn to the west of this large body (~3 km west of the Wonga Granite) within the tight, doubly plunging Mary Kathleen Syncline. Here the skarn assemblage has replaced calcareous cobble-pebble conglomerate, gabbro and banded calcareous sedimentary rocks (Oliver et al., 1999). The western limb of the syncline is sheared out by the Mary Kathleen Shear Zone.

Uranium is present dominantly as uraninite, which is distributed throughout the orebody as fine disseminations enclosed in allanite, which usually replaces garnet (Hawkins, 1975). The main REE-bearing minerals are allanite and Stillwellite (La borosilicate: Hawkins, 1975). Other ore-stage minerals include minor ferrohastingsite, quartz, epidote, titanite, hematite, chalcopyrite, pyrite, pyrrhotite and galena (Maas et al., 1987; Solomon and Groves, 1994). Minor Au also occurs with the uranium-REE assemblage (Oliver, 1995).

Neodymium-samarium dating of banded skarn from the main body of skarn yielded an age of 1766 ± 80 Ma (Maas et al., 1987), within error of the age of the Wonga Granite and related rhyolite dykes (~1726 Ma, ~1745 Ma and ~1737 Ma: Page 1983). However, massive garnet-pyroxene-feldspar skarn from the Elaine Dorothy U-REE prospect, 8 km south of Mary Kathleen yielded an age of ~1557 ± 40 Ma (Maas et al., 1987), consistent with uraninite U-Pb ages of ~1550 ± 15 Ma from Mary Kathleen itself (Page, 1983) and coeval with regional D_3. These two ages correspond with textural evidence suggesting two phases of mineralisation. Oliver et al. (1999) indicated that the uranium and REEs are associated with garnet veins and breccias that overprint the early-formed skarn.

Disagreement exists regarding the timing of the introduction of uranium and REEs. Maas et al. (1987) used Nd isotopes as a tracer to suggest that the REEs and, by implication, the uranium in the ores, were remobilised from the original skarn. In this interpretation, original introduction of the U-REE-Au assemblage was at ~1740 Ma, coeval with emplacement of the Wonga Granite and the associated contact metamorphism and metasomatism of the Corella Formation. Alternatively, Oliver et al. (1999) argued that introduction of most uranium and REEs occurred at ~1550 Ma, coincident with the regional D_3 deformation. Although acknowledging that the interpretation of Maas et al. (1987) was the simplest interpretation of the neodymium data, they argued that it was unlikely that fluids in a mesothermal environment could remobilize REEs to form the allanite-uraninite assemblage that characterizes the ores. Rather, they argued that the REEs, and by implication, uranium were derived from either a highly LREE-enriched source such as a metasediment or from an old (i.e. Archean) source. Neither potential source rock was recognised nor excluded by Maas et al. (1987). In the late introduction model of Oliver et al. (1999), the pre-existing skarn acted as a mechanical trap that focused fluids moving along the Mary Kathleen Shear Zone.

3.1.1.2. Broken Hill-type Zn-Pb-Ag deposits hosted by Soldiers Cap Group

The Cannington and Pegmont deposits (Table 1), which are hosted by the ~1676 Ma Soldiers Cap Group (Page and Sun, 1998; Walters and Bailey, 1998), are the earliest deposits in the North Australian Zinc Belt. The Cannington deposit has a Pb isotope model age of ~1665 Ma (using AGSO-CSIRO North Australia model of Sun et al., 1996: Table 2), which is similar (within uncertainty related to model precision) to the age of the host unit. The Soldiers Cap Group consists largely of turbiditic metapelite and metapsammite, although it contains significant tholeiitic amphibolite and metabasalt along with minor felsic volcaniclastic units (Beardsmore et al., 1988). The Ag-rich Cannington deposit, which is hosted by amphibolite facies migmatitic quartzofeldspathic gneiss, comprises four separate apparently stratiform lenses, ranging from Zn-rich to Pb-rich, with Ag highly enriched in Pb-rich ores (Walters and Bailey, 1998). The ores are associated with skarn-like alteration assemblages, including pyroxene, garnet, olivine, fluorite, apatite and quartz (Walters and Bailey, 1998; Chapman and Williams, 1998; Bodon, 1998). Quartzose biotite-sillimanite schist and feldspathic psammite with abundant almandine garnet extend up to 250 m from the lodes (Chapman and Williams, 1998) and are possibly an outer alteration zone. Relative to psammitic gneiss, garnet-rich, proximal alteration assemblages have lost Na, K and Rb, but gained Ca, P, Mn, Fe, Pb and Zn (Chapman and Williams, 1998).

3.1.1.3. The Dugald River Zn-Pb-Ag deposit

Although the largest Zn-Pb deposit (Table 1) to the east of the Kalkadoon-Leichhardt Belt, the Dugald River deposit is least understood deposit in the Mount Isa Province. This deposit is hosted by the Mount Roseby Schist, an upper greenschist to lower amphibolite grade sequence of mostly (scapolitic) mica schist and quartzite. The deposit is hosted in the Dugald Shale member, which contains graphitic schist and dolomitic limestone. The Mount Roseby Schist is overlain by the Knapdale Quartzite, which is characterized by dune crossbedding and, in turn overlain by dolomite of the Coocerina Formation and the Lady Clayre Dolomite (Blake, 1987). Based mostly on the presence of trough cross bedding and dolomite, this sequence is interpreted to have been deposited in a relatively shallow water, shelf environment. A psammitic sample of the Dugald River Shale member along strike from the Dugald River deposit yielded a maximum depositional age of 1686 ± 7 Ma (Carson et al., 2008), constraining the maximum age of the Dugald River deposit. Using the north Australia model, galena lead isotope data indicate a model age of ~1662 Ma (Carr et al., 2001: Table 2).

The chronostratigraphic position of the Dugald River Shale in the North Australian Basin System is not well constrained. If the maximum deposition age of ~1686 Ma is taken as close to a depositional age, these rocks would be a shallow water equivalent of the Soldiers Cap Group. If, on the other hand, the maximum depositional age is older than the depositional age, these rocks would be part of the Isa Superbasin.

The Dugald River deposit consists of a main lens up to 21-m-thick hosted by carbonaceous shale stratigraphically above dolomitic limestone, with discontinuous mineralised lenses present at higher stratigraphic levels in shale. The main lens can be traced over 2200 m along strike and has a depth extent of over 1000 m (Connor et al., 1990). Given the association with carbonate rocks, we tentatively interpret the Dugald River as the oldest Mount Isa-type deposit in the Mount Isa Province.

3.1.1.4. Mount Isa-type Zn-Pb-Ag deposits in the Isa Superbasin

Most Zn-Pb-Ag deposits (Table 1) in the North Australian Zinc Belt hosted by the Isa Superbasin, were deposited between ~1655 and 1635 Ma and are interpreted as Mount Isa-type deposits. The oldest group of these deposits includes the Mount Isa and Hilton-George Fisher deposits. These deposits are hosted by the Urquhart Shale, which consists of dolomitic and variably carbonaceous, pyrite-rich siltstone (Forrestal, 1990; Chapman, 2004) that has indistinguishable ages between ~1655 Ma and ~1652 Ma (Page et al., 2000). The deposits consist of a series of discrete, stacked lenses up to 80 m thick. These lenses consist of a series of 1 mm to 1 m Zn-Pb-rich layers that, when bulked, can be mined economically (Forrestal, 1990). Although the Hilton and George Fisher deposits have been considered as separate deposits, the two deposits appear to be part of one ore system that was subsequently offset by later faulting (c.f. Chapman, 2004).

Other Mount Isa-type deposits in the North Australian Zinc Belt are hosted by similar units, though at higher stratigraphic levels. The HYC deposit (in the Northern Territory) is hosted by ~1639 Ma Barney Creek Formation (Page et al., 2000); the Lady Loretta deposit is hosted by the ~1647 Ma (Page et al., 2000) Lady Loretta Formation, and the Century deposit is hosted by the ~1595 Ma (Page et al., 2000) Lawn Hill Formation. Like the deposits near Mount Isa, these deposits are characterised by multiple stacked, stratiform lenses (individual lenses over 100 m thick at HYC) that are hosted by pyritic, dolomitic and carbonaceous siltstone (Hancock and Purvis, 1990; Broadbent et al., 1998; Large et al., 2005). Another characteristic of Mount Isa-type deposits is the lack of well defined alteration zones. Although Large et al. (2000) defined extensive alteration zones using isotopes and geochemistry, alteration is subtle, with the most pronounced effects being changes in composition of carbonate minerals (Broadbent et al., 1998; Large et al., 2000). Of the Mount Isa-type deposits in the North Australian Zinc Belt, the most unusual is the Lady Loretta deposit. This deposit is characterised by a single ore lens that is up to 24 m thick that appears to grade into semi-massive barite along the northeastern margin (Hancock and Purvis, 1990).

The youngest deposit, Century, is hosted by the uppermost part of the Mount Isa Superbasin, with a depositional age of 1595 Ma (Page et al., 2000). Like the other deposits in the Mount Isa Superbasin, the host rocks to the Century deposit are dolomitic carbonaceous siltstone, but in this case the lead isotope model age as determined from the North Australia model is ~1573 Ma (Carr et al., 2001; Table 2), more than 20 million years younger than the age of the host rocks. Broadbent et al. (1998) interpret the Century deposit to have formed by replacement of the host rocks, citing the apparent age difference between the host and model age, and the crosscutting relationship of the ores to the host stratigraphy at the deposit scale. They inferred deposition at a depth of 1 km, with some analogies to Mississippi Valley-type deposits. In contrast, largely based on finite-difference computer modeling of fluid flow, Feltrin et al. (2009) suggested that Century was formed syngenetically, although with remobilisation during diagenesis and deformation.

3.1.1.5. Geodynamic setting of Zn-Pb-Ag mineralisation in the Mount Isa Province

Figure 45 schematically shows the location of major Zn-Pb deposits and the Soldiers Cap Group in the Calvert and Isa Superbasins. In this model the Broken Hill-type deposits (Cannington and Pegmont) are hosted by a deep water turbiditic basin in the east that developed during incision and granite emplacement to the west. This basin is inferred to have formed in a rift setting and it contains significant intrusive tholeiites (Beardsmore et al., 1988), which reflect extension, thinning crust and relatively high heat flow. In contrast, the Mount Isa-type deposits formed in the overlying Isa Superbasin, which, with the exception of minor tuffs and peperites (so-called "pinkites"), is amagmatic and is interpreted as a thermal sag or foreland basin. This basin unconformably overlies the Calvert Superbasin in the west, but may be conformable with the Soldiers Cap Group to the east. In the west, the Gun Unconformity represents a hiatus of about 20 million years (Neumann et al., 2007). As discussed above and below these sedimentological changes and the timing of mineralisation correspond with major changes in the North Australian apparent polar wander path, suggesting a close relationship to external tectonic events.

The deposits also display a systematic change in Pb isotope systematics, both in time (Figure 46a) and in space (Fig. 46b). As also discussed in Carr et al. (2001) and Large et al. (2005), the older Broken Hill-type deposits hosted by the Soldiers Cap Group in the east are characterised by relatively juvenile lead (μ = 12.74-12.76; calculated using the CSIRO-AGSO model of Sun et al., 1994). In contrast the younger Mount Isa-type deposits to the west in the Isa Superbasin are characterised by more evolved Pb (μ = 12.87-12.90), with the Dugald River deposit, which is located between these two groups, having intermediate lead (μ = 12.80). Although juvenile relative to overall lead from the North Australian Craton (D Huston, unpublished data), lead from the Broken Hill-type deposits is more evolved in comparison with similar aged deposits hosted in back-arc settings, such as the United Verde deposit in Arizona (Figure 46). These isotopic systematics are compatible with models whereby the Broken Hill-type deposits sourced lead from rifted continental crust, whereas the Mount Isa-type deposits sourced lead mostly from the underlying basins and continental crust. The Pb data are also compatible with Nd isotope systematics of Paleo- to Mesoproterozoic granites, which also record a gradation from more evolved to more primitive compositions from west to east.

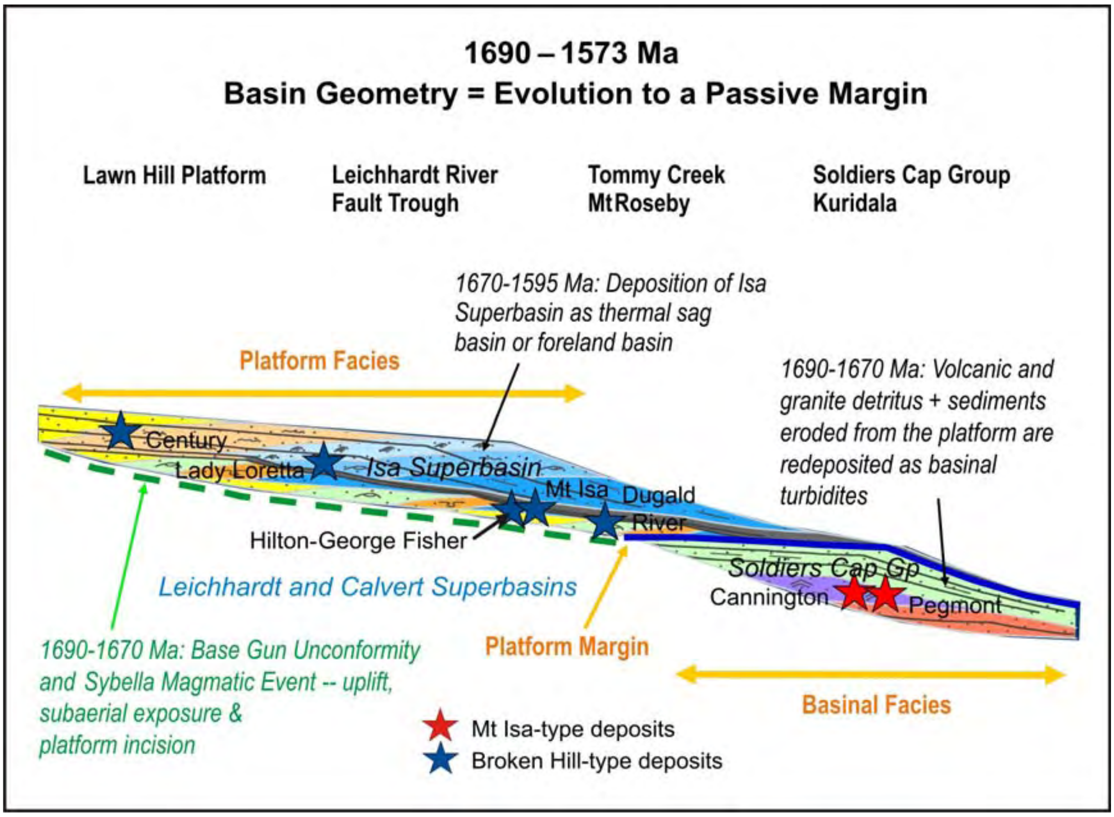


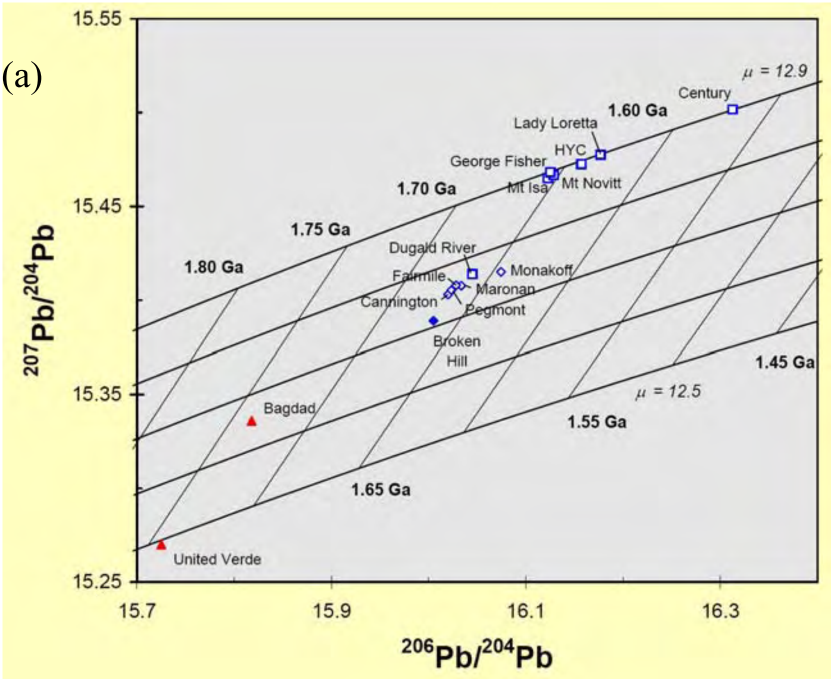
Figure 45. Schematic diagram showing the location of Mount Isa- and Broken Hill-type Zn-Pb-Ag deposits within the basin architecture of the Calvert and Isa Superbasins (architecture framework from P Southgate, pers. comm., 2006)..

3.1.1.6. Westmoreland uranium deposits (contribution from T Mernagh)

The Westmoreland mineral field, which is located near the south-eastern margin of the Palaeoproterozoic-Mesoproterozoic McArthur Basin, comprises at least 50 uranium prospects of various size and grade (Ahmad and Wygralak, 1990), but the three largest deposits are Redtree, Huarabagoo and Junagunna. These three deposits have a collective inferred and indicated resource of 23.6 kt U_3O_8 (Laramide Press Release 23/04/2009: Table 1).

The oldest rocks in the Westmoreland region are Palaeoproterozoic quartz-feldspar-mica schists and gneisses of the Murphy Metamorphics, which are only exposed in the Northern Territory. Palaeoproterozoic acid lavas and ignimbrites (Cliffdale Volcanics) unconformably overlie the metamorphics. The upper units of the Cliffdale Volcanics and the Nicholson Granite have been dated at ~1840 Ma (M. Ahmad, Northern Territory Geological Survey, personal communication). Multiphase intrusions of the Nicholson Granite Complex (granites and monzogranites) intrude the metamorphics and Cliffdale Volcanics. The basal unit, the Westmoreland Conglomerate, is a fluvial deposit, more than 1200 m thick, and comprises arkose, conglomerate and quartz arenites. The Westmoreland Conglomerate was subdivided into four stratigraphic units (Ahmad and Wygralak, 1990). Most of the uranium mineralisation is within the upper unit (Ptw4), which is porous, coarse-grained sandstone, conglomeratic in part, and 80 - 90 m thick. Basaltic lavas of the Seigal Volcanics conformably overlie the Westmoreland Conglomerate, and these are followed by dolomite, sandstone and basic and acid volcanics of the upper part of the Tawallah Group.

Aphyric, medium-grained, dolerite dykes intrude along north-east trending fault and fractures that intersect the Westmoreland Conglomerate. The Westmoreland deposits (Redtree, Junnagunna and Huarabagoo) lie along one of these dyke zones. These deposits comprise both stratiform and discordant uranium mineralised zones with grades ranging from 0.15 to over 2% U_3O_8. Stratiform mineralised zones up to 15 m thick are hosted entirely within the Westmoreland Conglomerate, commonly just below the Seigal Volcanics. Vertical, discordant zones are hosted by the Westmoreland Conglomerate and dolerite of the Redtree dyke zone and may be up to 40 m thick.



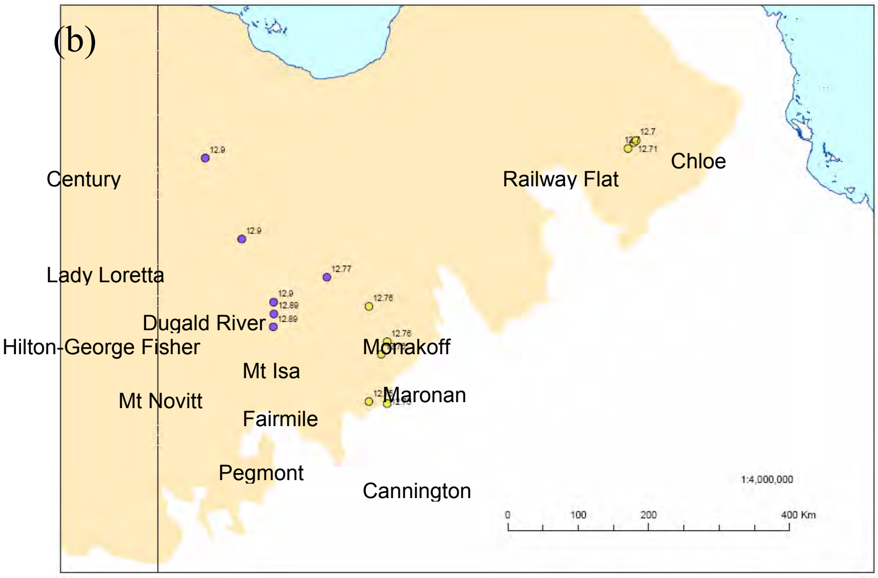


Figure 46 . (a) $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram showing the least radiogenic isotopic composition of galena from deposits in the Mount Isa Province. (b) spatial variations in μ. Data are from Table 2. Evolution curves, isochrons and m values calculated using the CSIRO-AGSO North Australia lead evolution model (Carr et al., 2001). In (a) red closed triangles indicate volcanic-hosted massive sulphide deposits from Yavapai Province in Laurentia; solid blue diamond indicates Broken Hill deposit, Curnamona Craton; open blue diamond indicate Broken Hill-type deposits, Mount Isa Province; open blue squares indicate Mount Isa-type deposits, Mount Isa Province. In (b) blue circles indicated Mount Isa-type deposits, and yellow circles indicate Broken Hill-type deposits.

Pitchblende is the main economic mineral in these deposits, but secondary uranium minerals of the phosphate, vanadate, silicate, arsenate and sulphate groups are dominant in weathered zones. In horizontal orebodies open to the surface, secondary minerals are associated with hematite, chlorite and sericite, and forms grain coatings and interstitial fillings. Uranium and gold coexist in places and this association is the youngest mineral phase. Parts of the Junnagunna horizontal-type mineralisation and of the vertical type mineralisation at Huarabagoo contain gold; values of up to 80 g/t have been obtained, but more commonly the gold assays about 0.2-7.0 g/t.

Polito et al. (2005) interpret that $^{40}Ar/^{39}Ar$ dating of illite in the Westmoreland uranium field shows that fluid migration began as early as 1680 ± 18 Ma and continued beyond 1645 ± 40 Ma. $^{207}Pb/^{206}Pb$ ages of uraninite (Polito et al., 2005) indicate that mineralisation formed around 1655 Ma but was later overprinted by fluids at 878 Ma. The mineralogy, age, and geochemistry of the Westmoreland uranium deposits is similar to that of the uranium deposits of the Alligator Rivers uranium field in the northern McArthur Basin suggesting that these deposits are also unconformity-related uranium systems, although localized above the unconformity.

3.1.1.7. The Mount Isa uranium field

One of the two most significant repositories of uranium in North Queensland is metasomatic deposits in the Mount Isa uranium field (Figure 47). Over 100 uranium deposits, prospects and occurrences are known in this field, with a major deposit at Valhalla and smaller deposits at Skal, Bikini, Duke Batman, Honey Pot, Andersons and Watta (Table 1). Collectively these deposits contain total resources of 47.2 kt U_3O_8. These deposits are hosted within the Leichhardt River Fault Trough, to the north of Mount Isa. This trough is filled by rocks of the Leichhardt Superbasin. In the Mount Isa uranium field this superbasin is dominated by tholeiitic basalt of the ~1780 Ma Eastern Creek Volcanics that overlie fluvial to shallow marine siliciclastics and volcanic rocks of the Bottletree Formation and Mount Guide Quartzite, which overlie basement. The Eastern Creek Volcanics is overlain by coarse- to medium-grained siliciclastics of the Myally Subgroup and fine-grained siliciclastics and dolostone of the Quilalar Formation, the uppermost unit of the Leichhardt Superbasin. These rocks are overlain by siliciclastic sedimentary rocks and bimodal volcanic rocks of the Calvert Superbasin and then by siliciclastic and dolomitic sedimentary rocks the Isa Superbasin (Polito et al., 2007).

The Mount Isa uranium field is bound by the Mount Isa-Twenty-nine Mile-Mount Gordon fault system against Isa Superbasin rocks to the west and by the Quilalar-Gorge Creek-St Paul Fault system against the Kalkadoon-Leichhardt Belt to the east (Figure 47). Based on a seismic traverse across the field (Hutton et al., 2009), these faults are interpreted as original extensional faults that defined the extent of the Leichhardt River Fault Trough. Rocks between these two fault systems underwent peak metamorphism under greenschist facies during D_3, with rocks in the Mount Isa uranium field within the chlorite zone at peak temperatures of 300-350°C (Foster and Rubenach, 2006). An age of metamorphism for this event of 1532 ± 7 Ma is suggested by the age of a syn-kinematic pegmatite (Connors and Page, 1995).

However, to the west of the Mount Isa Fault, the grade increases rapidly to amphibolite grade, beginning in the biotite zone, through the cordierite and sillimanite zones and into the sillimanite-K-feldspar zone over a distance of 15 km (Foster and Rubenach, 2006). Electron microprobe (Gibson et al., 2008) analyses of metamorphic monazite indicate multiple periods of metamorphic monazite growth, with growth at ~1636 Ma, ~1599 Ma (major peak), ~1542 Ma and ~1521 Ma. The major peak corresponds broadly with a regional 1600-1575 Ma timing for peak metamorphism and D_2 across the Mount Isa Province (Giles and Nutman, 2002; Hand and Rubatto, 2002), whereas the ~1542 Ma peak corresponds to the D_3 event recorded on the eastern side of the Mount Isa-Twenty-nine Mile-Mount Gordon fault system.

The eastern margin of the Mount Isa uranium field is also marked by a jump in metamorphic grade across the Quilalar-Gorge Creek-St Paul Fault system into the Kalkadoon-Leichhardt Belt, where basement rocks Leichhardt Superbasin rocks were metamorphosed to amphibolite facies. The age of metamorphism, however, is not known (Foster and Rubenach, 2006).

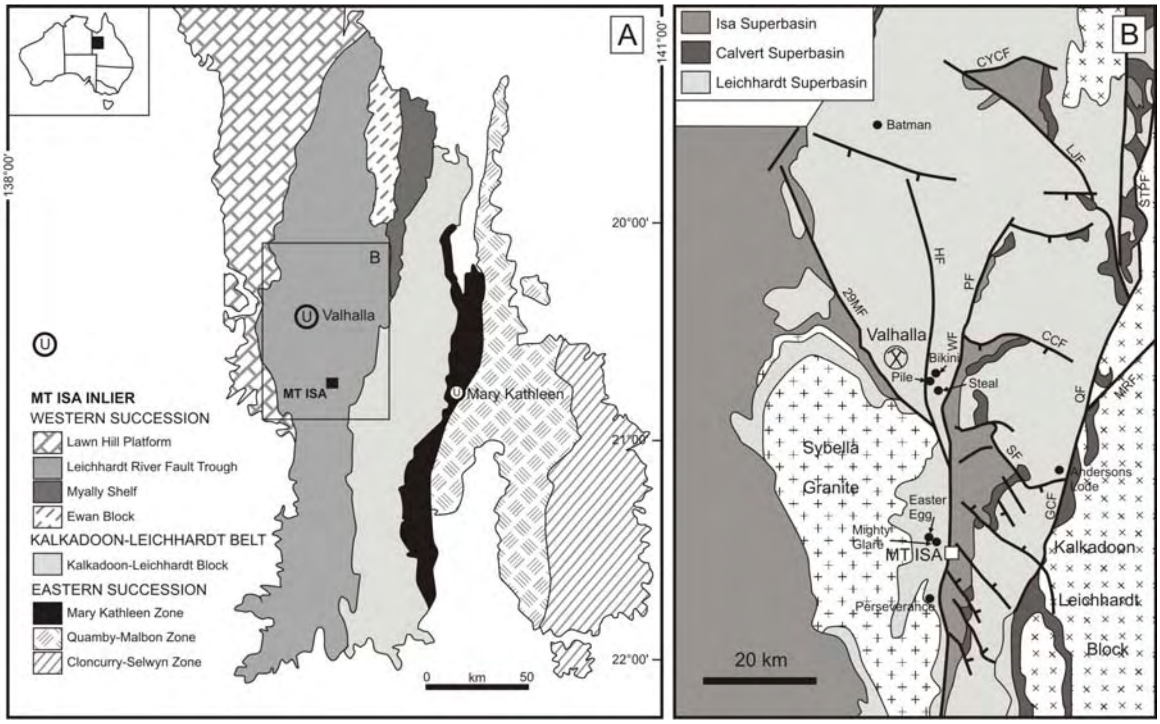


Figure 47. Geology of the Mount Isa uranium field (modified after Polito et al., 2009).

Schofield (2009), in an analysis of uranium contents in igneous rocks across Australia, has compiled uranium analyses of igneous rocks in the Mount Isa Province, including rocks from the Mount Isa uranium field. This analysis identifies the Sybella Granite, which forms a belt just to the west of the Mount Isa-Twenty-nine Mile fault system, as highly uranium enriched (mean 8.4 ppm based on 302 analyses with total range of 2-40 ppm: A Schofield, pers. comm., 2009) with a large proportion of analyses exceeding 20 ppm. In contrast, granites in the Kalkadoon-Leichhardt belt, to the east of the Quilalar-Gorge Creek-St Paul Fault system are closer to global average uranium contents (mean 5.3 ppm based on 304 analyses with total range of 1-35 ppm: A Schofield, pers. comm., 2009). Schofield (2009) also indicated that mafic igneous rocks from the Eastern Creek Volcanics (mean 2.2 ppm based on 29 least-altered analyses with total range of 0.5-6 ppm: A Schofield, pers. comm., 2009) are depleted in uranium relative to the granites, although enriched relative to average mafic rocks.

Regional alteration assemblages. Regional alteration assemblages affecting basaltic rocks in the Mount Isa uranium field (Figure 47) have been described as part of studies on uranium and copper mineral systems (Wyborn, 1987; Bain et al., 1992; Heinrich et al., 1995; Gregory et al., 2005). Wyborn (1987) identified four regional alteration assemblages that have affected basaltic rocks in the vicinity of the Mount Isa copper deposit and the Mount Isa uranium field. The earliest assemblage, which affects uncleaved rocks with relict igneous textures involves progressive replacement of igneous minerals by the assemblage albite-actinolite-chlorite with minor epidote, sphene, K-feldspar, biotite and chalcopyrite, the last mineral present in amygdales and veins. As rocks altered by this assemblage retain high magnetic susceptibility (Wyborn, 1987), it is likely that magnetite was stable during this alteration, which Heinrich et al. (1995) interpreted to have developed as the peak metamorphic assemblage. This early assemblage was characterised by gains in K_2O and local enrichment of Cu, particularly within vesicular flow tops (Wyborn, 1987).

The second assemblages described by Wyborn (1987) involved progressive replacement of the earlier assemblage by an epidote-quartz-sphene assemblage with variable actinolite, chalcopyrite, pyrite and hematite (Hannan et al., 1993; Heinrich et al., 1995). This assemblage not only formed epidosites (locally >50% epidote), but veins that cut metamorphic textures but are also boudinaged within the regional fabric, suggesting a syn-D_3 timing (Heinrich et al., 1995). This alteration resulted in an increase in Fe_2O_3/FeO, CaO and SiO_2 contents, but decreases in Na_2O, K_2O, MgO and Cu and very little change in U (Heinrich et al., 1995). To the north and east of Mount Isa, the epidote-quartz-sphene assemblage has been mapped using HYMAP (Yang et al., 2000), with some U prospects showing an association with this assemblage (cf. Gregory et al., 2005).

The third assemblage of Wyborn (1987), which replaces and veins the earlier assemblages, is dominated by calcite, albite, chlorite and magnetite with minor biotite and K-feldspar. This assemblage is extensive in comparison with a texturally-similar calcite-albite-hematite assemblage that is restricted to north-south-trending fracture zones that cross-cut earlier D_3 faults (Heinrich et al., 1995). This alteration involved increases in Na_2O, CaO, Fe_2O_3/FeO and CO_2 but decreases in K_2O and Mg, with no significant changes in U content. It is spatially associated with U prospects to the northeast of Mount Isa (Bain et al., 1992; Heinrich et al., 1995).

The last assemblage described by Wyborn (1987) was dominated by chlorite, albite and rutile, with variable sphene, pyrite, pyrrhotite, ilmenite and tourmaline and with biotite in K-rich rocks. This assemblage is most extensively developed in basaltic rocks below the Paroo Fault in the vicinity of the Mount Isa copper orebodies (Hannan et al., 1993; Heinrich et al., 1995). This assemblage is described as progressively removing Ca-bearing phases, suggesting that it post-dated the carbonate-Fe-oxide assemblage (Heinrich et al., 1995). Lehman (1991) estimated that this assemblage has affected ~30 km^3 of basalt in this area. A similar assemblage is developed in higher grade rocks to the west of the Mount Isa fault (Heinrich et al., 1995) and in an area 11 km south of the Cu orebody (Wyborn, 1987). Geochemically, this assemblage is associated with increases in SiO_2, MgO, but decreases in Na_2O, CaO, CO_2, Fe_2O_3/FeO and, importantly, copper.

Of the regional alteration assemblages described in the literature, metasomatic uranium deposits in the Mount Isa uranium field are most closely associated with the epidote-quartz-sphene assemblage and, particularly the calcite-albite-hematite assemblage, the latter developed along north-trending fractures that also host uranium prospects. Temporally, these assemblages are synchronous or slightly postdate peak-metamorphic conditions and D_3. The earlier albite-actinolite-chlorite assemblage appears to be a regional metamorphic assemblage, whereas the chlorite-albite-rutile assemblage appears to be later and possibly unrelated to the uranium deposits.

Although well developed in basalt of the Eastern Creek Volcanics, regional alteration assemblages do not appear to have an expression in siliciclastic sedimentary rocks, either in sedimentary lenses intercalated with basalt or in the underlying Mount Guide Quartzite and Bottletree Formation. This may suggest that the ore fluids were in equilibrium with these rocks.

Uranium deposits. Most of the deposits, prospects and occurrences in the Mount Isa uranium field are hosted by the Eastern Creek Volcanics, although a few prospects are present in rock of the underlying Mount Guide Quartzite (Leander Quartzite) and the overlying Myally Subgroup and Surprise Creek Formation of the Calvert Superbasin (Brooks, 1975).

The most significant deposit, Valhalla, consists of two lenses hosted by a clastic sedimentary lens within tholeiitic basalt of the Eastern Creek Volcanics (Figure 47). The larger, northern lens strikes NNW and plunges ~50° to the south (Eggers, 1999). Least altered host sedimentary rocks consist of fine-grained quartz-feldspathic sandstone and gritty siltstone with accessory biotite, muscovite and variable amounts of Fe and Mg- silicates, hematite and magnetite (Polito et al., 2009). The deposit is located ~800 m to the east of the Twenty-nine Mile Fault (Figure 47).

The ores are associated with a zone of variably albite-calcite-riebeckite-hematite altered sandstone/siltstone. This zone is commonly brecciated, with the ore zones mostly characterised by sub-angular to angular clasts of intensely altered sandstone/siltstone (to 20 mm) infilled by a matrix comprising the assemblage brannerite-apatite-zircon-calcite-hematite. The highest grade zones are marked by uraninite-hematite-dolomite-chlorite veins (Polito et al., 2009). The U-mineralised interval is also marked by LREE (to 500 ppm total LREE) and, particularly, Zr (to 4%) and HREE (to 140 ppm total HREE) enrichment. Both margins of the mineralised zone appear to have low-grade (to 0.4%) copper enrichment (Figure 3 of Polito et al., 2009). Polito et al. (2009) reported pyrite and lesser chalcopyrite and bornite as paragenetically late stage minerals, probably accounting for the localised copper enrichment.

Descriptions of other deposits and prospects in the Mount Isa uranium field are limited, with the best description of Anderson's Lode. Like Valhalla, this deposit is hosted by a sedimentary lens within tholeiitic basalt of the Eastern Creek Volcanics. The deposit has an irregular, tabular form, with dimensions of ~20 m × 60 m at surface that increase with depth (Brooks, 1975; Gregory et al., 2005). The body trends east-west, with a steep northerly plunge, parallel to the intersection between a north-stringing fracture cleavage (S_2) and an earlier penetrative cleavage (S_1; Bain et al., 1992). The uranium is preferentially enriched in siltstone beds (sandstone beds are generally barren), where it is closely associated with fluorapatite and lesser chlorite, biotite and magnetite. The ore assemblage includes brannerite and associated anatase, quartz and galena. Magnetite and titanite overgrow all earlier ore-related phases (Gregory et al., 2005). Gregory et al. (2005) also noted a correlation between uranium and gold. Although Anderson's Lode has some similarities to the Valhalla deposit, it also has some important differences to the Valhalla deposit, the most notable being the lack of an albite-riebeckite-bearing assemblage. Another important difference is the association with the Quilalar-Gorge Creek-St Paul Fault system along the eastern margin of the Mount Isa uranium field.

In addition to deposits in the low grade Leichhardt River Fault Trough, a number of uranium occurrences and prospects are present in higher grade rocks to the west of the Mount Isa-Twenty-nine Mile fault system (Figure 47). Gregory et al. (2005) described two of these prospects, at Eldorado and Lucky Break, as being hosted within or at the contact between amphibolite and muscovite-bearing schist within the Eastern Creek Volcanics. Uranium mineralisation is associated with hornblende-rich layers in the amphibolite where it has not been affected by epidote alteration. They interpreted that the uranium was emplaced during or before peak metamorphism based on the observation that uraninite is contained within peak metamorphic hornblende and titanite. However, inspection of their Figure 4C suggests that titanite and uraninite infill and, therefore, postdate hornblende, suggesting a syn- to post-metamorphic timing for uranium mineralisation or mobility.

Timing of mineralisation. At the Valhalla deposit, LA-HR-ICPMS analysis of brannerite yielded a range in ^{207}Pb-^{206}Pb ages between 584 ± 6 Ma and 1543 ± 15 Ma, with the latter age within error of an upper discordia intercept age of 1564 ± 27 Ma (Polito et al., 2007). These ages also overlap with a $^{40}Ar/^{39}Ar$ plateau age for riebeckite of 1551 ± 7 Ma (Polito et al., 2007). These results collectively suggest an age for the Valhalla deposit of 1550-1540 Ma, an age that corresponds in time with the early part of the third phase (D_3) of the Isan Orogeny (Murphy et al., 2008). Based on textural relationships, Gregory et al. (2005) suggested a pre- to syn-metamorphic timing for mineralisation at the Andersons deposit. ^{40}Ar-^{39}Ar dating of one uranium-mineralised biotite separate from biotite-chlorite-magnetite-hematite altered basalt yielded a plateau-like age of 1534 ± 4 Ma. A second sample yielded single step ages of between ~1554 Ma and 1524 Ma (Perkins et al., 1999). The plateau-like age is probably the best age estimate for the age of mineralisation, and the older age similar to the likely age of Valhalla, consistent with a syn-metamorphic (D_3) timing for mineralisation.

Based on textures at Anderson's Lode and Eldorado-Lucky Break, Gregory et al. (2005) interpreted these deposits as metamorphosed unconformity-related uranium deposits, an interpretation quite different to that advanced by Polito et al. (2009) at Valhalla. Although there are significant differences between these deposits vis-à-vis ore and alteration assemblages and geological setting, we consider it unlikely that two different styles of mineralisation were involved. Based on the textures at Eldorado-Lucky Break and the ^{40}Ar-^{39}Ar data at Anderson's Lode, we consider these deposits, as well as Valhalla, to be most likely metasomatic deposits formed during D_3.

3.1.1.8. Mount Isa copper orebodies

The Mount Isa deposit is unusual in that two major deposits, with quite distinct metallogenic characteristics and apparent timings, are juxtaposed. As opposed to the syngenetic or early diagenetic timing for Zn-Pb-Ag orebodies, the copper orebodies at Mount Isa are interpreted to be epigenetic, based largely on timing relationships between alteration assemblages and local structures. The copper orebodies, with global resources of 255 Mt grading 3.3% Cu (Perkins, 1990), are hosted by the ~1655 Ma (Page et al., 2000) Urquhart Shale, generally down dip from the Zn-Pb-Ag orebodies (Perkins, 1984, 1990). The host sequence, and the orebodies, are truncated further down dip by the Paroo Fault, which juxtaposes rocks of the Isa Superbasin (the Urquart Shale) against altered basalt of the ~1780 Ma Eastern Creek Volcanics (Page et al., 2000), which are part of the Leichhardt Superbasin. This fault is likely an original extensional fault that was inverted during the Isan Orogeny (G Gibson, pers comm., 2009).

As described by Perkins (1984, 1990) and Heinrich et al. (1995), the copper orebodies at Mount Isa are hosted within a silica-dolomite (quartz-dolomite-chalcopyrite±talc±pyrite±pyrrhotite) alteration zone that is discordant to stratigraphy and was emplaced late during the regional D_4 deformation event. The silica-dolomite alteration assemblage, which affects the Urquhart Shale, ranges in form from bedding-replacement, through to veins and pervasive brecciation. It has a close spatial relationship and is zoned away from the Eastern Creek Volcanics (Perkins, 1984). These volcanics are themselves intensely altered to a chlorite-rutile assemblage that has lost significant copper (Heinrich et al., 1995). Leaman (1991) indicated, based on three dimensional modeling of magnetic data, that this alteration zone has affected 30 km^3 of basalt. Heinrich et al. (1995) suggested that this Cu-depleted zone was the source of metal in the Mount Isa copper deposit.

Following the seminal work by Perkins (1984), a syn-tectonic (syn-D_4) timing for copper mineralisation at Mount Isa is broadly, though not universally, accepted. More recently, work by Perkins et al. (1999) suggests that this event occurred at ~1520 Ma. $^{40}Ar/^{39}Ar$ analyses of biotite associated with silica-dolomite assemblages yielded plateau-like ages of 1523 ± 3 Ma and 1516 ± 3 Ma (1σ), consistent with the timing of regional D_4 established elsewhere. As discussed in section 3.1.1.4, this age is apparently younger that the uranium deposits in the Mount Isa uranium field by up to 30 million years. This apparent age difference could result from differences in isotope systems used or from real geological differences. If the latter alternative is correct, the Mount Isa copper event significantly postdated the D_3-related uranium event, and these two deposit types were not formed as part of a single mineral system.

3.1.1.9. Iron-oxide copper-gold deposits of the Cloncurry district

After the Olympic Dam Province, the Cloncurry district in the eastern part of Mount Isa Province is the largest iron-oxide copper-gold mineral province in Australia. Exploration over the last 25 years has resulted in a number of significant Cu-Au discoveries, which are continuing with the outlining of a major deposit at Mount Elliott and a new style of Mo-Rh deposit at Merlin in the Mount Dore system in the last five years. The following section describes some of the more important deposits, and then discusses the age of mineralisation as well as potential regional controls on mineralisation.

Ernest Henry. The Ernest Henry deposit is hosted largely by variably altered andesitic rocks that may be correlated with ~1745 Ma metavolcanic rocks at surface to the west (Page and Sun, 1998). Mark et al. (2006) describe the following alteration assemblages at Ernest Henry: (1) sodic (albitic) and/or sodic-calcic (albite-actinolite-diopside-magnetite-scapolite-pyrite) → (2) pre-ore (biotite-magnetite-garnet-K-feldspar) → (3) ore-stage (K-feldspar-quartz-rutile-calcite-magnetite-pyrite-biotite-barite-chalcopyrite-hematite) → (4) post-ore (calcite-dolomite-quartz-biotite-actinolite-pyrite-magnetite). The ores are hosted by breccias with clasts of K-feldspar-altered andesite infilled by the ore-stage assemblage. Other minor to accessory minerals include molybdenite, coffinite and scheelite among others (Mark et al., 2006), suggesting that the ores are enriched in molybdenum, tungsten and uranium in addition to gold and copper. On average, the ores average 50 ppm U, with anomalous cobalt, molybdenum, rare earth elements, arsenic, fluorine and barium (Ryan, 1998). The pre-ore and ore-stage assemblages distinctly overprint the sodic and sodic-calcic assemblages (Mark et al., 2006).

E1. Approximately 8 km to the east of the Ernest Henry, a significant resource has been defined in the E1 camp, which comprises of three separate mineralised zones, E1 North, E1 East and E1 South, associated with magnetic anomalies (www.excoresources.com.au). Very little public information is available about the deposit, although the website indicates that the E1 deposit is hosted by banded ironstone and contains uranium.

Roseby. The Roseby project consists of eleven separate mineralised zones that are hosted by the Corella Formation over a distance of ~20 km (www.universalresources.com.au). Theses zones are grouped into two resource types, deposits dominated by native copper, and sulphide deposits. The former formed by supergene upgrading of sulfide resources, and have significantly lower gold tenor (averaging 0.01 g/t versus 0.18 g/t Au). The largest native copper resource is the Blackard deposit, with total resources of 46.25 Mt grading 0.63% Cu and 0.01 g/t Au, whereas the largest sulphide deposit, Little Eva, contains 30.37 Mt grading 0.78% Cu and 0.14 g/t Au (www.universalresources.com.au). In addition, Universal Resources interpret that the mineralised zones include both iron oxide copper-gold and sediment-hosted (i.e. Zambian copperbelt-type) deposits.

Rocklands. The Rocklands deposit, which are hosted by a metamorphosed succession of siltstone, sandstone, quartz-magnetite rock, calcareous rocks and calc-silicates in the northern nose of the Duck Creek Anticline (Beams, 2009), consists of a several mineralised parallel zones, the largest of which is the Las Minerale zone, with total resource of 25 Mt grading 2% Cu equivalent (www.cudeco.com.au). Gold in the primary mineralised zone typically grades between 0.2 and 0.5 g/t (Beams, 2009).

Primary sulfide zones developed along steeply dipping, west-northwest-trending zones and comprise jigsaw-type hydrothermal breccias, with wall rock clasts initially mantled by hydrothermal biotite and then the breccias infilled by a actinolite-magnetite assemblage, followed by a calcite-pyrite-chalcopyrite-magnetite-quartz assemblage. Thin, planar veins infilled by red feldspar, pyrite and chalcopyrite are present peripheral to the main mineralised zones (Beams, 2009). Minor garnet, fluorite and rare molybdenite are also present in mineralised rock. Beams (2009) inferred that the mineralised zones follow pre-existing structures occupied by dolerite dikes.

Starra. Other Cu-Au-bearing deposits typically grouped into the iron-oxide copper-gold class include the Osbourne, Eloise, Starra, Mount Dore, Mount Elliott, Greenmount, Great Australia and Monakoff (Table 1). Although grouped into the iron-oxide copper-gold class, these deposits have very diverse characteristics, ranging from quartz-rich lodes, replaced hornblende-biotite-altered rocks, replaced magnetite ironstones, skarn, carbonate veins, and disseminations (Williams et al., 2005). This diversity has led to differing genetic models. Early models for ironstone-hosted or associated deposits (e.g., Starra and Osbourne [aka Trough Tank] and Monakoff) invoked a syngenetic timing for mineralisation (e.g., Davidson et al., 1989), although subsequent studies (e.g., Rotherham et al., 1998; Adshead-Bell, 1998) inferred an epigenetic, syn- to late-D_4 (regional structural nomenclature) timing for ironstone formation and copper-gold mineralisation. In both the Starra and Osbourne deposits, gold and copper are hosted by banded, magnetite- and, locally, hematite-rich ironstone (Davidson et al., 1998; Rotherham et al., 1998). Rotherham et al. (1998) described a four part paragenetic sequence at Starra: (1) quartz-albite-scapolite-actinolite (sodic-calcic) → (2) biotite-magnetite-hematite-quartz-pyrite (localized K-Fe metasomatism and ironstone formation; syn-D_4) → (3) quartz-anhydrite-calcite-hematite-gold-barite (early ore-stage; late- to post-D_4) → (4) calcite-bornite-chalcocite-pyrite-chalcopyrite-chlorite-muscovite-magnetite (late ore-stage; late- to post-D_4). In addition to copper and gold, the Starra system is also anomalous in tungsten and locally anomalous in tin (Davidson et al., 1989).

Osborne. High-grade copper-gold ore zones at Osborne are largely associated with massive, crystalline quartz ("silica flooding"; with minor pyrite-magnetite±siderite±talc) that has largely replaced banded ironstone (Adshead et al., 1998). This ironstone is interpreted to have formed syngenetically and differs from the Starra ironstone in having significant (1-4%) apatite (Davidson et al., 1989; Adshead et al., 1998). Adshead et al. (1998) described the ore assemblage as being dominated by chalcopyrite that is associated with quartz, calcite, chlorite, muscovite, magnetite, pyrite and/or pyrrhotite and a number of minor phases, including gold and molybdenite. When disseminated within the banded ironstone and not associated with silica flooding, the ores are associated with hematite-pyrite-magnetite alteration of the ironstone. Adshead et al. (1998) also noted that pyrrhotite-rich ores tend to be relatively enriched in copper, whereas gold is enriched in pyrrhotite-poor assemblages, particularly hematite-pyrite-magnetite-altered ironstone. The Osborne deposit is also anomalous in cobalt, molybdenum, silver, selenium, bismuth, mercury, tellurium, tin, fluorine and chlorine (Adshead et al., 1998).

Monakoff. The Monakoff deposit is less well described, but shares a close association with strataform iron formation. Davidson (1998) indicates that this deposit is characterised by the replacement of the iron formation by a massive barite-carbonate-fluorite±chalcopyrite-magnetite lens with accessory siderite, garnet and pyrite, and minor to trace molybdenite, uranium minerals, galena, sphalerite, arsenopyrite and nickel sulphide minerals. Like other ironstone-related deposits, Monakoff is enriched in cobalt, arsenic, molybdenite and tungsten, but unlike the other deposits, it is also enriched in barium, zinc, lead and nickel (Davidson, 1998).

Great Australia. The Great Australia deposit, located 1 km south of the town of Cloncurry and 20 km west-southwest of the Monakoff deposit, is hosted by mafic rocks of the Toole Creek Volcanics within or adjacent to a splay off the Cloncurry Fault (Cannell and Davidson, 1998). Rocks up to 70 m of the mineralised lodes are strongly altered, with moderately altered rocks extending further. Cannell and Davidson (1998) recognised four alteration assemblages: regional albite-actinolite-magnetite → ore-related biotite±sericite±hematite → ore related albite-magnetite-actinolite → post-ore chlorite-dolomite-hematite. Hypogene ores, which are concentrated in structurally-controlled tabular zones, comprise two assemblages, dolomite-calcite-quartz-pyrite- chalcopyrite± chlorite± actinolite± albite ±

magnetite ± hematite and quartz- albite- actinolite- pyrite- chalcopyrite- magnetite± biotite± carbonate± chlorite. Supergene ore, which were mined in the 1990s, comprise malachite, chrysocolla, cuprite, chalcocite and native copper (Cannell and Davidson, 1998).

Eloise. Many of the other iron-oxide copper-gold deposits in the Cloncurry district do not have as strong an association with magnetite and, in particular, hematite as that demonstrated at the Ernest Henry, Starra, Osbourne and Monakoff deposits. At Eloise (Baker and Laing, 1998), the mineralised zone is associated with a north-south-striking D_4 shear zone. The mineralised zone consists of foliation-parallel veins, stockwork zones and massive sulphide lenses. Using ratios between Fe-S-O minerals, Baker and Laing (1998) demonstrated a deposit-scale zonation in ore assemblages, from magnetite dominant in the south to pyrrhotite-dominant in the north. In the highest-grade zones, the massive sulphide lenses are localised within the pyrrhotite-dominated zone. The ores form stage III and IV of a six stage paragenesis. Like many other iron-oxide copper-gold deposits, the earliest stage consists of a pervasive albite-quartz assemblage that is overprinted by stage II hornblende-biotite-quartz. This latter stage is overprinted by a stage III assemblage consisting of pyrrhotite-chalcopyrite-calcite-chlorite-magnetite with minor pyrite. Gold is inferred to accompany this stage based on assay data (Baker and Laing, 1998). The later stages of the paragenesis appear to be less important, with stage IV comprising cross-cutting veins with a similar mineralogy to stage III (Baker and Liang, 1998).

Mount Elliott. Recent drilling in the vicinity of the old Mount Elliott mine by Ivanhoe Australia has identified significant new (mostly primary) resources totaling 475 Mt grading 0.5% Cu and 0.3 g/t Au Ivanhoe Australia 2008 annual report). The Mount Elliott system consists of a four discrete lenses (Mount Elliott, Swan, Swell and Courbould) that are hosted by carbonaceous phyllites and quartz-mica schist that are part of the Kuridala Formation. The lenses are located within the NW-trending, composite Mount Elliott Fault Zone, with mineralised zones bound by steeply-dipping reverse faults (Fortowski and McCracken, 1998).

The carbonaceous phyllites were initially altered to an albitic alteration assemblage that was subsequently overprinted by a later skarn assemblage (Fortowski and McCracken, 1998). The albitic assemblage is characterised by initial bleaching of the phyllites, resulting from destruction of graphite and biotite and the growth of the assemblage quartz-albite-sericite±pyrite, with minor to trace pyrrhotite and fluorite, followed by progressive hematite dusting along fractures and foliation planes (Fortowski and McCracken, 1998). The skarn assemblage is characterised by the assemblage K-feldspar-calcite-clinopyroxene with local sphene and scapolite. This assemblage is overprinted by veins and breccias that are characterised by a chalcopyrite-pyrrhotite-pyrite-magnetite-clinopyroxene-scapolite-calcite assemblage, with pyrrhotite dominant over magnetite in the upper part of the system and grading to a deep, barren magnetite core. Chalcopyrite is associated with both pyrrhotite and magnetite (Fortowski and McCracken, 1998).

Greenmount. At the Greenmount deposit, bleached albitised black shale of the Marimo Slate host quartz-microcline-pyrite veins with minor chalcopyrite. The albitic alteration assemblage also contains subordinate sericite and lesser hematite, rutile, tourmaline and dolomite. Chalcopyrite and pyrite are present as disseminated grains within the albitised rock. Other minor to trace primary minerals reported include marcasite, cobaltite, sphalerite and pyrrhotite (Krcmarov, 1995). Greenmount is inferred to be localised along the western margin of a NW-trending positive flower structure associated with sinistral transpression by Hodgson (1998), who interpreted that mineralisation and alteration coincided with brittle faulting associated with regional D_4.

Mount Dore. Recent exploration by Ivanhoe Australia in the Mount Dore system has resulted not only in upgrading the Mount Dore resource (Table 1), but identified a new Mo-rich zone. As described before, molybdenite is a common minor mineral in many of the iron-oxide copper-gold deposits in the Cloncurry district, but this discovery, the Merlin zone, is the only known deposit with molybdenum as the main economic commodity. Ivanhoe Australia released a JORC-compliant mineral resource totaling 13 Mt grading 0.8% Mo, 14 g/t Re, 0.2% Cu and 4.8 g/t Ag (www.ivanhoeaustralia.com) that is open both to the north and south. The Mount Dore-Merlin system is located ~20 km south of the Mount Elliott deposit, and just northeast of the Starra gold-copper deposit.

As very little public domain information is available about the Mount Dore-Merlin system, the following description is based mostly on documents obtained from the Ivanhoe Australia website (accessed May 2009), with additional information from Lazo and Pal (2009). Figure 48 shows two cross sections, one through the Mount Dore zone and the second through the Merlin zone.

The Mount Dore-Merlin mineralised system (Figure 48) is hosted by siliciclastic rocks of the Kuridala Formation 2-3 km to the northeast of the Starra deposit. The host sequence, which strikes north-south and dips moderately to the east, consists of a sequence that grades from a mixture of sandstone and siltstone, through a 50-100 m thick interval of silicified siltstone with black shale at the top and into a 200-300 m unit of phyllite/schist and black shale. Recent mapping by the Geological Survey of Queensland equates this sequence with the ~1680-1670 Ma Soldiers Cap Group, which is present in the Snake Creek Anticline. The contact between the phyllite-dominated and siltstone-dominated units is commonly sheared, and the phyllite-dominated unit is in faulted contact with the Mount Dore Granite. The Mount Dore Granite is interpreted to have been thrust over the host sequence, and the thrust appears to cut the Cu-rich zone on the northern section (www.ivanhoeaustralia.com).

Both mineralised zones are hosted by the finer-grained siliciclastic sedimentary rocks, with the Cu-rich zones hosted mostly by the phyllite-dominated unit, whereas the Mo-rich zones are hosted mostly by silicified siltstone and black shale that underlie this unit. Along the northern cross section, where phyllite and black shale are differentiated, the Cu-rich zones are commonly centered on black shale intervals, and the lower Mo-rich zone appears to grade into a Cu-rich zone down dip. The Mo-rich zone commonly overlaps shale intervals (www.ivanhoeaustralia.com).

Most of the known Cu-rich resource comprises secondary oxides, carbonates and silicates (mainly chrysocolla, cuprite, chalcotrichite and pseudomalachite) that grade with depth through a transition zone dominated by chalcocite and into hypogene sulphide zone. Lazo and Pal (2009) recognised two major episodes of primary sulphide mineralization: an early chalcopyrite-pyrite-sphalerite-bornite assemblage emplaced into brecciated siltstone and shale and a later chalcopyrite-pyrite-sphalerite assemblage in dolomite-hosted breccia. The early assemblage is associated with a K-feldspar-quartz alteration assemblage, and trace to minor galena, cobaltite, arsenopyrite and molybdenite accompany the hypogene sulphide assemblages.

The Merlin zone, which overprints the Cu-rich resource (Lazo and Pal, 2009), is hosted in an east-dipping chloritic shear and breccia system that is developed along the shear between the upper phyllite and lower siltstone-dominated units. The molybdenite commonly occurs as the matrix of breccias formed along this shear zone, although a substantial portion is presented as disseminated grains or along fractures in albite-silica±clay altered siltstone and shale below the shear zone. Clasts within the mineralised breccias are commonly K-feldspar altered, and albite altered sandstone is commonly hematite stained. Analysis of assay data released as part of the resource announcement (www.ivanhoeaustralia.com) suggests that within the Merlin zone, two different metal assemblages are present: Mo-Re and Cu-Au-Ag, with Co and Zn broadly associating with Cu. This may suggest two discrete, though possibly related, metallogenic events.

Kalman. The Kalman deposit consists of a Mo-rich core (26 Mt @0.11% Mo, 2.75 g/t Re, 0.26% Cu and 0.13 g/t Au within an overall resource of 61 Mt grading 0.32% Cu, 0.15 g/t Au, 0.05% Mo and 1.2 g/t Re (Leahy, 2009). This deposit may represent the link between Mo-Re deposits such as Merlin and the broad Cu-Au association that characterises the eastern Mount Isa Province. This deposit is localised along the Pilgrim fault and hosted by mixed siliciclastic and carbonate rocks of the Corella Formation, which also includes intrusive and extrusive mafic volcanic rocks (Leahy, 2009). These rocks have been metamorphosed to amphibolite grade.

The mineralised zone is hosted by and interpreted to overprint calc-silicate rocks characterised by alkali feldspar, with lesser tremolite, apatite, biotite and sphene. These rocks were metasomatised during the early onset of mineralisation to give a albite-actinolite-calcite-chlorite assemblage with fine inclusions of hematite within albite giving the rock the characteristic "red-rock" alteration style (Leahey, 2009). The main stage of mineralisation is characterised by a calcite-chlorite-minor quartz assemblage and lacks development of pervasive silicification and quartz veining. Two major pulses of mineralisation are inferred: an early pulse that introduced molybdenum accompanied by uranium and rare-earth elements, and a later pulse that introduced copper and gold. The early phase defines the core of the hydrothermal system and is characterised by disseminations and discontinuous veinlets containing mainly molybdenite. These disseminations and veins, which overprint albitite, also are accompanied by calcite, chlorite, minor apatite and trace allanite. the uranium is present as uraninite. The later, apparently overprinting pulse is characterised by a disseminated and vein-hosted chalcopyrite-pyrite-gold assemblage associated with albite in the veins (Leahey, 2009). Leahey (2009) recognised a third, generally minor, pulse characterised by quartz±calcite veins containing chalcopyrite±pyrite.

Uranium mineralisation. Although the main commodities in the Cloncurry district are copper, gold and, most recently, molybdenum, uranium is present at anomalous, though uneconomic, levels in several of the iron-oxide copper-gold deposits, including the Ernest Henry deposit, which averages 50 ppm U, and the Swan lens in the Mount Elliott system, which, based on assays released in a 2007 Ivanhoe Mines press release (http://www.ivanhoe-mines.com/i/pdf/2007-01-18_NR.pdf), has grades between 20 and 400 ppm over long intersections, and spot grades to 2200 ppm. Plotting of these data, however, indicate that the uranium and copper assays are not correlated (Huston et al., 2009). At Kalman, uranium appears to associated with molybdenum (Leahey, 2009).

Uranium is also present as a stand alone commodity at several prospects in the Cloncurry district, particularly in the vicinity of Kuridala, although public domain literature about these prospects is limited. The following descriptions are based largely on the Ivanhoe Mines (www.ivanhoe-mines.com) and Ivanhoe Australia (www.ivanhoeaustralia.com) websites. The most significant results have been at the Robert Heg prospect, which has historical assays of up to 9300 ppm U_3O_8 over 11 m. At this deposit, uranium is hosted by a chloritic shear zone, with low grade, possibly disseminated uranium within granite and calc-silicate rocks. Other nearby prospects include Dairy Bore, Old Fence and U2.

In the Mount Elliott area, uranium has been detected at the Amethyst Castle and Metal Ridge prospects. At Amethyst Castle, high grade, chalcocite mineralised breccias were intersected in several drill holes (www.ivanhoeaustralia.com). These breccias are polylithic with a hematite matrix and chalcocite present both in the matrix and clasts. Elsewhere chalcocite-bornite-chalcopyrite-carbonate veins and vein breccias are present. Alteration assemblages include silica, albite and hematite, and the hosts include biotite schist and granite. Uranium grades typically range between a few 10s to several 100s of ppm, with a maximum grade (over 1 m) of 1800 ppm. Like other deposits in the Cloncurry district, published assays suggest that copper and gold are correlated, but there does not appear to be correlation between copper and uranium.

Summary of deposit characteristics. As described above, deposits in the Cloncurry district are quite diverse, although there are some unifying themes. Although it varies in abundance, magnetite is present in all deposits, as is chalcopyrite and pyrite. In most deposits, there is an early albitic alteration assemblage that is overprinted by later K±Fe-bearing or calcic skarn assemblages. The ore assemblage overprints these latter assemblages, largely as veins and/or breccias. Typically these deposits are characterized by a Cu-Au-Co-(Mo-W-U-Sn) assemblage with some deposits also characterized by Ba, F, Zn, Pb and/or Ni, and in most cases, the ores were introduced during regional D_4.

These deposits are hosted by a range of host rocks, ranging from epigenetic and syngenetic ironstone, through carbonaceous phyllite, quartz-mica schist, black shale and meta-arkose through to intermediate metavolcanic rocks and amphibolites. Another diverse characteristic is the Fe-S-O assemblage, with the relative abundance of pyrrhotite and hematite apparently governing Cu/Au ratios. At Osborne, pyrrhotite-rich zones are copper-rich, whereas hematite-rich zones are gold-rich. This relationship appears to hold regionally, with hematite-rich deposits such as Starra being relatively gold-rich (Cu/Au $\sim 0.5 \times 10^5$), and pyrrhotite-rich deposits, such as Mount Elliott and Osborne (Cu/Au $\sim 1.7 \times 10^5$ and 2.3×10^5), being copper-rich.

The main metal assemblage present in these deposits is Cu-Au; in some deposits Co, Ag and Zn are associated with this assemblage. At the Merlin deposit, a Mo-Re assemblage is also present, although within an overall Cu-Au dominated system. Molybdenite is recorded in a number of other deposits, suggesting the Mo-Re assemblage may be more common, although not at the bonanza grades observed at Merlin. In addition, where assayed for, uranium also appears to be an important component of these systems, although the lack of correlation between it and the Cu-Au assemblage may suggest different depositional settings and may indicate uranium potential outside of Cu-Au-mineralised zones in these deposits.

Regional alteration assemblages. Although not directly associated with copper-gold ore, early sodic and sodic-calcic alteration assemblages are a characteristic shared by many iron-oxide copper-gold deposits in the Cloncurry district and elsewhere around the world (Williams et al., 2005). Regionally, sodic and sodic-calcic alteration assemblages are widespread in the eastern part of the Mount Isa Province, affecting the rocks east of the Kalkadoon-Leichhardt Belt, particularly the Soldiers Cap Group. Oliver et al. (2004) recognised three episodes of albitic alteration, with the last being the most extensive and most likely associated with iron-oxide copper-gold deposits of the Cloncurry district. This episode is interpreted to have formed between 1550 Ma and 1500 Ma, coeval with emplacement of the Williams-Naruku Granites, which are also locally albite altered. In addition to albite, the regional alteration assemblage may include minor to trace titanite, amphibole, clinopyroxene, biotite, apatite, epidote, magnetite, hematite and pyrite (Oliver et al., 2004). The altered zones are typically crosscutting, commonly occurring along D_4 high-strain zones, in vein and in breccias. Typically these regional assemblages are interpreted to have formed between 400 and 600°C, at pressures of 200-450 MPa (Oliver et al., 2004).

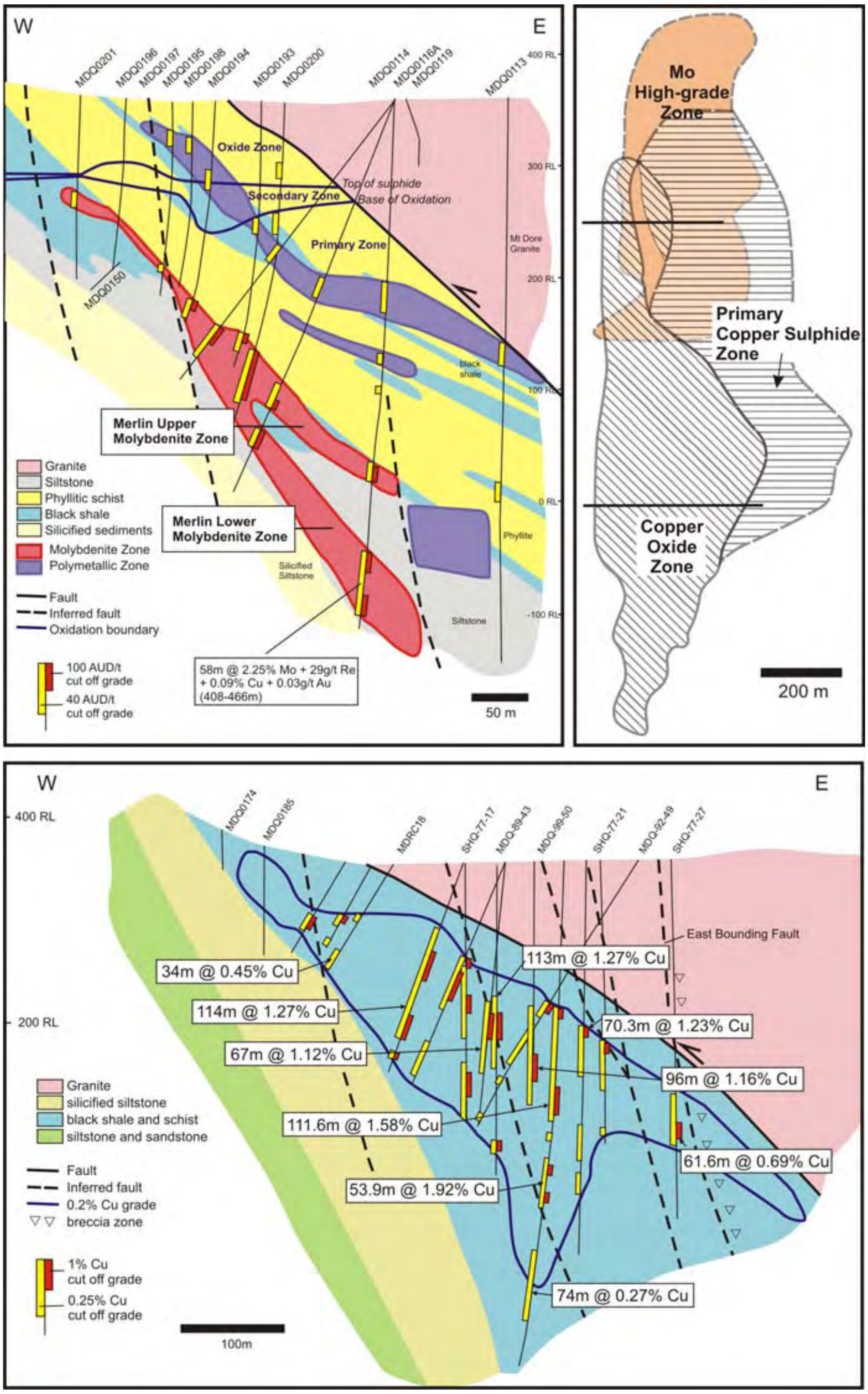


Figure 48. Cross sections showing the geology of the Mount Dore-Merlin ore system (after www.ivanhoeaustralia.com).

Age of mineralisation. Over the years, structural studies at a number of deposits in the Cloncurry district have indicated a syn- to late-D_4 timing for mineralisation. However, more recent geochronological work has begun to pin down the absolute timing of mineralisation. Table 3 summarises the results of these studies, which include a number of different isotopic systems and minerals. With the possible exception of the Osborne deposit, all deposits appear to have formed in the range 1530 to 1500 Ma. This range overlaps the likely age of regional albitic alteration and also the emplacement ages of granites that form the Williams-Naruku granite suite (Table 2). The data from

Osborne are problematic, with two quite different timings (~1595 Ma or <1540 Ma) suggested for mineralisation. A possible resolution may be that there were two events (cf. Rubenach et al., 2001).

Regional controls on iron-oxide copper-gold mineralisation. The results of the 2006 Mt Isa and 2007 Cloncurry-Georgetown-Charters Towers seismic surveys suggest that the eastern margin of the Mount Isa Province is bounded by a west-dipping suture juxtaposing this province with a two layered crustal block to the east, comprising the Numil Seismic Province and the Kowanyama-Etheridge Province (Korsch et al., 2009c; Henson et al., 2009; Huston et al., 2009: Figure 49). This suture, which is also imaged by magnetotelluric data (Figure 49) and by inversions of aeromagnetic data (Chopping et al., 2009), is interpreted to be old, possibly the consequence of subduction and accretion of the Numil Province prior to 1850 Ma (Korsch et al., 2009c; Huston et al. 2009).

When projected onto line 07GA-IG1 (using the trend of magnetic anomalies), the Ernest Henry deposit is located in the hangingwall of the crustal discontinuity (Figure 49), in a similar position to that inferred for the Olympic Dam IOCG(U) deposit in South Australia. This deposit is also located above a suture between inferred Archean and Proterozoic crust that is visible in both seismic and MT data (Lyons and Goleby, 2005). Other deposits in the eastern Mount Isa IOCG province appear to have a similar position relative to the inferred suture (Figure 50). In the northern part of the district, the surface projection of this suture is marked by the eastern margins of a gravity ridge and a major change between highly magnetic and less magnetic crust (Figure 50). In the southern part of the district, the location of the suture is difficult to map. Either it follows approximately the position of the Cloncurry Fault (Fig. 50) or the edge of the gravity ridge; the position of this suture corresponds approximately with the western margin of the Carpentaria conductance anomaly of Lilley et al. (2001).

With the exception of the Eloise deposit, all iron-oxide copper-gold deposits are localised in the hanging wall of this suture, approximately 20-50 km west of the projection to surface (Figure 50). This suggests that the rocks to the west of this suture, from the Tasman Line in the south to the Gulf of Carpentaria to the north have potential for iron-oxide copper-gold deposits.

3.1.1.10. Other copper deposits

Outside of the Mount Isa deposit and the Cloncurry district, the Mount Isa Province contains a plethora of copper prospects and deposits in a large variety of settings. Brooks (1975) reported over 1000 copper-bearing deposits, prospects and occurrences in virtually all rock units in the Mount Isa Province. Although most production and resources have been from the Mount Isa copper orebodies and, to a lesser extent, iron-oxide copper-gold deposits of the Cloncurry district, other districts within the Mount Isa Province have produced copper. The most significant of these include deposits along the northern margin of the Mount Isa uranium field and deposits in the Kalkadoon-Leichhardt Belt.

The northern part of the Mount Isa uranium field contains a number of structurally controlled, epigenetic copper deposits, some of which also contain cobalt. The most significant are those at Gunpowder (including the Esperanza and Mammoth deposits) and Mount Annie (Table 1). The Esperanza and Mammoth deposits are localised along curvilinear northeast- to east-trending faults linked to the Mount Gordon and related faults (Figure 45). Unlike the metasomatic uranium deposits of the Mount Isa uranium field, these deposits are hosted by rocks that overly the Eastern Creek Volcanics (Richardson and Moy, 1998): the Myally Subgroup, which overlies the Eastern Creek Volcanics, and the Esperanza Formation, which is part of the Isa Superbasin. The ores are characterised by disseminated and veinlet chalcopyrite and pyrite, chalcopyrite-pyrite±chlorite veins and massive sulphide. At both deposits the ores are zoned, with bornite- and chalcocite-bearing assemblages above and lateral to chalcopyrite-dominated zones (Mitchell and Moore, 1975; Richardson and Moy, 1998). The bornite- and chalcocite-bearing zones have been interpreted as both hypogene (Mitchell and Moore, 1975) and supergene assemblages (Richardson and Moy, 1998); Mitchell and Moore (1975) interpreted sooty chalcocite developed in the upper 70 m of the Mammoth deposit as supergene. These small deposits differ in two important ways from the Mount Isa copper deposit: (1) the deposits lack pyrrhotite, which is an important hydrothermal mineral at Mount Isa (Perkins, 1984), and (2) the deposits lack extensive silica-dolomite alteration zones, the dominant alteration assemblage at Mount Isa (Perkins, 1984). Rather, the dominant iron mineral at the Esperanza and Mammoth deposits is pyrite with the possibility of fine hypogene hematite at Mammoth (Mitchell and Moore, 1975), and the hosts to the Mammoth ores are characterised by muscovite-hematite-pyrite-chlorite alteration assemblages (Richardson and Moy, 1998).

The Lady Annie group of deposits (including Mount Clarke and Mount Kelly), which is hosted by the lower part of the Paradise Creek Formation, is dominated by oxide ores, which, with depth, grade into transitional and then sulphide ores. The oxidized ores, which are present to depths of 70 m, above the base of weathering, comprise malachite, cuprite, tenorite and chrysocolla together with minor azurite and native copper (Lewis, 1975). Below the oxidized zone is a mixed transitional zone, which overlies the sulphide zone. Lewis (1975) indicates that the sulphide zone is zoned from an uppermost chalcocite zone, through a chalcocite-pyrite zone, a chalcocite-pyrite-bornite-chalcopyrite zone into a basal chalcopyrite-pyrite zone, which he interpreted as zonation through a supergene zone into primary chalcopyrite-pyrite ore. In the sulphide zone, copper sulphide minerals are present in carbonate and quartz veins and vein breccias. The sulphide zone at depth appears to be structurally controlled with significant intersections commonly associated with fault-related silicification (www.copperco.com.au; accessed May 2009).

The most significant deposits in the Kalkadoon-Leichhardt Belt are the Mount Cuthbert and Mount Watson deposits (Table 1). The Mount Cuthbert deposit is hosted by the Argylla Formation, which comprises sheared tuffaceous metasedimentary rocks, arkose, phyllite and schist with felsic intrusions (Cavaney, 1975). These rocks have experienced greenschist facies metamorphism and potassic metasomatism. The ores are shear hosted and consist of chalcopyrite, pyrite and minor pyrrhotite in a gangue of quartz and/or dolomite. This primary ore grades upwards into supergene ores dominated by chalcocite and then into oxide ore with malachite, cuprite and chrysocolla (Cavaney, 1975).

3.1.1.11. Sundry deposits

Although the Mount Isa Province is known as both a major Zn-Pb-Ag and a Cu-Au metallogenic province, it is also endowed with other commodities such as uranium (sections 3.1.1.5 through 3.1.1.7) and with minor gold-only deposits. In addition, the Georgina Basin, which onlaps the Mount Isa Province on the west and south contain significant phosphate deposits.

The only significant gold deposit known in the Mount Isa Province, the Tick Hill deposit, is hosted within the Mary Kathleen Fold Belt by a fault-bounded enclave of calc-silicate, siliciclastic and pelitic rocks of the Corella Formation and volcaniclastic rocks of the Argylla Formation, all of which were metamorphosed to amphibolite grade (Forrestal et al., 1998). Although small in tonnage (Table 1), the Tick Hill deposit was very high grade, averaging nearly an ounce per tonne (~30 g/t). The gold is hosted by laminated quartz-feldspar rock along the moderately west-dipping contact between footwall pelitic schist, possibly of the Argylla Formation, and hanging wall calc-silicate rocks of the Corella formation. In detail, the lode rock is overlain directly by a massive quartzite with local foliated zone and with local magnetite-rich lenses. The lode rock also contains internal lenses of quartz-chlorite schist (Forrestal et al., 1998).

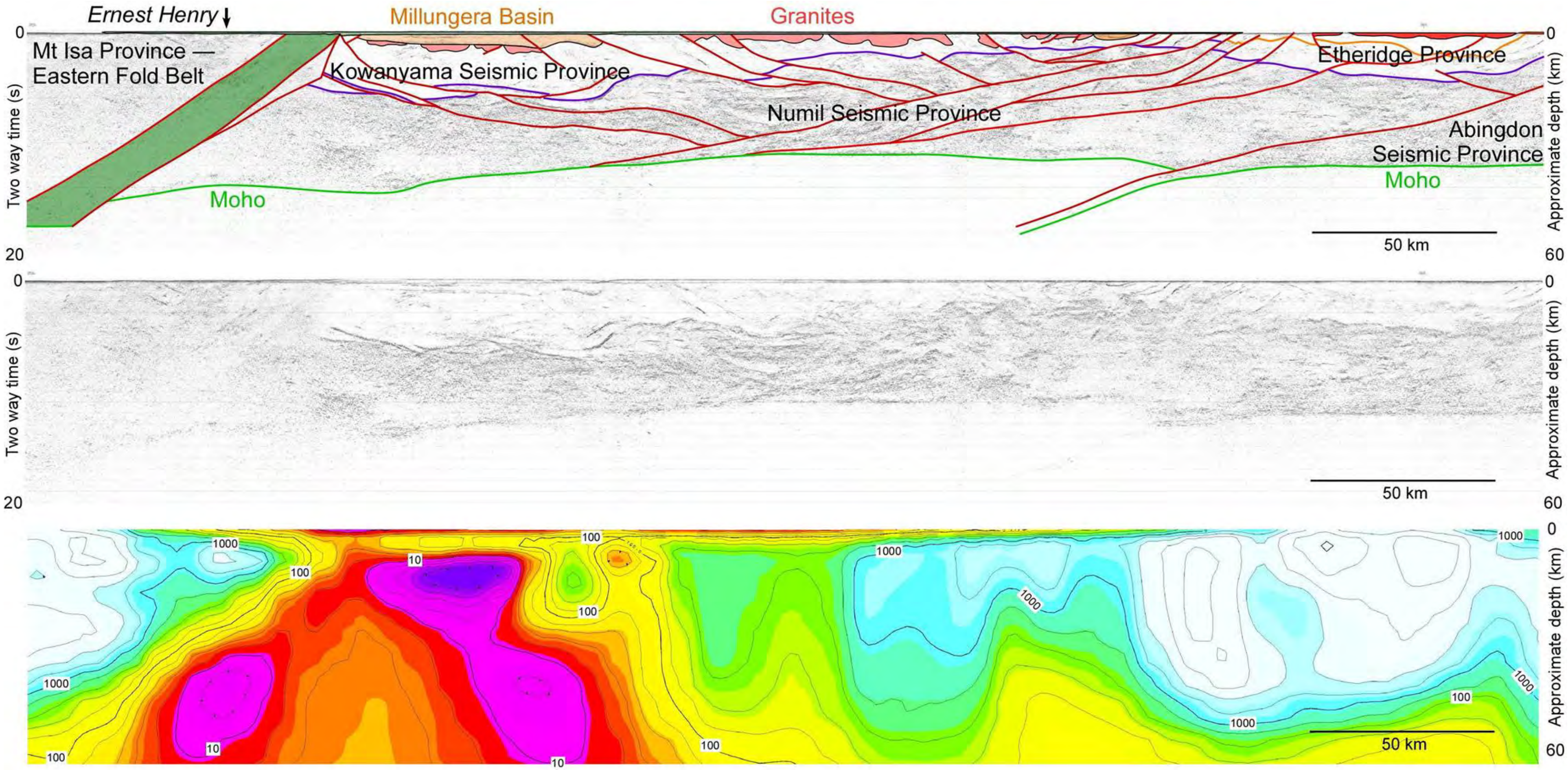


Figure 49. Images of seismic section 07GA-IG1 showing interpreted section (top), uninterpreted data (middle) and modelled magnetotelluric data (bottom).

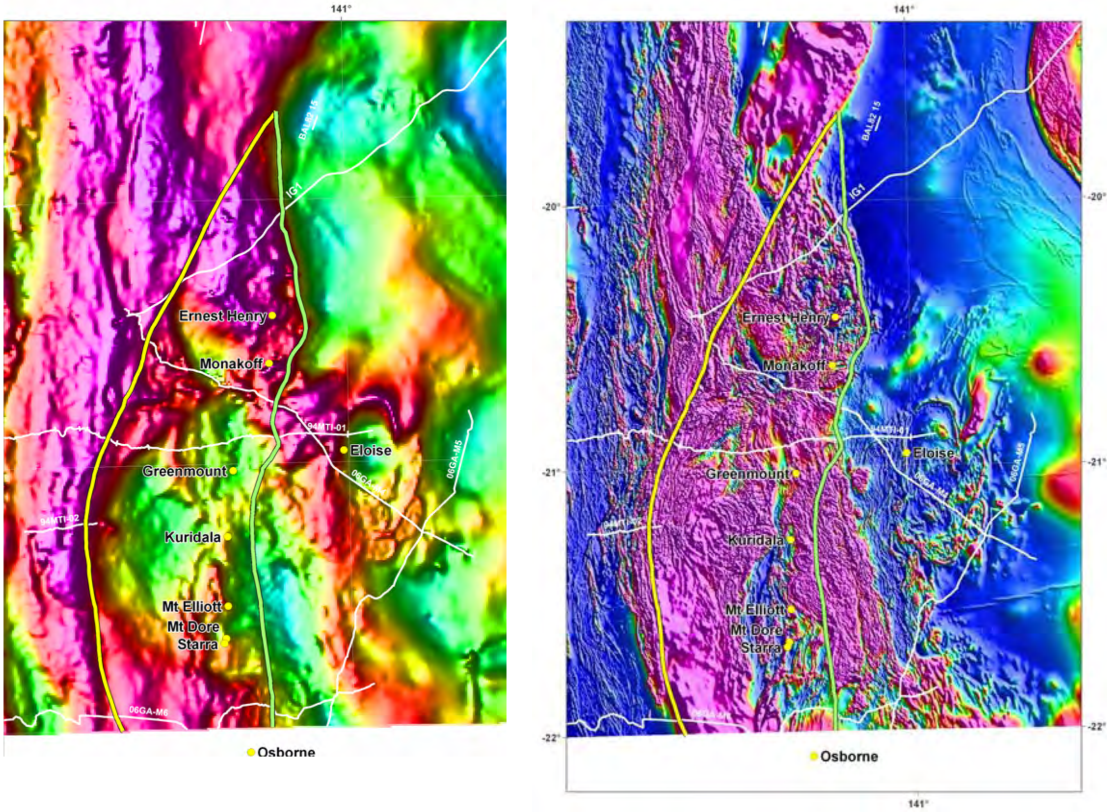


Figure 50. Images of the eastern part the Mount Isa Province showing the locations of seismic lines, the inferred position of Isa-Numil suture (yellow-green line in centre of image) and locations of known iron-oxide copper-gold deposits of the Cloncurry district: (a) Reduced-to-pole aeromagnetic data; and (b) Bouger-normalised gravity data. Hot colours (e.g. red and purple) indicate high values, whereas cool colours (e.g. blue and green) indicate low values.

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Table 2. Summary of geochronological studies of iron-oxide copper-gold deposits in the Cloncurry district, northwest Queensland.

Deposit Preferr	ed age (Ma)	Comments Reference	
Ernest Henry	1514	^{40}Ar-^{39}Ar and SHRIMP U-Pb analyses of pre-, syn- and post-ore minerals yield a range of ages between 1540 and 1476 Ma, whereas Re-Os analyses of molybdenite indicated an age of ~1595 Ma. The most robust ages (SHRIMP U-Pb analyses) on titanite associated with pre-ore biotite-magnetite alteration yielded and age of 1514 ± 24 Ma, which is inconsistent with the molybdenite age. ^{40}Ar-^{39}Ar analysis of post-ore biotite yielded an age of 1514 ± 6 Ma.	Twyerould (1997); Perkins and Wyborn (1998); Gauthier et al. (2001); Mark et al. (2006)
Eloise 15	30- 1514	^{40}Ar-^{39}Ar analyses of pre- (hornblende) to post-ore (muscovite) minerals yielded age range of 1530 to 1514 Ma. The ~1530 Ma age is preferred due higher closure temperature of hornblende and the close spatial association between pre-ore hornblende and the ore assemblages.	Baker et al. (2001)
Osborne <15	40 and/or 1595	Initial ^{40}Ar-^{39}Ar analyses of post-metamorphic and pre-ore hornblende and biotite yielded similar ages of ~1540 Ma, which was interpreted as the maximum age of mineralisation and the minimum age of metamorphism (Perkins and Wyborn, 1998). Subsequently, Gauthier et al. (2001) interpreted a ~1595 Ma age for mineralisation based on TIMS analyses of hydrothermal titanite and Re-Os analyses of molybdenite.	Perkins and Wyborn (1998)
Starra 15	03	^{40}Ar-^{39}Ar analyses of ore-related biotite yielded ages of ~1503 and 1496 Ma.	Perkins and Wyborn (1998)
Monakoff 15	08	^{40}Ar-^{39}Ar analyses of ore-related biotite.	Pollard and Perkins (1997)
Regional Na-Ca alteration assemblages	1525	Discordia from hydrothermal titanite associated with regional albitic assemblages yielded ages of 1521 ± 5 Ma, 1527 ± 7 Ma (both from Mary Kathleen fold belt) and 1524 ± 16 Ma (from Cloncurry district). An early age of 1555 ± 9 Ma was also recorded in a sample that yielded the ~1527 Ma age.	Oliver et al. (2004)
Williams-Naruku magmatic suite	1550-1500	Total range is 1547 to 1501 Ma, with three apparent pulses at 1550-1545 Ma, 1530-1520 Ma and 1520-1500 Ma.	Page and Sun (1998)

The gold-bearing lodestone is a quartz-rich rock with layers of biotite, hornblende, albite, magnetite, hematite, pyrite, sphene, scapolite and apatite, with minor calcite and epidote. Forrestal et al. (1998) interpret this rock to be silicified calc-silicate rock, scapolite schist and amphibolite. Gold is hosted by quartz-feldspar laminate bands within the lode rocks. The laminated bands are characterised by strong quartz veining, silicification and intense sodium metasomatism. The laminate bands are commonly foliated, and the lodestone is interpreted as a mylonite (Forrestal et al., 1998). This rock and the internal fabric has been folded about D_3 folds, leading to the interpretation that gold mineralisation predated D_3 and was associated with development of an extensional shear zone (Forrestal et al., 1998), possibly corresponding to the early (~1740 Ma) extensional event documented by Holcombe et al. (1991) and supported by Gibson et al. (2008). Alternatively, Pb-Pb ages from coarse pyrite separates suggest an age of ~1530 Ma (D Groves and I McNaughton, cited in Forrestal et al., 1998). If the former age is correct, Tick Hill would be the oldest deposit known in the Mount Isa Province, whereas if the latter age is correct, mineralisation may have been coeval with iron-oxide copper-gold deposits further to the east in the Cloncurry district.

Middle Cambrian formations within the Georgina Basin contain a number of phosphate deposits, with total resources in excess of 3.5 Gt of phosphorite. Known deposits, which are hosted dominantly by Middle Cambrian rocks, are mostly located along the eastern margin of the basin or within remnant outliers of the basin exposed on the Proterozoic basement. Freeman et al. (1990) recorded four phosphate depositional events, during the Ordian (deposits in the Thorntonia Limestone, and in the Lower Hay River, Arthur Creek and Border Waterhole Formations), Templetonian (deposits in the Monastery Creek Phosphorite Member of the Beetle Creek Formation and the Wonarah and Burton beds), late Floran (deposits in the Gowers Formation) and Llanvirn (deposits in the Mithaka Formation). Of these the first three events are Middle Cambrian in age, and the last is Middle Ordovician in age. The most significant deposits are from the second event in the Beetle Creek Formation. This includes the Duchess (Phosphate Hill) deposit with total resources in excess of 1.4 Gt (Table 1). These deposits formed during basinal flooding (Freeman et al., 1990).

3.1.1.12. Metallogenesis of the Mount Isa Province: temporal and genetic relationships between deposits

The Mount Isa Province is one of the richest mineral provinces in the world, hosting part of the world's largest known zinc province, as well as major copper and copper-gold, significant uranium and high grade gold deposits.

Although absolute age data are not available, the oldest deposit in the Mount Isa Province may be the Tick Hill gold deposit, which is interpreted to be related to an extensional shear zone that developed at ~1740 Ma (Forrestal et al., 1998). This may suggest that extensional shear zones associated with the Wonga extensional event (Holcombe et al., 1991; Gibson et al., 2008) have potential for shear-related lode gold deposits. Alternatively, if the unpublished ~1530 Ma Pb-Pb age of Groves and McNaughton (in Forrestal et al., 1998), is accepted, the Tick Hill deposit would be related to the 1530-1500 Ma iron-oxide copper-gold event that characterises the Cloncurry district.

The oldest reliable age for mineralisation is ~1670 Ma for Broken Hill-type zinc-lead-silver deposits in the Soldiers Cap Group. This age is based on galena lead isotope model ages which are similar to the age of the host sequence. These deposits, which include the Cannington and Pegmont deposits, are interpreted to have formed in relatively deep water during a rift event during which the Soldiers Cap Group was deposited. Tholeiitic magmatism associated with the opening of this rift drove hydrothermal fluid flow to form the syngenetic deposits.

The Leichhardt River Fault Trough is host to Mount Isa-type zinc-lead-silver deposits at Mount Isa and Hilton-George Fisher. Stratigraphic ages and lead isotope model ages suggest that these deposits, which are hosted by the lower part of the Mount Isa Superbasin, formed at ~1655 Ma.

In addition to the metasomatic uranium deposits described above, the Leichhardt River Fault Trough is host to world class zinc-lead deposits at Mount Isa and Hilton and a world class copper deposit, also at Mount Isa. The Mount Isa uranium field also hosts a number of smaller copper±cobalt deposits, including Mammoth and Esperanza (Figure 45). Although the zinc-lead deposits are generally (with the important exception of Perkins and Bell, 1998) considered to have been deposited syngenetically or diagenetically at ~1655 Ma, the copper deposits are generally considered to be epigenetic (Van Dijk, 1991), with $^{40}Ar/^{39}Ar$ dating of ore related biotite suggesting an age of ~1520 Ma for the Mount Isa copper deposit (Perkins et al., 1999). The ages of the Mammoth and Esperanza deposits are not well known, although modelling of lead isotope data from the Mammoth deposit suggests an age of ~1540 Ma (Carr et al., 2001). Given uncertainties in these dating methods, we consider the age estimates preliminary. Taken at face value, the data suggest that the Mount Isa copper deposits were deposited up to 30 million years after the metasomatic uranium deposits at Valhalla and Anderson's Lode. However, the Carr et al. (2001) age estimate for Mammoth-Esperanza is consistent with the ages obtained from Valhalla and Anderson's Lode, raising the possibility that these deposits formed from a single district-scale mineral system.

Based on similarities in Fe-S-O mineral assemblages (i.e. pyrite-hematite, without pyrrhotite) and apparent mineralisation ages, we interpret that the metasomatic uranium and epigenetic copper deposits in the Mount Isa uranium field as cogenetic and deposited from the same oxidised fluids. However, existing geochronological data suggest that the Mount Isa copper deposit may not be part of this mineral system, but rather a slightly younger system.

3.1.2. Geology, geodynamic evolution and metallogenesis of the Etheridge Province

The Etheridge Province forms the easternmost extent of Paleo- to Mesoproterozoic rocks in North Queensland, and is bound on the east by the Tasman Line. Though not as mineralised as the Mount Isa Province, it contains a variety of mineral resources, with significant gold production in the Croydon goldfield. Based on similar lithologies and similar age data, the Etheridge Group, which forms the basal known unit in the Etheridge Province, has been correlated with the Soldiers Cap Group in the Mount Isa Province and interpreted to have formed in an extensional basin (Gibson et al., 2008). This interpretation is supported to an extent by recently acquired seismic data on a traverse between Cloncurry and Croydon (Korsch et al., 2009c: Figure 49). In this interpretation, the Etheridge Province appears to extend underneath the Eromanga/Carpentaria Basin into the Kowanyama Province, which is juxtaposed along the Isa-Numil Suture with the Mount Isa Province.

The stratigraphic, magmatic and metamorphic history of the Etheridge Province has recently been summarized by Withnall et al. (2009b). The following description is based on that summary and references therein, which are based on studies of exposed rocks in the Georgetown and Croydon areas. Exposed rocks in the Etheridge Provinces have a large range in metamorphic grade, with rocks in the east (Einasleigh Metamorphics) characterised by high grade (amphibolite and granulite facies) whereas rocks to the west (Etheridge and Langlovale Groups) are of much lower (greenschist and sub-greenschist facies) grade. Lithological units within the lower Etheridge Group (Robertson River Subgroup) can be traced across metamorphic gradients into the Einasleigh Metamorphics, suggesting partial correlation (Withnall et al., 2009b; Figure 51).

Owing to geochronological studies of Black et al. (2005) and Baker (2007) and unpublished results of N. Neumann, the depositional ages of the rocks in the Etheridge and Langlovale Groups and the Einasleigh Metamorphics are reasonably well constrained. The best constraint on lowermost Robertson River Subgroup is a laser ablation zircon age of the Dead Horse Metabasalt at ~1663 Ma (Baker, 2007), which is compatible with maximum depositional ages of surrounding units (~1695 Ma, ~1785 Ma and ~1786 Ma: Fig 51) and a more precise SHRIMP age of the Cobbold Metadolerite of ~1656 Ma (Black et al., 2005). Geochemically, these mafic rocks, which characterise the Robertson River Subgroup are continental tholeiites (Withnall, 1985; Baker, 2007). The Robertson River Subgroup comprises variably calcareous and dolomitic sandstone, siltstone and mudstone interpreted to have been deposited in an upwardly deepening basin (Withnall et al., 1997). These rocks are characterised by a major Archean component in their detrital zircon component (Withnall et al., 2009b), which differs from equivalent rocks in the Mount Isa Province (Neumann et al., 2009).

The upper part of the Etheridge Group comprises variably carbonaceous siltstone and mudstone, with local sandstone. These rocks have maximum depositional ages of ~1655 Ma and ~1650 Ma, with a provenance signature dominated by Proterozoic zircons, which differs to that of the underlying rocks (Withnall et al., 2009b). These differences are also reflected by Nd data, which suggests that the source of the underlying Robertson River Subgroup was sourced from a more evolved source than the upper Etheridge Group (A Lambeck, unpublished data in Withnall et al., 2009b). A Lambeck (pers. comm., 2008) notes a similar relationship between pre-1655 and post-1655 Ma rocks in the Isa Province.

As discussed by Withnall et al. (1997), parts of the Einasleigh Metamorphics can be correlated across a metamorphic gradient with lower units of the Robertson River Subgroup (Figure 51). However, the stratigraphically lower parts of the Einasleigh Metamorphics may be older than the Robertson River Subgroup. Two samples of leucogneiss from the Einasleigh Metamorphics returned unimodal populations at ~1705 Ma (Black et al., 2005). Although these are strictly maximum depositional ages, the simple populations suggest the ages approximate depositional ages, an interpretation supported by ages of orthogneiss and amphibolite that intrude the Einasleigh Metamorphics, which yielded ages of 1695-1685 Ma and ~1675 Ma, respectively (Black et al., 1998; N Neumann, unpublished data). These results are consistent with the interpretation that the basal part of the Einasleigh Metamorphics may be older than the Robertson River Subgroup, an interpretation consistent with the presence of an older fabric that predates amphibolites.

In the western part of the Etheridge Province, the Etheridge Group is overlain unconformably by sandstone, mudstone and shale of the Langlovale Group (Withnall et al., 1997, 2009b). The Malacura Formation in the lower Langlovale Group yielded a maximum depositional age of ~1625 Ma (N Neumann, unpublished data, in Withnall et al., 2009b). These rocks are overlain unconformably by felsic ignimbrites of the Croydon Volcanic Group, which has an age of ~1552 Ma (Black and McCulloch, 1990) and is comagmatic, within error, with the ~1558 Ma (Black and McCulloch, 1990) reduced Esmeralda Supersuite (S-type or contaminated I-type). The Forsayth Supersuite, which intrudes the Einasleigh Metamorphics to the east, has a similar age of between 1560 and 1550 Ma (Black et al., 1998, 2005).

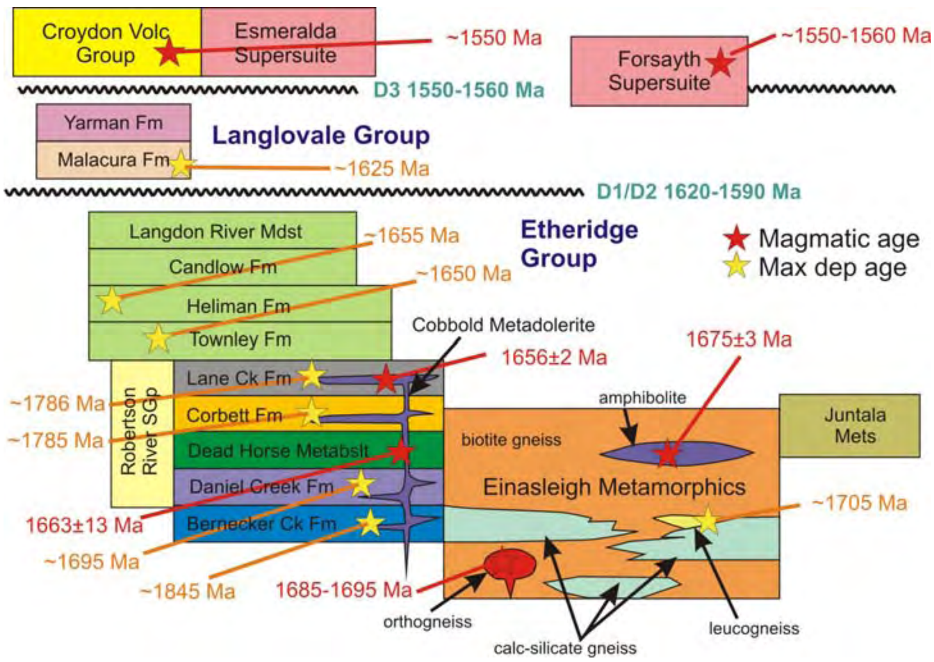

Figure 51. Diagram showing age constraints in correlations in the Etheridge Province (modified after Withnall et al., 2009b).

The deformation history of the Etheridge Province is complex, and studies of this history have resulted in conflicting results in some cases. Based on a synthesis of available studies, Withnall et al. (2009b) proposed the following Proterozoic structural and metamorphic history: (1) 1690-1675 Ma deformation and metamorphism in the lower part of the Einasleigh Metamorphics, (2) north-south shortening at ~1620 Ma (D_1), (3) east-west shortening at ~1590 Ma (D_2), (4) uplift and retrogressive metamorphism between 1590 and 1560 Ma, (5) northwest-southeast shortening accompanied by low pressure, high temperature metamorphism and emplacement of the Forsayth Supersuite at 1560-1550 Ma (D_3), (6) eruption of the Croydon Volcanic Group and emplacement of the Esmeralda Supersuite at ~1550 Ma, and (7) deformation at ~1510 Ma (D_4). This deformation history in many ways is similar to that seen in the Mount Isa Province.

Known mineral deposits in the Etheridge Province are diverse, though, in general, small in size. In comparison to the Mount Isa Province, the style, controls, and particularly, the age of mineralisation is poorly described and constrained. In the following discussion, the deposits have been grouped into five groups: (1) epigenetic tin and zinc-tin-copper deposits in the Croydon area, (2) Broken Hill-type zinc-lead-silver deposits in the Einasleigh Metamorphics, (3) epigenetic copper-gold deposits hosted by the Einasleigh Metamorphics, (4) epigenetic gold deposits of Croydon goldfield, and (5) epigenetic uranium deposits hosted by Forsayth Supersuite Granites. With the possible exception of the epigenetic copper-gold deposits, none of these deposits have definitive constraints on the age of deposition. Although they are generally considered to be Proterozoic in age, it is possible that they may be related to Silurian of Carboniferous-Permian magmatism that also affects rocks of the Etheridge Province.

3.1.2.1. Epigenetic tin and zinc-tin-copper deposits – Croydon area

Minor Sn production occurred within the Stanhills tinfield, Croydon region, with mineralisation associated with the S-type granites of the Esmeralda Supersuite. Lode deposits occur within both the granites and the surrounding volcanic rocks of the Croydon Volcanic Group. Mineralisation includes chlorite-quartz-cassiterite-sulphide (pyrite, galena, sphalerite, chalcopyrite, arsenopyrite) and quartz-white mica-cassiterite greisen lodes, present as veins, pipes and more irregular bodies (Denaro et al., 1997). Age constraints for these tin deposits are very limited. Carr and Sun (1997) report a CSIRO-AGSO model age of ~1550 Ma for galena from the Comet 212 tin deposit, which is similar to the age of the Esmeralda Granite. Moreover, the isotopic ratios of this galena are similar to, though slightly less radiogenic than, the least radiogenic analysis of feldspar from this granite (Figure 52). This relationship suggests that the lead in these tin deposits has a similar age and may have been derived from the Esmeralda Granite, consistent with the close association of these deposits with the granite. However, it is possible that some of the tin is related to Carboniferous-Permian magmatism, which is related to extensive tin mineralisation throughout northern Queensland. Although there are apparently no outcropping granites of this age, interpretation of aeromagnetic data shows that the Carboniferous-Permian magmatism occurs just to the north of the region, as part of the Townsville- Mornington Island Belt.

In 2005, Goldaura Pty Ltd intersected steeply dipping polymetallic veins below 120 m of Eromanga-Carpentaria Basin cover approximately 40 km to the north-northeast of Croydon. These veins were intersected by drill holes targeting isolated "bullseye" aeromagnetic anomalies. This is the most significant recent discovery in the Etheridge Province. The following description is taken from the Goldaura website (www.goldaura.com.au; accessed June 2009), discussion with Ken Chapple (Managing Director, Gold Aura) and from site visits in August 2008.

The mineralisation is hosted by steeply dipping veins with variable strike. These veins, which range in apparent thickness from a less than a millimetre to several metres, are dominated by sulphides with significant siderite and quartz, and lesser sericite, topaz, illite, fluorite and apatite gangue. The dominant sulphide is magnetic pyrrhotite, with major dark-coloured, Fe-rich sphalerite and minor to trace arsenopyrite, pyrite, marcasite, chalcopyrite, galena, cassiterite and stannite. Announced assay results indicate both long, low grade intersections (e.g., 133 m grading 1.1% Zn, 18 g/t Ag, 0.15% Sn and 0.04% Cu: hole A2-001) and narrower higher grade intervals (e.g., 5 m grading 8.0% Zn, 109 g/t Ag, 0.58% Sn and 0.57% Cu: hole A2-001).

The host to the vein consists of folded, thinly to thickly bedded mudstone with lesser siltstone and very fine-grained sandstone. Samples of siltstone and sandstone are currently being processed for detrital zircon SHRIMP analyses. Table 4 presents the results of two lead isotope analyses of galena from the veins. These analyses plot between less radiogenic analyses of ~1675 Ma Broken Hill-type deposits hosted by the Einasleigh Metamorphics (see below) and ~410 Ma vein deposits in the Charters Towers goldfield. Although model ages have been calculated using the CSIRO-AGSO model (Carr et al., 2001), they are not regarded as reliable as the Croydon zinc-tin deposits have relatively low levels of lead, which leaves the isotope values susceptible to later resetting (to younger model ages), and the model is not likely to be reliable for these radiogenic analyses. However, as the analyses are intermediate between deposits with likely Paleoproterozoic and Silurian ages, a Proterozoic age is preferred for mineralisation. ^{40}Ar-^{39}Ar analyses are currently being undertaken of muscovite (sericite) intimately associated with sulphide minerals in the veins to establish a more robust age for these zinc-tin deposits.

3.1.2.2. Broken Hill-type zinc-lead-silver deposits – Einasleigh Metamorphics

The Einasleigh Metamorphics to the south of the town of Einasleigh contain a number of small to moderate sized (Table 1) Broken Hill-type zinc-lead-silver deposits, including the Chloe-Jackson-Stella system (previously known as Mount Misery) and the Railway Flat deposit. Like the nearby copper-gold deposits at Einasleigh and Kaiser Bill, these zinc-lead deposits appear to be confined to a specific stratigraphic level within the Einasleigh Metamorphics, within a sequence characterised by a change from a calcareous psammitic unit (possibly correlating with the Bernecker Creek Formation: Figure 51) upwards to a finer-grained psammopelitic unit (possibly correlating with the Daniel Creek Formation). The zinc-rich systems appear to be associated with the upper psammopelitic unit (Denaro et al., 1997; Lees and Buckle, 2009).

The immediate host to these deposits are psammitic and pelitic biotite quartzofeldspathic gneiss with interleaved amphibolite and pegmatite. At the Chloe deposit, mineral assemblages are symmetrically zoned from an inner pyrrhotite-calcite-pyroxene-sphalerite assemblage through a garnet (Ca-rich almandine and andradite)-pyroxene (diopside-hedenbergite)-amphibole-magnetite-quartz-sphalerite assemblage into an unmineralised quartz-epidote assemblage that passes into unaltered gneiss (Lees and Buckle, 2009; Stanton, 1982). Minor opaque minerals include pyrite, chalcopyrite, magnetite and galena; minor gangue minerals in the mineralised zone include amphibole (actinolite and hornblende) and stilpnomelane (Stanton, 1982). Texturally, ore minerals appear to replace the host rocks, including biotite gneiss, psammite, amphibolite and pegmatite (Lees and Buckle, 2009). At the Railway Flat deposit, two foliation-parallel lenses are present, centred on sulphide breccias (durchbewegang texture) that are overprinted by sphalerite-galena±chalcopyrite stringers (Lees and Buckle, 2009).

Table 3. High precision lead isotope composition of galena from selected deposits in the Etheridge Province.

Deposit	Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Model age (Ma)	μ
Chloe	2008 839032	16.049	15.394	35.789	1.644	12.70
Kaiser Bill	2008 839036	17.462	15.537	38.404	0.940	12.55
Kaiser Bill	2008 839037	17.466	15.548	38.453	0.947	12.58
Einasleigh barite	2008 839038	15.955	15.376	35.668	1.686	12.70
Railway Flat	2008 839040	15.975	15.381	35.679	1.678	12.71
Chloe	2007 167009-01	15.986	15.383	35.682	1.673	12.70
Snake Creek	2007 167008-02	17.169	15.544	36.793	1.113	12.66
Croydon Zn	2008 839023	17.513	15.553	37.461	0.925	12.58
Croydon Zn	2008 839023 (repeat)	17.515	15.555	37.465	0.925	12.58
Croydon Zn	2008 839024	17.316	15.536	37.313	1.022	12.59

Isotopic data with bearing on the age of the Chloe and Railway Flat deposits is complex and, unfortunately, not definitive. These data include lead isotope data, generally from galena analyses, and Re-Os analyses of molybdenite. Figure 52 shows the lead isotope data, which include conventional analyses of Carr and Sun (1997) and more precise ICP-MS analyses undertaken as part of this study. The recent data are similar to the earlier analyses. Data from the Railway Flat deposit form a single cluster with model ages of 1680-1650 Ma. Data from the Chloe deposit have two clusters, a least radiogenic cluster (1675-1645 Ma) that is similar to the Railway Flat cluster and has similar model ages, and a more radiogenic cluster with model ages of 1595-1570 Ma that is similar to analyses of the Teasdale Cu-Au prospect (see below). These results and the geological observations described above, are consistent with the interpretation that the Broken Hill-type deposits were formed at 1680-1650 Ma, consistent with the likely age of the host units, and then recrystallised or remobilised, with partial isotopic resetting, during retrogression at ~1590 Ma, or during high temperature, low pressure metamorphism at 1560-1550 Ma. This remobilisation accounts for textural relationships suggesting that the pyrrhotite-base metal assemblage replace the host rocks.

The more interesting results are from Re-Os analyses of molybdenite at Chloe, which yielded an age of 412.7 ± 1.4 Ma (D Huston and R Creaser, unpublished data). Molybdenite is an atypical mineral in the Chloe-Jackson-Stella system, present only in the analysed sample. It is also atypical for Broken Hill type deposits. Hence, we interpret this age to be the result of the overprinting of a Paleoproterozoic Broken Hill-type mineral system by a Silurian, granite-related Mo-bearing system. Alternatively, these deposits could be Silurian skarn deposits, although the lead isotope data are inconsistent (not radiogenic enough) with this interpretation. In any case, this result raises the possibility of intrusion-related Mo (and possible Sn-W and Cu-Au) deposits associated with Silurian granites in the Etheridge Province and younger provinces to the east.

In addition to the lead isotope results presented above, Table 4 presents the results of limited sulphur isotope analyses on samples from the Chloe deposit. Two analyses from the Chloe deposit are very similar at between 5.9 and 6.8‰. These results are slightly higher to the range of values (-0.9 to 1.1‰) reported for Broken Hill, New South Wales (Lawrence and Rafter, 1962; Stanton and Rafter, 1967).

Table 4. Sulphur isotope analyses of samples from the Chloe and Einasleigh deposits (analyses by S Golding, University of Queensland).

Sample	Mineral	$\delta^{34}S$ (‰)
Chloe		
2008839032	Pyrrhotite	5.9
2008839040	Pyrrhotite	6.8
Einasleigh		
Einasleigh dump	Chalcopyrite	8.3
2008839038	Sphalerite	22.5
2008839038	Barite	31.3

Correlation of the Einasleigh Metamorphics with the lower part of the Robertson River Subgroup, in particular the Bernecker Creek and Daniel Creek Formations, suggest that this unit has potential for unmetamorphosed Broken Hill-type deposits. Onley (1978; in Denaro et al., 1997) reported anomalous zinc, lead and copper in the Daniel Creek Formation, which would correlate with the inferred position of the Broken Hill-type deposits in the Einasleigh Metamorphics. Further up in the stratigraphy, stratabound zinc enrichment is noted in both the Townley and Candlow Formations in the upper Etheridge Group (Denaro et al., 1997).

3.1.2.3. Iron-oxide copper-gold deposits – Einasleigh Metamorphics

In addition to the Broken Hill-type deposits described above, the Einasleigh Metamorphics host copper-silver-gold deposits at a similar, although slightly lower stratigraphic position. These deposits, which include the Einasleigh, Kaiser Bill and Teasdale deposits, are hosted by calc-silicate gneisses (Denaro et al., 1997). Based on data of Denaro et al. (1997), copper has been produced from the Einasleigh (0.126 Mt grading 6.04% Cu, 0.52 g/t Au and 30 g/t Ag) and Teasdale (31.5 t grading 5.4% Cu), with minor, unrecorded production at Kaiser Bill. Table 1 summarises JORC-compliant resources at Einasleigh and Kaiser Bill.

These deposits, particularly Kaiser Bill and Teasdale, are associated with magnetic anomalies caused by the presence of magnetite and pyrrhotite in the ores. In general, these deposits are characterised by an ore assemblage of pyrrhotite-chalcopyrite-pyrite with accessory to trace molybdenite, sphalerite and galena (Lees and Buckle, 2009).

The Einasleigh deposit is hosted by a sequence of biotite-quartzofeldspathic gneiss and psammopelite with amphibolite and pegmatite. Lees and Buckle (2009) recognised two types of mineralisation: (1)

higher-grade tabular bodies of semi-massive to massive pyrrhotite-chalcopyrite-pyrite with magnetite, and (2) lower grade, skarn-like tabular bodies with barite and stringer to disseminated sulphide minerals. The massive sulphide bodies are structurally controlled and contain marginal breccias and relic fragments of host rocks. These bodies also contain cubanite and accessory to minor uraninite, monazite and allanite; late stage veins are characterised by the assemblage chlorite-calcite-siderite±sphalerite±arsenopyrite±tellurides (Denaro et al., 1997; Evins et al., 2007). The skarn-like bodies are characterised by a barite-andradite-clinopyroxene-epidote, quartz-epidote, epidote-chlorite, and oligoclase-carbonate assemblages, with the barite-bearing assemblage containing disseminated pyrite, sphalerite, chalcopyrite and galena (Denaro et al., 1997; Evins et al., 2007; this study). A single sulphur isotopes from the massive pyrrhotite-chalcopyrite indicated a value of 8.3‰, whereas sphalerite and barite from the baritic body yielded values of 22.5‰ and 32.3‰, respectively.

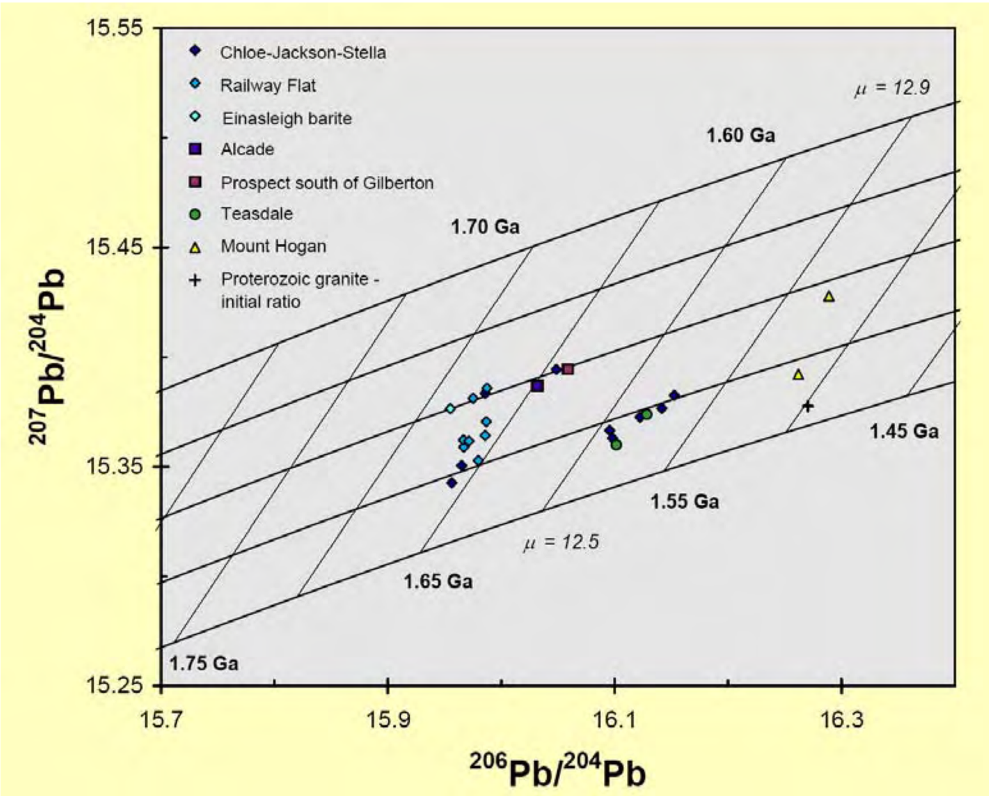

Figure 52. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram showing the isotopic composition of galena from deposits in the Etheridge Province. Data from Table 3 and Carr and Sun (1997).

The Kaiser Bill deposit comprises disseminated to semi-massive sulphide and magnetite within metasediments near the contact with granite gneiss. In detail, the sulphide minerals comprise replacements, breccia infill, veins and stringers in silica-chlorite±epidote±actinolite altered biotite gneiss, amphibolite and pegmatite (Lees and Buckle, 2009). At surface the Teasdale prospect is characterised by two bands of gossanous quartz-magnetite gneiss (Denaro et al., 1997).

Like the nearby zinc-lead-silver deposits, geochronological data for copper-silver-gold deposits in the Einasleigh Metamorphics are complex and in some ways conflicting. Four sets of geochronological data have bearing on the age of these deposits: (1) lead isotope data from galena, (2) electron microprobe uranium-lead data for monazite, (3) rhenium-osmium isotope data from molybdenite, and (4) laser ablation ICP-MS analyses of zircon (Carr and Sun, 1997; Evins et al., 2007; Evins et al., 2007). The lead isotope data can be divided into three groups (Figure 52): (1) a single analysis from a barite-rich body from Einasleigh that yielded a CSIRO-AGSO model age of ~1686 Ma, (2) two analyses from the Teasdale prospect with model ages of around 1585-1580 Ma, and (3) radiogenic analyses from Cu-rich zones from the Einasleigh and Kaiser Bill deposits (not shown in Figure 52). As lead is only a minor to trace metal in the Cu-rich zones at Einasleigh and Kaiser Bill, it is likely that the lead isotope data for these deposits has been reset. However, the similarity of the two analyses from the Teasdale prospect and the presence of lead as an integral part of the Teasdale geochemical assemblage (Denaro et al., 1997) suggests that the 1600-1590 Ma model age may be realistic, particularly as it is partly supported by electron microprobe monazite data (see below). The ~1686 Ma model age for the barite-rich lens at Einasleigh may suggest that it represents early syngenetic mineralisation, possibly similar in character to the Broken Hill-type deposits at Railway Flat and Chloe.

Electron microprobe uranium-lead analyses of monazite by Evins et al. (2007) yielded an age range 1400 to 1682 Ma, with a major peak at ~1590 Ma. This major peak, which came from samples outside of the alteration zone, is interpreted as the age of the last major period of metamorphism, whereas a subsidiary peak, which was derived from samples related to ore-related alteration and brecciation, yielded ages of 1430 Ma to 1400 Ma. This age was supported by a molybdenite rhenium-osmium age of ~1394 Ma, leading Evins et al. (2007) to suggest an age of ~1400 Ma for mineralisation (Evins et al., 2007). However, this age does not correspond to known thermal-tectonic events in the Etheridge Province. Alternatively, the ~1590 Ma age that characterises the main monazite peak may date mineralisation as it is similar to the lead isotope model age at the Teasdale prospect. Evins et al. (2007) used laser ablation ICP-MS analysis of zircon to date a microgranite dyke that cuts garnet-pyroxene skarn at ~1564 Ma, suggesting that calc-silicate alteration predated this age, which is consistent with a ~1590 Ma timing for mineralisation. The young molybdenite age could either be a consequence of the physical decoupling of Re and ^{187}Os in molybdenite, which for inhomogeneous samples can produce erroneous ages (Selby et al., 2004), or partial resetting of the molybdenite during the Silurian overprint described above.

Most geological and geochronological data suggest that the copper-silver-gold deposits are epigenetic and were deposited at either ~1590 Ma or ~1400 Ma. In addition, all deposits are characterised by the presence of magnetite, leading to the conclusion that these deposits are iron-oxide copper-gold deposits, a conclusion shared by Lees and Buckle (2009). Iron-oxide copper-gold deposits are commonly spatially associated with Broken Hill-type deposits, as observed in the Cloncurry district in the Mount Isa Province (Ernest Henry and Cannington) and in the Broken Hill Province in New South Wales (Portia and Broken Hill), and regional albitic alteration, a characteristic of iron-oxide copper-gold districts is also present in the Einasleigh Metamorphics (I Withnall, pers. comm., 2005).

3.1.2.4. Epigenetic gold deposits of unknown age – Croydon goldfield

The Croydon goldfield, in the western part of the exposed Etheridge Province, historically has been a significant producer of gold bullion, with total production of just under 60 t through 1991, with most (52.0 t) production between 1886 and 1958. A small resource of 2.9 t of gold remained in 1997 (Denaro et al., 1997). The gold was hosted by lodes in both the Esmeralda Granite and Croydon Volcanic Group. Lodes in the Esmeralda Granite produced about 80% of the 1886-1952 bullion, with a fineness of 536, whereas the Croydon Volcanic Group produced the remainder at a fineness of 737. The modern (1981-1990) production of 7.6 t gold bullion had a fineness of 373 (Edwards, 1953; Denaro et al., 1997). These figures indicate a total gold production of about 33 t, with ~27 t of silver.). Production for each deposit was small, with the larger deposits including Golden Gate (16t Au) and True Blue (3 t Au).

The auriferous lodes comprise multiple quartz veins that strike north to northwest, with the dominant direction more to the northwest. The veins dip mostly gently to moderately (15-40) to the northeast, although some veins dip more steeply, particularly north-striking veins hosted by the Croydon

Volcanic Group (Denaro et al., 1997; Warnick, 1985). Denaro et al. (1997) report three lode types: (1) quartz stockwork breccias (most common), (2) euhedral buck quartz veins, and (3) sheeted quartz veins. The lodes are commonly associated with sericitic and silicic alteration assemblages, with minor chloritic assemblages. The width of the lodes varies up to 9 m, and individual lodes can be traced for over 5 km. The greatest enrichment of gold occurs where the veins cut graphite-rich portions of the granite (Denaro et al., 1997).

Mineralogically the quartz veins are sulphide-poor, with pyrite and arsenopyrite being the main opaque minerals, with accessory to trace galena (which commonly indicates high gold grades), sphalerite, chalcopyrite, electrum and native silver (Denaro et al., 1997). Elevated chromium and nickel have been documented within the auriferous quartz (Wynn and Edser, 1989; cited in Denaro et al., 1997). Potassium-argon dating of sericite from altered granite yielded ages between 353 and 293 Ma, although Henderson (1989) interpreted these results to be a Permo-Carboniferous overprint superimposed on an original Proterozoic ore system. Denaro et al. (1997) also interpreted the Croydon goldfield as most likely having a Proterozoic age.

3.1.2.5. Granite-hosted uranium and gold deposits of uncertain age

The eastern part of the exposed Etheridge Province contains a number of shear-related mineral deposits hosted by Proterozoic granites, the most important being the Mount Hogan and Oasis deposits. In addition to similar geological settings, these deposits are also uranium-rich. Whereas the Oasis deposit is a uranium-only deposit, the Mount Hogan gold deposit contains significant uranium grades. Of these deposits, the Mount Hogan is best described. This deposit comprises thin (2-600 mm), en echelon quartz veins within sericite-chlorite altered biotite granite of the ~1558 Ma (N Kositcin, unpublished data) Mount Hogan Granite (Denaro et al., 1997). These altered zones, which are 6-30 m wide, dip shallowly (mostly 15-20 toward the metamorphic country rock). The orebody at Mount Hogan consists of a series of sinusoidal quartz-sulphide veins in flat dipping shears. Accessory to minor minerals in these veins include pyrite, arsenopyrite, galena, tetrahedrite and electrum. Unlike other vein gold deposits in the Etheridge Province, the Mount Hogan deposit also contains accessory molybdenite, (purple) fluorite, pitchblende, phosphuranylite and uraninite, along with torbernite and metatorbernite in oxidised zones (O'Rourke and Bennell, 1977; Denaro et al., 1997). O'Rourke and Bennell (1977) indicate that the uranium is intimately associated with quartz veining and sericitic alteration of the granite, which was accompanied by the introduction of gold, base metal sulphide minerals and pyrite. The age of these deposits is problematic. Rubidium-strontium and potassium-argon dating of the alteration assemblage at Mount Hogan yielded an age of ~400 Ma (Bain et al., 1984), though Denaro et al. (1997) preferred a late Paleozoic age, similar to the Maureen deposit (see below). However, these Paleozoic ages are both inconsistent with lead isotope analyses of galena presented by Carr and Sun (1997). These results, shown in Figure 9, indicate CSIRO-AGSO model ages of 1530-1515 Ma, with a similar composition to the estimated initial ratios of Proterozoic granites in the Etheridge Province. These results are consistent with a Proterozoic age of mineralisation and possible derivation from Proterozoic granites and are difficult to reconcile with a Paleozoic age of mineralisation.

The Oasis deposit is located several kilometres to the west of the Lynd Mylonite Zone, which marks the eastern exposed margin of the Etheridge Province. The following description is based on the Mega Uranium website (www.megauranium.com), discussion with Mega Uranium geologists, and observations from a site visit in August 2007 and analytical results on samples collected from that visit. The deposit is hosted by the north-trending, steeply dipping shear zone that cuts the ~1558 Ma (N Kositcin, unpublished data) Mywyn Granite. This granite consists of a foliated, feldspar porphyritic biotite granite. The mineralised zone is a steeply dipping, tabular zone up to 15 m thick (mostly < 10 m) that has been traced 300 m along strike and up to 175 m in depth. Typical grades for this zone are between 0.12 and 0.17% U_3O_8. The uranium is hosted by quartz-biotite schist, with the main uranium mineral being uraninite that occurs within biotite. At surface, a strong, north-trending fabric is present that dips 60-70° to the west; shear sense indicators indicate reverse motion with west side up. This shear zone is flanked on both sides by a zone of albite and biotite alteration of the granite. Other than a maximum age defined by the age of the host granite, the age of the Oasis deposit is unconstrained, although ^{40}Ar-^{39}Ar analyses of biotite are being undertaken and will be reported separately.

3.1.3. Mineral potential of Proterozoic North Queensland

Based on the above discussion and recent acquisition of seismic data between Mount Isa and Georgetown, the evolution of the northeastern margin of the North Australia can be divided into five Proterozoic metallogenic periods:

1. Convergence between Mount Isa, Numil and Abingdon Provinces (> 1860 Ma);
2. Wonga extension and magmatism (~1740 Ma);
3. Extension and deposition of the Etheridge and Kowanyama Provinces (1700-1670 Ma);
4. Deposition of the Isa Superbasin (1660-1590 Ma); and
5. Isan orogenic system (1590-1500 Ma).

In addition to these periods, recognition of the Millungera Basin (Korsch et al., 2009c) indicates the potential for additional mineralising periods associated with the deposition and deformation of this basin, which is constrained to between the Paleoproterozoic and Cenozoic.

3.1.3.1. Convergence between Mount Isa, Numil and Abingdon Provinces (> 1860 Ma)

Seismic data suggest the presence of two major crustal boundaries between the Mount Isa Province in the west and the Georgetown-Croydon region in the east (Figure 49). Although other interpretations of the data are possible (e.g., strike-slip fault: G. Gibson, pers. comm., 2009), Korsch et al. (2009c) interpreted these boundaries to be convergent boundaries dividing three separate crustal blocks: the Isa Province and the Numil and Abingdon Seismic Provinces (Figure 49). However, the timing of these boundaries is not well constrained, with a minimum age of ~1710 for both boundaries provided by the oldest known age of the overlying Etheridge-Kowanyama Province (Withnall et al., 2009b). Moreover, the relative timing between the Isa-Numil suture and the Numil-Abingdon subduction zone is unknown.

Isa-Numil Suture. Recognition of a west-dipping suture between the Mount Isa Province and the Numil Seismic Province implies the presence of a convergent margin along the eastern margin of the Mount Isa Province prior to the accretion of the Numil Seismic Province. Based on the presence of tonalite-trondhjemite-granodiorite (TTG) suite granites (McDonald et al., 1997), older parts of the Kalkadoon-Leichhardt Belt, to the west of the suture, could be the magmatic arc that developed along this west-verging convergent margin, with a potential backarc basin further to the west. This geodynamic setting implies potential for magmatic-related or high sulphidation VHMS Cu-Au-Mo systems in the Kalkadoon-Leichhardt Belt (Figure 53), and Zn-Pb-rich VHMS and magmatic Sn-W systems further to the west (not shown). Given the moderate to high grade metamorphism that characterises this belt, VHMS and magmatic Sn-W mineral systems are more likely to be preserved.

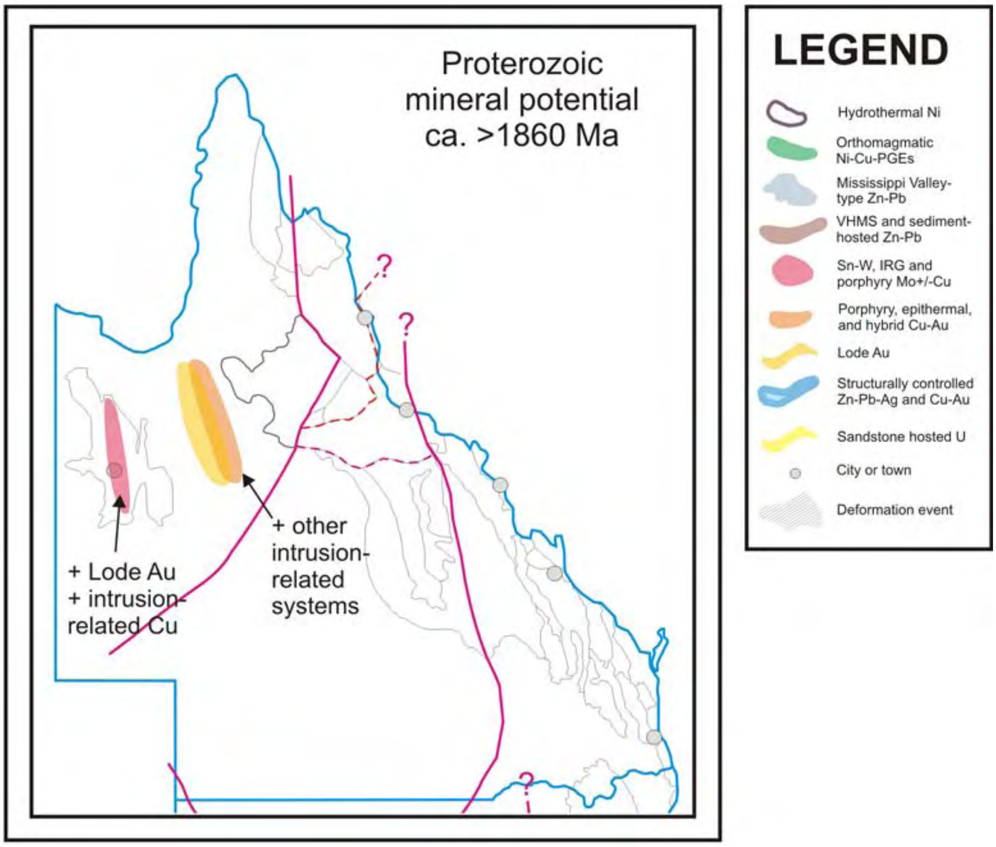

Figure 53. Mineral potential of North Queensland for the period >1860 Ma.

The Numil-Abingdon subduction zone. The possible convergence between the Numil and Abingdon Seismic Provinces, which resulted in a fossil subduction zone being preserved (Korsch et al., 2009c), also likely involved the development of a magmatic arc and possible development of a backarc basin. A potential location of this arc is the broad culmination of the Numil Seismic Province on line 07GA-IG1 (Figure 49). In Figure 53, the orientation of the Numil-Abingdon subduction zone is assumed to be broadly northwest (Henson et al., 2009), although this is poorly constrained. At its closest point, the upper boundary of the Numil Seismic Province is interpreted to be within 1 s TWT (~3 km) of the surface. Hence, although of academic interest, these targets have minimal exploration significance, unless the upper boundary of the Numil Seismic Province is closer to the surface elsewhere in North Queensland. Potentially of more significance are a series of crustal-penetrating shear zones interpreted to reach subcrop below the Carpentaria Basin in the vicinity of the Numil culmination. These are discussed in section 3.1.3.5.

3.1.3.2. Wonga extension and magmatism (~1740 Ma)

Holcombe et al. (1991) identified an extensional event closely associated with the ~1740 Ma Wonga magmatic event that affected older rocks in the Isa Province, including the Mary Kathleen belt. Skarn-related uranium deposits at Mary Kathleen and possibly lode gold mineralisation at Tick Hill appear to be associated with this event, which may have been an early manifestation of extension that produced the Calvert Superbasin. We consider that the older parts of the Mount Isa Province, including basement and the Leichhardt Superbasin, but particularly the Kalkadoon-Leichhardt and Mary Kathleen belts prospective for these deposit types (Figure 54).

3.1.3.3. Extension and deposition of the Etheridge and Kowanyama Provinces (1700-1670 Ma)

As suggested by Gibson et al. (2008), the Soldiers Cap Group and at least parts of the Etheridge Group formed in a deepening basin associated with broadly east-west extension. We interpret that the Etheridge-Kowanyama Province (Figure 49) formed as a result of this extension. In addition to the deposition of turbidites, this extension was also associated with the emplacement of tholeiitic sills, and possibly, volcanics (Beardsmore et al., 1988; Withnall et al., 2009b). An extensional environment with active tholeiitic magmatism is a characteristic of the depositional environment of Broken Hill-type deposits (Huston et al., 2006). Broken Hill-type deposits are known to have formed in the Etheridge-Kowanyama Province, both in the Eastern Succession (e.g., Soldiers Cap Group) of the Mount Isa Province and in the exposed Etheridge Province (e.g., Einasleigh Metamorphics). Hence we infer that Broken Hill-type potential extends under the Eromanga Basin from both the Isa and Etheridge Provinces and into the Bernecker and Daniel Creek Formation in the Etheridge Province (Figure 55).

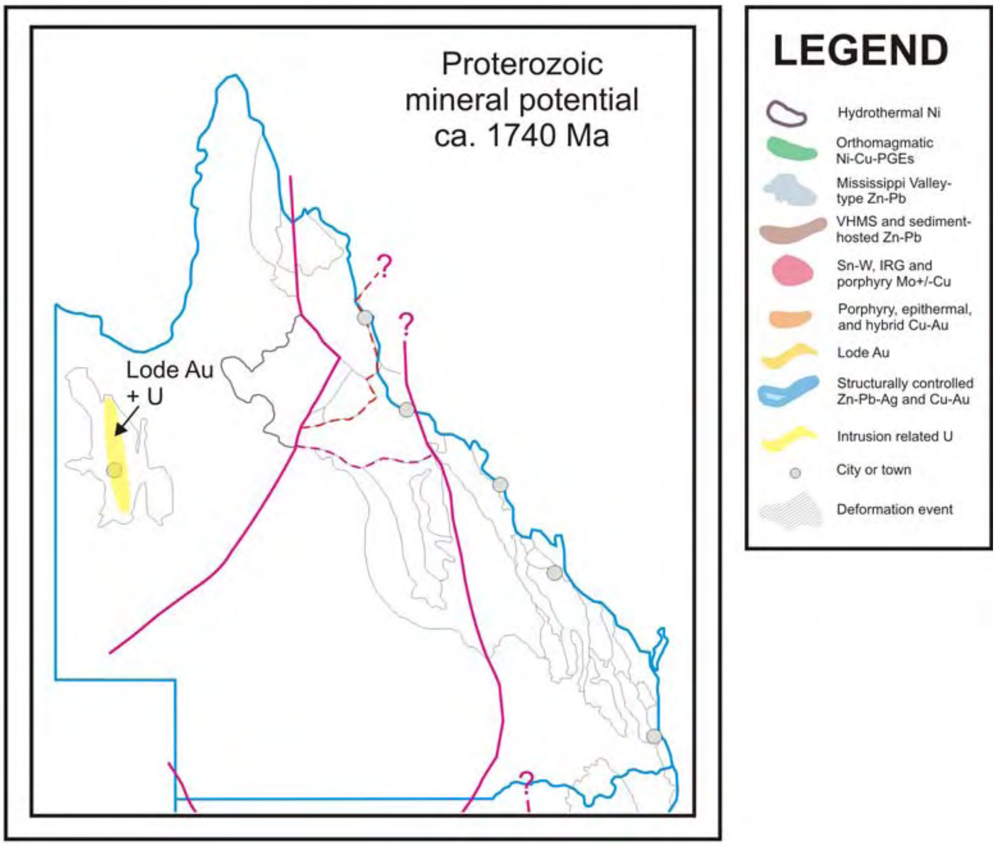

Figure 54. Mineral potential of North Queensland for the period ~1740 Ma.

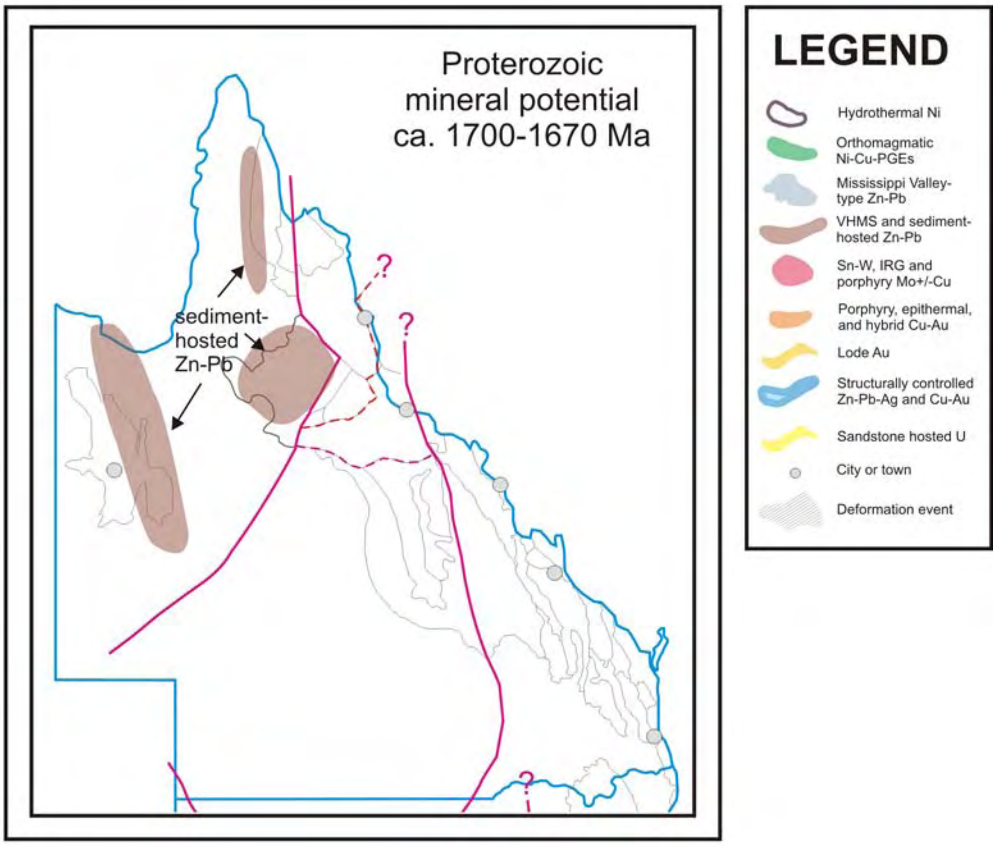

Figure 55. Mineral potential of North Queensland for the period 1700-1670 Ma.

3.1.3.4. Deposition of the Isa Superbasin (1670-1590 Ma)

Formation of the Zn-Pb-Ag deposits that make up the North Australian Zinc Belt occurred between 1660 Ma and 1575 Ma, mostly overlapping with deposition and initial deformation of the Isa Superbasin. These deposits appear to have been deposited as pulses associated with changes in plate motions associated with likely plate margin processes (e.g., collision of the Warumpi Province at 1640-1635 Ma: Scrimgeour et al., 2005) as indicated by abrupt changes in the apparent polar wander path (Idnurm, 2000). Some unconformity uranium deposits in the North Australian Craton also appear to be associated with these changes in the apparent polar wander path, suggesting the distal effects of plate margin processes may also have driven these hydrothermal systems. For instance, the timing of the Westmoreland uranium deposits appear to coincide with the age of the Mount Isa and Hilton-George Fisher Zn-Pb-Ag deposits at ~1655 Ma, and the age of the Narbalek uranium deposit appears to coincide with the age of the HYC Zn-Pb-Ag deposit at ~1640 Ma (Huston, 2009). Hence, there appears to be linkage of Mount Isa-type Zn-Pb-Ag and unconformity uranium deposit in time, although insufficient data are available to assess spatial relationships, if present.

Based on this analysis, all parts of the Isa Superbasin are considered to have potential for Mount Isa-type Zn-Pb-Ag deposits (Figure 56), particularly near (inverted) extensional faults associated with the development of the basin. In addition, unconformities juxtaposing oxidised basinal assemblages with reduced basement assemblages have potential for unconformity uranium deposits. This particularly applies to unconformities between the North Australian Basin System and underlying basement rocks such as the Murphy Inlier (Figure 56) and the Kalkadoon-Leichhardt Belt, but also applies to unconformities internal to the North Australian Basin System such as those of the Calvert and/or Isa Superbasin with reduced rocks (e.g., Eastern Creek Volcanics) of the Leichhardt Superbasin.

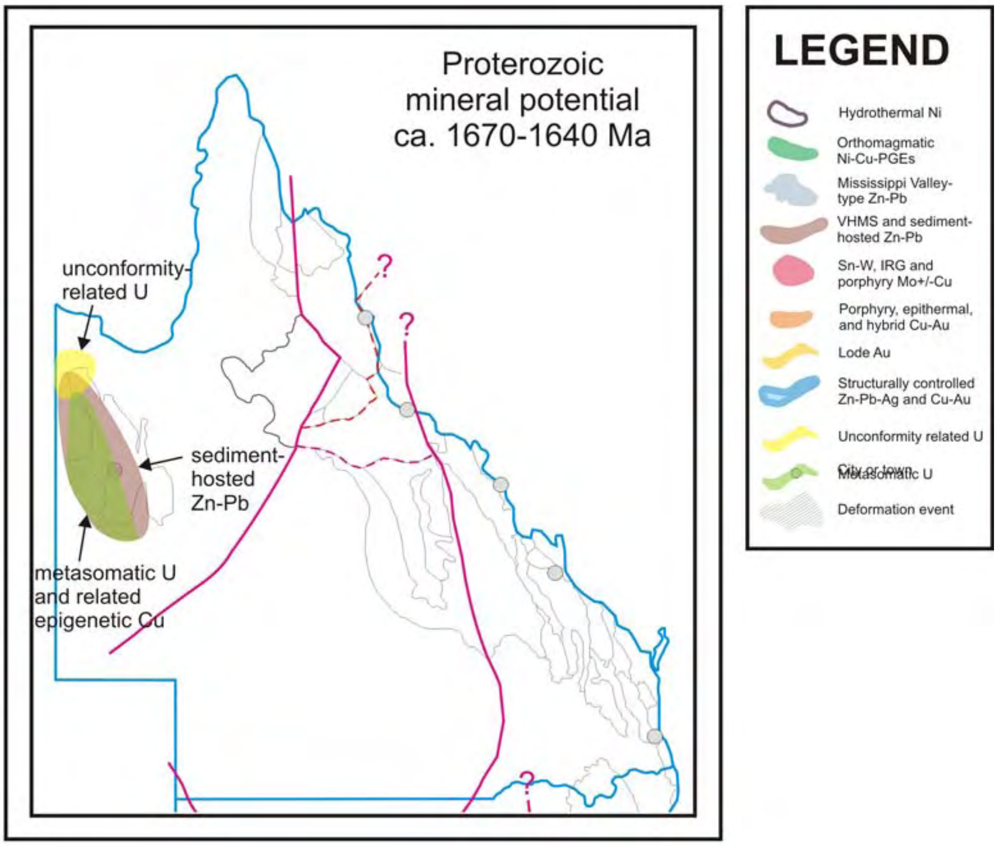

Figure 56. Mineral potential of North Queensland for the period 1670-1640 Ma.

3.1.3.5. The Isan Orogenic System (1640-1500 Ma)

Following and partly overlapping the deposition Isa Superbasin, the Isan Orogenic System is a complex system involving four separate events (1640-1620 Ma, 1600-1565 Ma, 1560-1540 Ma and 1530-1500 Ma) that may be correlatable into the Etheridge Province (e.g., Betts et al., 2006; Withnall et al., 2009b). Some of these deformation events were associated with or overlapped magmatic events including the Williams Supersuite in the Isa Province at 1550-1500 Ma and the Forsayth and 1560-1550 Ma Esmeralda Supersuites in the Etheridge Province.

D_1: 1640-1620 Ma. The 1640-1620 Ma, which may be linked to the Leibig Event in the Northern Territory, involved north-directed thrusting, possibly associated with the docking of the Warumpi Province along the southern margin of the North Australian Craton. The HYC (Northern Territory) and Lady Loretta Zn-Pb and the Narbarlek (Northern Territory) uranium deposits may have formed as a consequence of fluid flow associated with the distal effects of this deformation event

D_2: 1600-1565 Ma. As discussed above, some geochronological data suggest that the Century Zn-Pb-Ag deposit and, possibly, iron-oxide copper-gold deposits in the Etheridge Province near Einasleigh formed early during the Isan Orogenic system, probably during D_2. Hence, rocks of the upper part of

the Isa Superbasin have potential for Mount Isa-type Zn-Pb-Ag deposits, and rocks in the lower part of the Etheridge Group, including extensions below the Carpentaria Basin have potential for iron-oxide copper-gold deposits (Figure 57).

D_3: 1560-1540 Ma. A significant result of the seismic study is the recognition that structures and boundaries established early in the history of the eastern North Australian Craton control or form the locus for mineralisation that formed during later events, in particular during the Isan Orogeny. Geochronological data suggest that metasomatic uranium deposits in the western part of the Mount Isa Province formed between 1560 Ma and 1520 Ma (summarised in Neumann, 2007; Polito et al., 2009), coincident mostly with the D_2 phase of the Isan Orogeny.

Seismic data on line 06GA-M3 (Hutton et al., 2009) suggest that the western part of the Mount Isa Province, particularly the Leichhardt River Fault Trough, is characterised by an original extensional geometry that was inverted during the Isan Orogeny. Metasomatic uranium deposits in the Mount Isa uranium field (e.g., Valhalla) are spatially associated with these inverted extensional faults, which are also marked by a major change in metamorphic grade. The largest deposits in this field are localised to the east of the U-rich Sybella Granite, suggesting that juxtaposition of the reactivated faults, metamorphic gradients and location near U-rich granite source rocks was critical in forming large metasomatic uranium deposits. These characteristics extend along the western margin of the Leichhardt River Fault Trough to the south, suggesting potential for these deposits in this area (Figure 57). Moreover, epigenetic copper deposits such as those in the Mount Gordon field are also associated with these faults or their splays, suggesting linkages with the uranium mineral system and a similar distribution of mineral potential.

As described in section 3.1.2.1, epigenetic tin-bearing deposits, possibly including the recently discovered Croydon Zn-Sn-Cu veins, are spatially and probably temporally associated with Esmeralda Supersuite Granites in the Croydon area. The Mount Hogan gold deposit is unusual in comparison with other gold deposits in the Etheridge Province in that there is a close association of gold with uranium, but also in that the lead isotope signature of the ores is similar to that of Proterozoic granites. If these granites sourced the ores, then other Proterozoic granites of the Forsayth Supersuite and metasedimentary rocks they intrude have potential for epigenetic gold and uranium deposits.

Potentially of more significance in the Croydon area are a series of crustal-penetrating shear zones interpreted to reach subcrop below the Carpentaria Basin in the vicinity of the Numil culmination. Relationships between seismic reflections suggest that these faults had both normal and reverse senses of motion, with possible initiation as extensional faults with subsequent periods of inversion. Crust-penetrating shear zones are known to be associated with lode gold deposits, for example, in the Yilgarn goldfields (Goleby et al., 2004). Interpretation of the geometry of these crustal penetrating shear zones suggest a northwesterly strike, consistent with the orientation of gold-bearing veins in the Esmeralda Granite and Croydon Volcanics. If gold deposits in the Croydon goldfield are linked to these structures, whatever their age, potential for additional discoveries exists both the northwest and southeast of Croydon, including areas under cover (Figure 57).

D_4: 1530-1500 Ma. As discussed in section 3.1.1.9, the Isa-Numil suture may influence the location of IOCG(U) mineral systems that formed during the Isan Orogeny, well after the likely accretion of the Numil Province onto the North Australian Craton. After the Olympic Dam IOCG province, the eastern part of the Mount Isa Province is the most significant IOCG province in Australia, containing deposits such as Ernest Henry and Mount Dore deposits. When projected onto seismic line 07GA-IG1, the Ernest Henry deposit is located in the hangingwall of the previously-formed Isa-Numil suture, in a similar position to that inferred for the Olympic Dam deposit, which is located above a suture between inferred Archean and Proterozoic crust (Lyons and Goleby, 2005). Deposits in the eastern Mount Isa IOCG province are localised to the west of, and in the hangingwall of, this suture. These observations

suggest that the suture is a first-order control on deposit location, and indicate that IOCG(U) potential extends to the west of the suture both south of the Cloncurry district and north of Ernest Henry toward the Gulf of Carpentaria (Figure 57).

Although generally regarded as a zinc province, the Isa Province is characterised by an unusually high abundance of copper deposits and prospects, with the Mount Isa copper deposit the largest copper accumulation in Australia outside of Olympic Dam. These copper occurrences are known through most of the Isa Province, although there may be different origins. The Mount Isa copper deposit appears to have formed at ~1520 Ma during D_4, suggesting that this event is the most significant copper event. In addition to structural controls, an important control on ore localisation appears to be proximity to chlorite-altered, copper-depleted Eastern Creek volcanics, suggesting that mafic volcanics as a source, combined with a plumbing system active during D3 are important controls on these deposits.

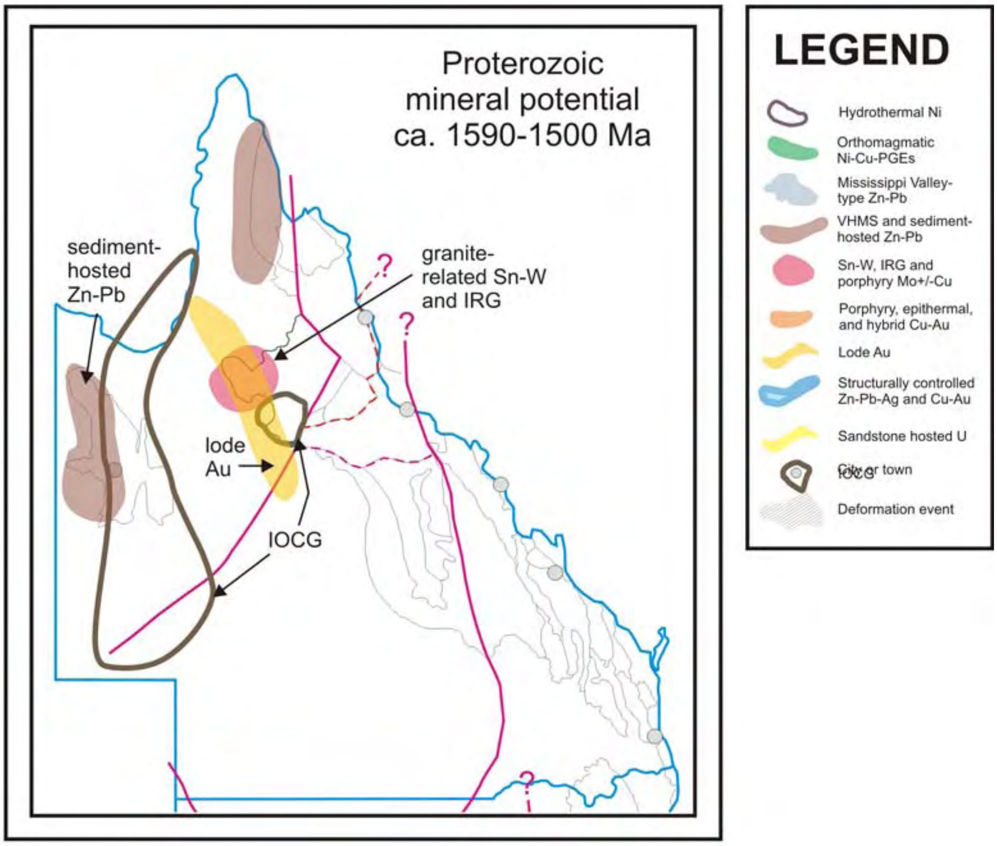

Figure 57. Mineral potential of North Queensland for the period 1590-1500 Ma.

3.1.3.6. Younger potential systems

One of the more important discoveries of the 2006 and 2007 seismic surveys was the imaging of the previously unknown Millungera Basin, which underlies the Carpentaria-Eromanga Basin and overlies the Kowanyama Seismic Province to the east of the Mount Isa Province. Seismic images on lines 07GA-IG1 (Figure 49: Korsch et al., 2009c), 06GA-M4 and 06GA-M5 (Hutton et al., 2009) provide the only evidence for this basin, possibly apart from isolated sandstone and conglomerate outcrops at Mount Fort Bowen and Mount Brown. Geological relationships suggest that the basin age lies between Mesoproterozoic and Early Mesozoic. Basin systems within this age range include Mesoproterozoic basins such as the Roper Basin, the undated Inorunie Basin, the Neoproterozoic-Paleozoic Central Australian Basin System, and Paleozoic basins such as the Devonian Adavale Basin. One likely candidate is the Central Australian Basin System, as a constituent - the Georgina Basin - is exposed to the west and south of the Mount Isa Province.

Although covered by a few hundred metres of sediment of the Eromanga-Carpentaria Basin, seismic and potential field data suggest that the Millungera Basin and the underlying rocks may have potential for geothermal energy. Zones with non-reflective seismic character below the Basin are interpreted as granite. Four such zones are recognised, with widths of up to 14 km and thicknesses of up to 0.7 s (~2 km). Inversion of magnetic and gravity data suggest that the two central non-reflective zones have moderate density and high magnetic susceptibility – interpreted as intermediate, magnetite-series granite, and the two marginal bodies have low density and are poorly magnetised – interpreted as felsic, non-magnetic granite. The latter are considered to have greater potential as heat sources for geothermal systems as they are interpreted as being more highly fractionated, i.e., higher U and Th..

The Millungera Basin may also have potential for petroleum and uranium systems, but current data are insufficient to assess this potential. Although the seismic data suggest that petroleum traps may be present, no data are available to assess the presence of source kitchens, and the current maximum depth estimates of the basin of ~3 km may not be within the oil window. As this basin has been folded (Fig. 49), it is likely, however, that significant erosion of this basin occurred prior to deposition of the Carpentaria-Eromanga Basin, and the presence of granites may have elevated the geothermal gradient. Similarly, although this basin may have potential for unconformity-related and/or sandstone-hosted U deposits, available data are inadequate to ascertain whether U-rich source rocks, possible fluid pathways or suitable traps exist.

3.2. Delamerian cycle (>600-490 Ma)

Although relatively restricted in extent, Late Neoproterozoic to Late Cambrian rocks of the Tasman Orogen host a diverse suite of mineral deposits. The earliest known mineral deposits in the Tasman Orogen are located along the western margin of the fold belt in association with Cambrian rift sequences in Western Tasmania and in the Koonenberry Belt in western New South Wales (see Huston et al., 2009). The most significant deposits in this system are Kuroko-type VHMS and related deposits hosted by the Mount Read Volcanics of western Tasmania. Other deposit types include Ni-Cu and PGE deposits associated with gabbroic and ultramafic intrusive bodies, as well as small Besshi-type VHMS deposits. Mineralisation of this age in North Queensland, however, is scarce – major deposits are either older or mostly younger.

3.2.1. Mineral potential

As documented by Huston et al. (2009), although significant potential for mineral deposits of the Delamerian cycle exists in eastern Australia, outcropping rocks of this age are very limited in extent in the North Queensland region. The most extensive exposure of these rocks are submarine metasedimentary rocks in the Charters Towers area, particularly the Charters Towers and Argentine Metamorphics, the Barnard area (Barnard Metamorphics) and the Anakie area (Anakie Metamorphics), with less extensive exposure in the Coen (Sefton Metamorphics), Greenvale (Halls Reward Metamorphics) and, possibly Georgetown (Inorunie Group) areas. With the exception of the Inorunie Group in the Georgetown area, these metasedimentary rocks are accompanied by mafic volcanism and are interpreted to have formed in continental rift basins, raising the possibility of Besshi-type volcanic-hosted massive sulphide deposits in these basins (Figure 58).

In addition, these rocks have been intruded by Delamerian cycle granites in the Anakie Inlier (S-type) suggesting potential for intrusion-related Sn and/or W deposits. Moreover, rocks older that 490 Ma that have been affected by the Delamerian Orogeny (Figure 59) may have potential for lode Au deposits. All other major orogenies, including the Benambran, Tabberabberan and Kanimblan Orogenies, in the Tasman Orogen have temporally and spatially associated lode Au events (previous report), raising the expectation for a similar association in Delamerian-age fold belts. Cobar-type structurally controlled Cu-Au and Zn-Pb deposits may be associated with Delamerian inversion of Delamerian cycle deep water basins, particularly in the Thomson Orogen.

3.3. Benambran cycle (490-430 Ma)

The period between 490 and 440 Ma is one of the most richly mineralised periods in the geologic history of the Tasman Orogen in eastern Australia, including 455-440 Ma lode Au deposits in the Victorian goldfield, and 450-440 Ma porphyry Cu-Au and related epithermal Au deposits in the Macquarie Arc of central New South Wales (See Huston et al., 2009). In the North Queensland region, the most significant mineralisation includes moderate-sized VHMS deposits in the ~480 Ma Seventy Mile Range Group, Balcooma Metavolcanic Group and Eland Metavolcanics.

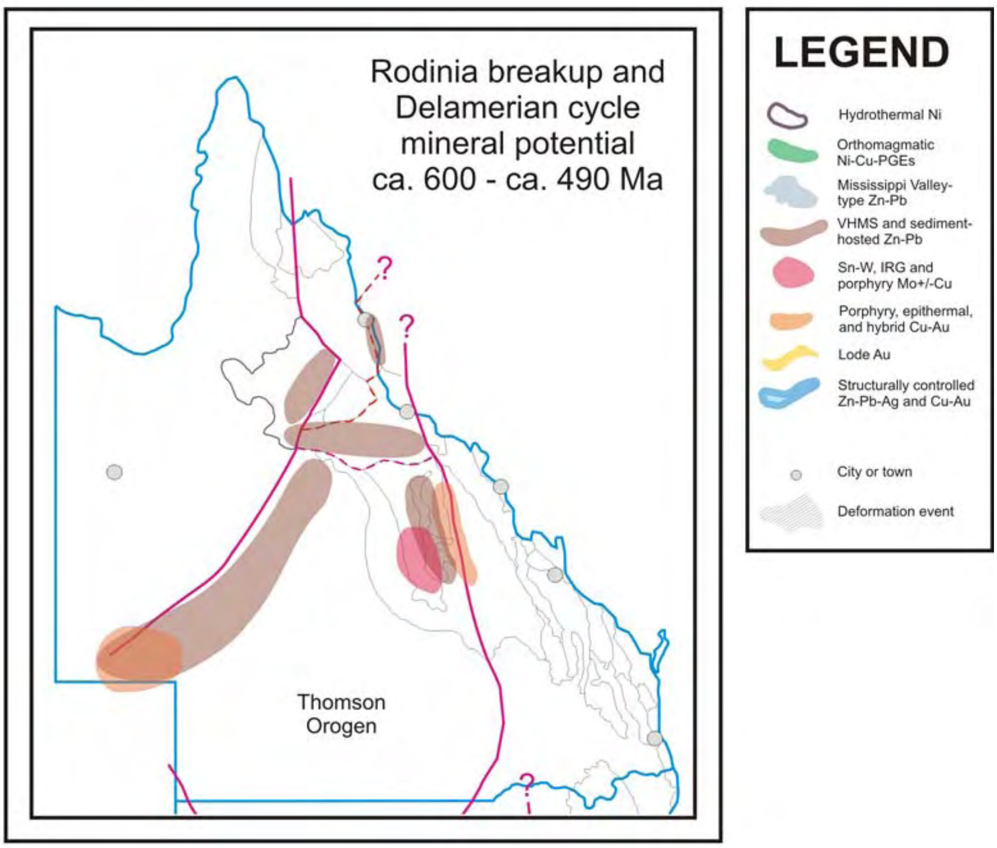

Figure 58. Mineral potential of the Delamerian cycle.

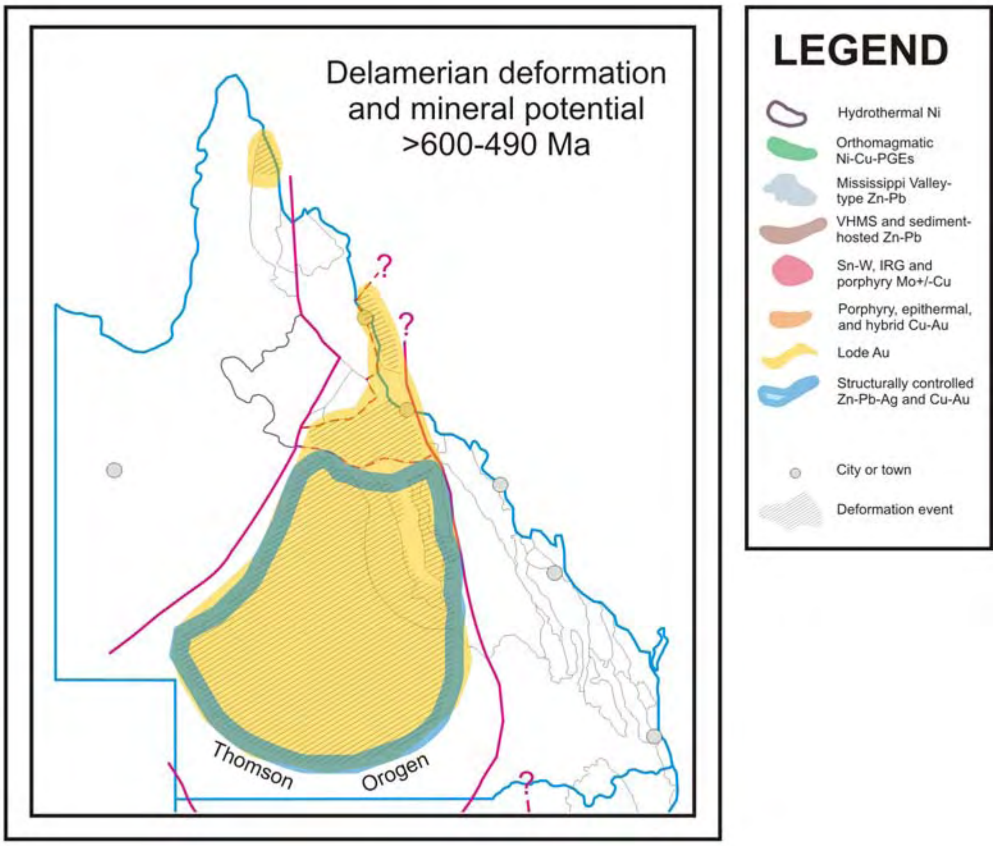

Figure 59. Mineral potential of the Delamerian Orogeny.

3.3.1. VHMS and related deposits, Seventy Mile Range Group and Balcooma Metamorphics

Early Ordovician rocks of the Seventy Mile Range Group and equivalent Balcooma Metavolcanic Group and Eland Metavolcanics form two semi-continuous belts along the northern margin of the Thomson Orogen in northern Queensland (Figure 60). The Seventy Mile Range Group consists of mostly low metamorphic grade volcanic and related sedimentary rocks that form an east-west trending belt that can be traced for over 200 km to the south of Charters Towers. The Balcooma Metavolcanic Group and Eland Metavolcanics form a north-northeast trending belt of medium metamorphic grade metavolcanic and metasedimentary rocks that can be traced discontinuously over 100 km. Although these two belts of rocks are separated at present by over 200 km, lithological similarities and limited geochronological data suggest that they were once part of a continuous belt. Importantly, both of these belts contain significant VHMS deposits, with global resources of 1.0 Mt Zn, 0.3 Mt Pb, 0.37 Mt Cu, 3.5 t Au and 0.72 kt Ag, and 0.35 Mt Zn, 0.15 Mt Pb, 0.12 Mt Cu, 3.9 t Au and 0.36 kt Ag for the Seventy Mile Range and Balcooma belts, respectively (based on compilation in Hutton and Withnall, 2007).

The Seventy Mile Range Group (Figure 60) comprises four units, the Puddler Creek Formation, the Mount Windsor Volcanics, the Trooper Creek Formation, and the Rollston Range Formation. The Puddler Creek Formation comprises continentally derived siliciclastic rocks intruded by mafic dykes. The Mount Windsor Volcanics are dominated by rhyolitic to dacitic volcanic rocks with minor andesite, whereas the overlying Trooper Creek Formation is dominated by intermediate to mafic volcanism with associated siliciclastic rocks. The uppermost Rollston Range Formation comprises volcaniclastic sandstone and siltstone (Henderson, 1986; Berry et al., 1992; Hutton and Withnall, 2007). An unpublished age of ~479 Ma for the Mount Windsor Volcanics implies a lower Ordovician age for this sequence (Hutton et al., 1997).

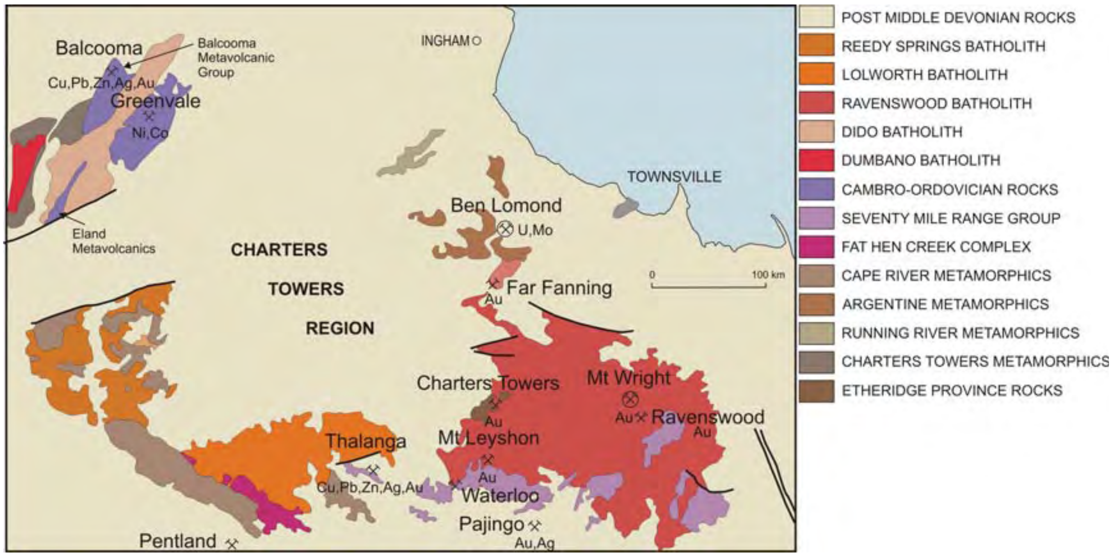

Figure 60 . Geology of the Thalanga Subprovince, North Queensland, showing locations of Ordovician (meta-) volcanic belts and VHMS deposits and prospects.

The major deposit in the Seventy Mile Range Group, Thalanga (6.35 Mt @12.3% Zn, 3.9% Pb, 2.2% Cu and 99 g/t Ag: Hutton and Withnall, 2007), is localised along the contact between the Mount Windsor Volcanics and the Trooper Creek Formation. This deposit is tabular and is associated with a quartz-sericite-pyrite±chlorite alteration envelope (Berry et al., 1992; Paulick et al., 2001). The stratigraphically highest deposit, Liontown, is hosted at the contact between the Trooper Creek Formation; the other deposits (Handcuff, Waterloo-Agincourt, Magpie and Highway-Reward) are hosted at various stratigraphic levels within the Trooper Creek Formation (Berry et al., 1992). With the exception of the Waterloo-Agincourt deposit, all VHMS deposits in the Seventy Mile Range Group are characterised by pyritic quartz-sericite and quartz-chlorite alteration assemblages (Berry et al., 1992). The small, though very high-grade Waterloo deposit (0.372 Mt @ 19.7% Zn, 2.8% Pb, 3.38% Cu, 2.0 g/t Au and 94 g/t Ag: Hutton and Withnall, 2007) is characterised by a pyritic sericite-quartz±pyrophyllite alteration assemblage (Huston et al., 1995; Monecke et al., 2006), suggesting affinities with high sulphidation VHMS and related deposits such as at Mount Lyell in western Tasmania. All VHMS deposits in the Seventy Mile Range Group contain barite.

The Balcooma Metavolcanic Group (Figure 60) comprises rhyolitic metavolcanic, metasedimentary rocks and minor metamorphosed mafic volcanic rocks that have been metamorphosed to lower to middle amphibolite grade (Hutton and Withnall, 2007). It is likely that metamorphosed felsic volcanic rocks that underlie the Balcooma and Dry River South deposits (Huston et al., 1992) correlate with the Mount Windsor Volcanics (Hutton and Withnall, 2007). Metasedimentary rocks that overlie Dry River South and host the Balcooma deposit may correlate with the basal part of the Trooper Creek Formation. Felsic to intermediate volcanic rocks and sedimentary rocks to the west (Huston et al., 1992) probably equate to the middle to upper parts of the Trooper Creek Formation. This interpretation is supported by SHRIMP U-Pb zircon analyses of a felsic volcaniclastic lens underlying the Balcooma deposit, which gave an age of ~480 Ma (M. Fanning, unpub. data, in Rae, 2001) and of unaltered quartz-feldspar porphyry sills, which intruded the Balcooma deposit and gave an age of ~472 Ma (Withnall et al., 1991).

The Balcooma Metavolcanic Group contains two moderate-sized VHMS deposits, the Balcooma and Dry River South-Surveyor deposits, which collectively contain 6.22 Mt grading 5.70% Zn, 2.48% Pb, 1.98% Cu, 0.63 g/t Au and 57 g/t Ag (Hutton and Withnall, 2007) in addition to a low grade massive pyrite body at Boyds. These deposits are localised along the transition between underlying metavolcanic rocks and overlying metasedimentary rocks near the base of the sequence. The Balcooma deposit is associated mostly with intensely chloritic alteration assemblages and lesser quartz-muscovite assemblages, whereas the Dry River South-Surveyor deposit is associated with pyritic quartz-muscovite assemblages and relatively minor chlorite-rich assemblages (Huston et al., 1992). Unlike deposits in the Seventy Mile Range Group the Balcooma and Dry River South-Surveyor deposits lack barite. However, a small baritic prospect, West Boyds Creek, is present in the younger rocks to the west.

The Eland Metavolcanics (Figure 60) include a sequence of andesitic to basaltic volcaniclastic rocks with minor marble and chert, which have been metamorphosed to upper greenschist grade and are possibly correlated with the Trooper Creek Formation (Hutton and Withnall, 2007). Although no significant prospects are known in this belt, correlation with the Trooper Creek Formation suggests significant potential for VHMS deposits exist.

Stolz (1995) interpreted the Seventy Mile Range Group to have formed in an evolving back-arc basin developed by extension of continental lithosphere. The earliest mafic dykes in the Puddler Creek Formation represent an alkaline intraplate association formed during the extension of a continental margin as subduction initiated. Emplacement of the Mount Windsor Volcanics followed as extension continued and a back-arc rift developed. Neodymium isotope data suggests that the felsic volcanic rocks of this unit formed in part by melting of Precambrian crust (Stolz, 1995). Continued extension eventually resulted in mantle melting to produce the felsic to intermediate volcanic rocks of the Trooper Creek Formation. The sedimentary rocks of the Rolston Range Formation represent reworking of volcaniclastic material form the Trooper Creek Formation (Stolz, 1995).

3.3.2. Mineral potential

Synthesis and analysis of geological and metallogenic data suggest that the Benambran cycle in North Queensland may have been characterised by two geodynamic systems:

1. an interpreted arc and associated back-arc, which may extend north from northern New South Wales along the eastern margin of the Thomson orogen, and
2. the Benambran Orogeny.

3.3.2.1. Northern extension of South Thomson arc

As summarised by Watkins (2007), drill holes in the Bourke-Louth area of New South Wales intersected intermediate to mafic volcanic rocks with calc-alkaline to shoshonitic affinities and arc-like signatures. Limited age data suggest that these rocks were deposited between ~485 and 440 Ma, and these rocks have been interpreted as an arc developed along the southern margin of the Thomson Orogen (i.e. the South Thomson arc). Additional data (Section 1.4.3. of Champion et al., 2009) suggest that volcanic rocks of this age may extend along the eastern margin of the Thomson Orogen, through the Anakie Inlier and towards the Seventy Mile Range Group and Balcooma Metamorphics. 480-460 Ma oxidised, low pressure tonalites (Netherwood, Saddington and Cockie Springs bodies; geochemistry from Withnall and Lang, 1993) to the east (i.e. outboard) of the back-arc Balcooma Metamorphics have primitive ε_{Nd} (+7 to +8: D Champion, unpublished data), which is consistent with them forming part of this inferred magmatic arc. Volcanic rocks of this age have also been intersected beneath cover in the central and western Thomson Orogen, where they are interpreted to have formed during extension and crustal thinning (Draper, 2006), raising the possibility of a back-arc basin inboard from the South Thomson arc. Available data allow the possibility that the South Thomson arc was a small part of a 485-440 Ma linked arc-backarc tectonic system that extended along the eastern margin of the Thomson Orogen from the Balcooma Metamorphics in the north to the Bourke-Louth area in the south, with the majority of the system under cover.

This admittedly speculative tectonic system has significant mineral potential in addition to the known VHMS (e.g., Thalanga and Balcooma) and hybrid Cu-Au deposits (e.g., Waterloo) in the Seventy Mile Range Group and Balcooma Metamorphics (Figure 61). In particular, the Ordovician Eland Metamorphics and Paddys Creek Phyllite, and possibly the Lugano Metamorphics, to the east of the Balcooma Metamorphics have potential for hybrid Cu-Au deposits as they are outboard of the Ordovician backarc basin and are intruded by the Cockie Springs Tonalite. This potential is enhanced by the presence of several Cu-Au(Zn) prospects in these rocks.

Potential for VHMS and hybrid Cu-Au deposits extends southwards into extension-related volcanic rocks undercover in the central Thomson Orogen (Figure 61). These rocks also have potential for epithermal systems, depending on water depth, by analogy with the Drummond Basin and possibly intrusion-related Sn-W and Au deposits. Other belts that have potential for VHMS deposits include the Broken River Province, particularly along the eastern side of the Palmerston Fault, and the Anakie Inlier (including the Fork Lagoons Beds).

In addition to VHMS potential in back-arc basins, the magmatic arc inferred along the eastern and southern margins of the Thomson Orogen also has potential for porphyry Cu-Au and epithermal deposits. The northern extent of this arc may include Ordovician intrusions in the vicinity of Charters Towers. The Anakie Inlier may also have potential for porphyry Cu deposits associated with the inferred arc. This potential extends along the eastern and southern margins into the Bourke-Louth area where arc volcanics have been intersected in drill core (Watkins, 2007).

Preliminary Nd-Sm data from mafic to ultramafic rocks the Gray Creek Complex in northern Queensland (Figure 56) yielded a three-point $^{143}Nd/^{144}Nd$-$^{147}Sm/^{144}Nd$ array with an apparent age of 466 ± 37 Ma (MSWD = 0.63: D Huston and R Maas, unpublished data). Although there are other interpretations of the geologic significance of this array (i.e. mixing array), the apparent age is consistent with geological relationships and suggests that these rocks have an age of ~470 Ma, with initial $\varepsilon Nd \sim +8$, indicating a juvenile source. These rocks have potential for orthomagmatic Ni-Cu-PGE deposits along with known supergene Ni-Co deposits (e.g., Greenvale). Moreover, the rift environment inferred for these rocks also has some potential for Cyprus- or Besshi-type VHMS deposits, and, where intruded by granites (e.g., Dido Granodiorite), these rocks have potential for hydrothermal Ni deposits.

Although significant lode Au deposits associated with Benambran deformation in Eastern Australia are restricted to the Bendigo, and Stawell Zones of the Victorian goldfields, this deformation event is widespread in northern Queensland. Although many of the lode gold deposits in the North Queensland region are slightly younger (see next section), it is feasible that Benambran age deposits do exist.

Potential for structurally-controlled Cu-Au and Zn-Pb deposit also exists where Benambran deformation has inverted pre-existing siliciclastic-dominated marine basins (Figure 62). This, for example, includes parts of the Anakie Inlier, where Withnall et al. (1995) report an undated, structurally-controlled Cu deposit at West Copperfield.

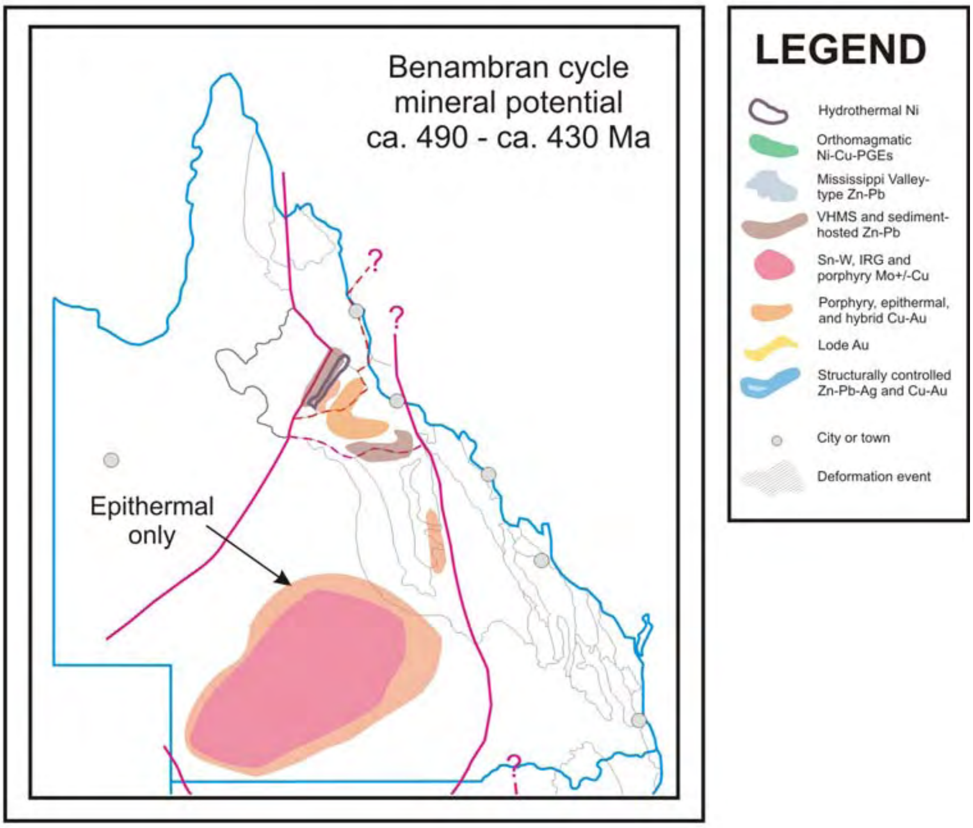

Figure 61. Mineral potential of the Benambran cycle.

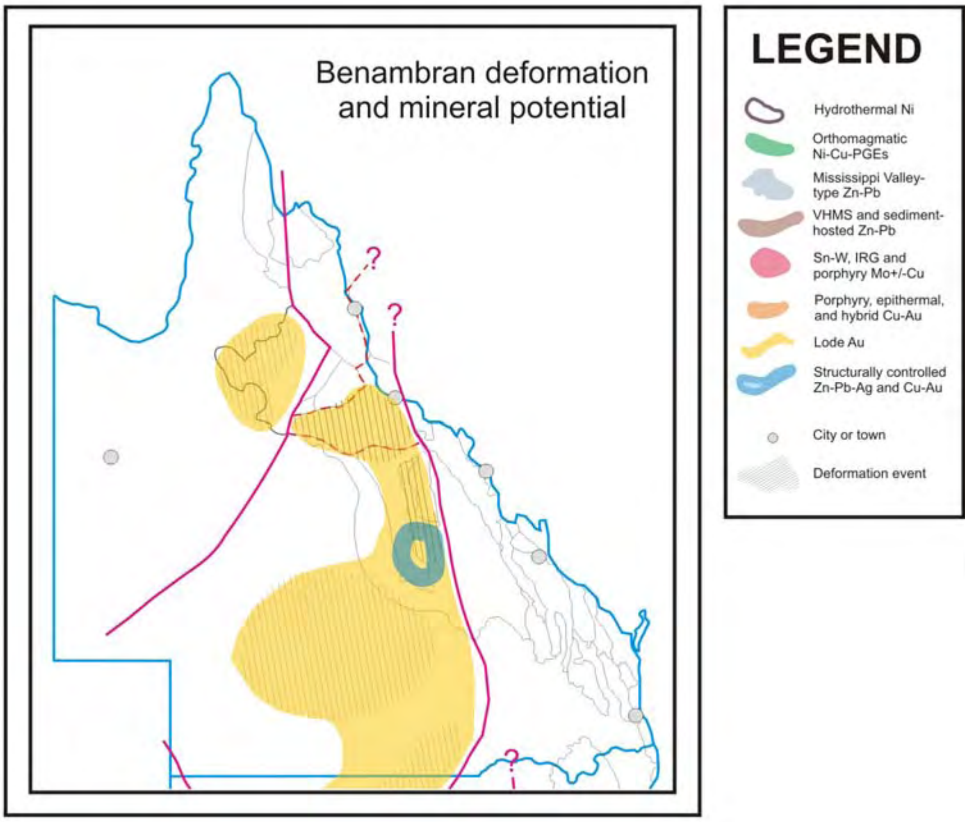

Figure 62. Mineral potential of the Benambran Orogeny.

3.4. Tabberabberan cycle (430-380 Ma)

Although not as well mineralised as in the southern Tasman Orogen, the Tabberabberan cycle encompasses some important deposits, including Middle to Late Silurian (420-410 Ma) VHMS deposits that formed in the Hodgkinson Province and lode gold deposits that formed during the 420-400 Ma Bindian Orogeny. The Bindian Orogeny was metallogenically important in northern Queensland, producing the Charters Towers goldfields as well as smaller deposits within the Georgetown region (Etheridge goldfield). Although no significant granite-related deposits are known to have been deposited during the Tabberabberan cycle, circumstantial evidence, such as the ~412 Ma molybdenite Re-Os age at the Chloe deposit (section 3.1.2.2) suggest potential for such deposits may be associated with the Pama magmatic association (see below).

3.4.1. Late Silurian VHMS and related deposits, Hodgkinson Province

The Hodgkinson Formation, which consists largely of monotonous siliciclastic arenite and mudstone (Bultitude et al., 1997), contains several small Cu-Zn deposits interpreted as Besshi-type VHMS deposits. This unit also contains minor conglomerate, chert, tholeiitic basalt and limestone. Fossils within the limestone lenses indicate a Late Silurian or Early Devonian (Lochkovian: 416-411 Ma) to Late Devonian (Famennian: 375-360 Ma) age (Bultitude et al., 1997. These rocks contain a number of small, apparently stratiform Cu-Zn deposits, the most significant of which include the Mount Molloy, Dianne and OK deposits. The largest production came from the Dianne deposit, which produced 18,000 t of Cu (Garrad, in Bain and Draper, 1997); the OK deposit produced 7934 t Cu (and 97 kg Ag and 12.8 kg Au) from just over 88,000 t of ore (http://www.axiom-mining.com, accessed 11 August 2008); no production is recorded from the Mount Molloy deposit.

The Mount Molloy deposit is hosted by carbonaceous and pyritic shale, whereas the Dianne deposit is hosted by an interbedded shale-greywacke package. In contrast, the OK deposit is hosted by mafic volcanic rocks. At the Mount Molloy and OK deposits, massive sulphide zones are underlain by stockwork zones. The Dianne deposit also comprises massive sulphide, but lacks the stockwork zone. The main ore minerals in all three deposits are pyrite, chalcopyrite and sphalerite, with minor tetrahedrite-tennantite also present at the OK deposit (Garrad, in Bain and Draper, 1997).

3.4.2. Lode gold deposits, Charters Towers goldfield

Although the 420-400 Ma Au event in the Victorian goldfields was a relatively minor event, a significant Au event of similar age occurred in North Queensland. The Charters Towers goldfield and nearby deposits produced over 6 Moz (180 t) Au between 1872 and 1918 in addition to major quantities of Ag, Pb and Cu (Kreuzer, 2005). These deposits, which are mostly hosted by phases of the Mount Ravenswood batholith, comprise auriferous massive (buck), comb-textured and brecciated quartz veins that average 10% sulphide minerals. The sulphide minerals include pyrite, sphalerite and galena, with local arsenopyrite, chalcopyrite and tetrahedrite-tennantite and minor gold and gold tellurides. The veins are associated with narrow (to 0.1 m) alteration selvages characterised by a sericite-calcite-ankerite-pyrite assemblage (Peters and Golding, 1989).

$^{40}Ar/^{39}Ar$ data of Kreuzer (2005) from the Charters Towers and nearby Hadleigh Castle goldfields indicated ages of ~407 Ma for both goldfields (total range: 400-412 Ma), consistent with previous K-Ar and $^{40}Ar/^{39}Ar$ data of Morrison (1988) and Perkins and Kennedy (1998). As noted by Kreuzer (2005), these ages overlap those of some regional granites (e.g., Deane, Carse-O-Gowrie, Chippendale and Broughton River granodiorites), although not the host Millchester Creek tonalite. This relationship, combined with Nd and Pb isotope data and granite compositional data, led Kreuzer (2005) to conclude that the Charters Towers deposits were lode (orogenic) Au rather than intrusion-related Au deposits.

Although small in comparison (20 t total production), vein Au deposits of the Etheridge goldfield (Bain et al., 1998) in the Etheridge Province to the northwest share many similarities with the Charters Towers goldfield. Unlike the Charters Towers deposits, the Etheridge deposits are largely hosted by Mesoproterozoic granite (most of the larger deposits), Mesoproterozoic metasedimentary and metabasic rocks, with only minor Siluro-Devonian granite hosts. The majority of deposits appear to lie within a north-south belt in the central-eastern part of the Georgetown area, within rocks of amphibolite-grade metamorphism and appear to have a spatial association, at least, with Silurian granites of the Pama Association (e.g., Bain et al., 1988). Like the Charters Towers deposits, the Georgetown deposits consist of sulphide-rich (pyrite, sphalerite, galena and chalcopyrite) quartz veins up to 5m-wide and have Pb isotope model ages of 426-398 Ma. Smaller goldfields in the Coen region, which are hosted by ~407 Ma granites, also have similarities to the Charters Towers goldfields (Bain et al., 1998). This suggests that the ~410 Ma lode gold event was relatively widespread through North Queensland.

As discussed in section 3.1.2.4, lode gold mineralisation occurs within the Croydon area, hosted by both the Croydon Volcanic Group and the granites of the Esmeralda Supersuite (Warnick, 1985; Denaro et al., 1997). The timing of mineralisation is uncertain and may be either Proterozoic or late Palaeozoic. K-Ar dating (on sericite) gives ages between 353 and 293 Ma (Henderson, 1989) but it is uncertain whether these reflect resetting or primary mineralisation ages. Both Henderson (1989) and Denaro et al. (1997) suggested the mineralisation was Mesoproterozoic.

3.4.3. Mineral potential

Synthesis and analysis of geological and metallogenic data suggest that the Tabberabberan cycle in North Queensland was characterised by:

1. North Queensland arc-backarc system;
2. Bindian Orogeny; and
3. Tabberabberan Orogeny.

3.4.3.1. North Queensland arc-backarc system

In North Queensland, the dominant tectonic system involved deposition of turbidite with lesser tholeiitic basalt and limestone between the Early Silurian and Early Carboniferous in the Hodgkinson Province. This deposition is linked in time with the emplacement of both I- and S-type granites, some of which have arc-like affinities, in the Pama Association that extends around the Hodgkinson and Broken River provinces from Charters Towers in the south to Cape York in the north. These rocks were affected by a thermotectonic event, which temporally corresponds with the Bindian Orogeny, at 410-400 Ma (see section 3.4.3.2), which coincided with a hiatus in sedimentation in the Graveyard Creek Subprovince and a change in sedimentation style in the Hodgkinson Province. Sedimentation in North Queensland appears to have continued through the Tabberabberan Orogeny.

Two broad tectonic models have been proposed for this tectonic system, both of which infer west-dipping subduction. In the first model (e.g., Henderson, 1987), the Hodgkinson and Broken River Provinces are interpreted as fore-arc basins with the Pama Association as the arc. Alternatively, the

Hodgkinson Province is interpreted as a backarc (Arnold and Fawkner, 1980). Determining confidently the likely tectonic model has important implications for mineralisation. If the Hodgkinson Province is forearc, the Pama Association is likely the associated magmatic arc and the backarc would be located further inland. In such a situation, the granites of the Pama Association might be associated with porphyry and epithermal mineral systems, although subsequent erosion may have removed such deposits (Figure 63). In addition, there would be potential for backarc-related mineral (e.g., VHMS) systems further inboard to the west. If the Hodgkinson Province is a backarc, however, the Pama Association may have potential for intrusion-related Sn, W and Mo deposits. This inference is supported by the ~412 Ma molybdenite age at Chloe discussed in section 3.1.2.2. Unfortunately, the Pama Association is not associated with significant mineralisation, although the presence of VHMS deposits in the Hodgkinson Province is more consistent with a backarc setting for this province.

3.4.3.2. Bindian Orogeny

The Bindian Orogeny is the major event in northern Queensland, producing the Charters Towers goldfield (~407 Ma) and smaller goldfields in the Etheridge Province. In northern Queensland, gold deposition overlaps in time with Pama Association granites, although Kruezer (2005) inferred that deposits in the, Charters Towers Goldfield were orogenic, and not intrusion-related, in origin. Based on this distribution we consider that rocks affected by the Bindian Orogeny all have potential for lode Au deposits (Figure 64), although these rocks in the Thomson Orogen have the highest potential, particularly in the vicinity of Charters Towers. Inversion of basins formed during the Bindian cycle during the Bindian Orogeny also may produce Cobar-type Cu- Au and/or Zn-Pb-Ag deposits (Figure 64).

3.4.3.3 Tabberabberan Orogeny

We consider that extensional basins of the Bindian-Tabberabberan Cycle and basins of uncertain origin, such as the Hodgkinson in North Queensland have potential for epigenetic base metal deposits in the vicinity of structures related to Tabberabberan inversion (Figure 64).

3.4.3.4. Other mineral systems

In addition to the potential described above, we also consider that the Bindian-Tabberabberan Cycle has potential for Irish-style or Mississippi Valley-type Zn-Pb deposits associated with carbonate rocks in the Hodgkinson and Broken River Provinces of North Queensland (Figure 63).

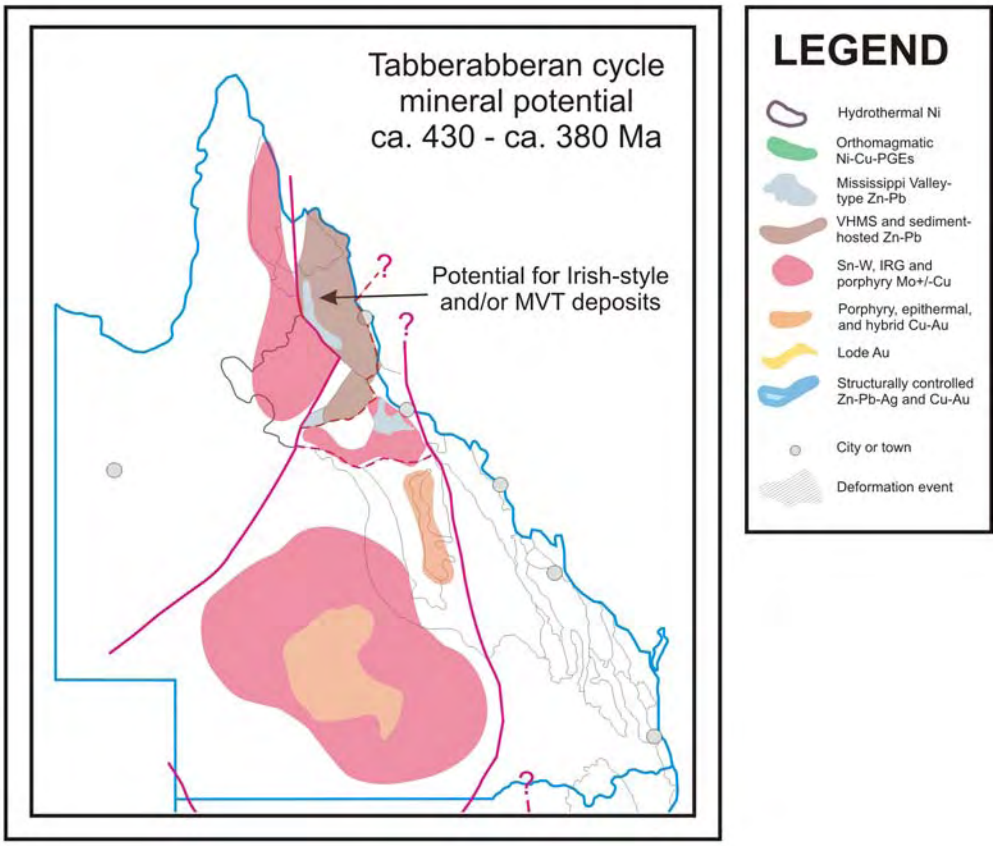

Figure 63. Mineral potential of the Tabberabberan cycle.

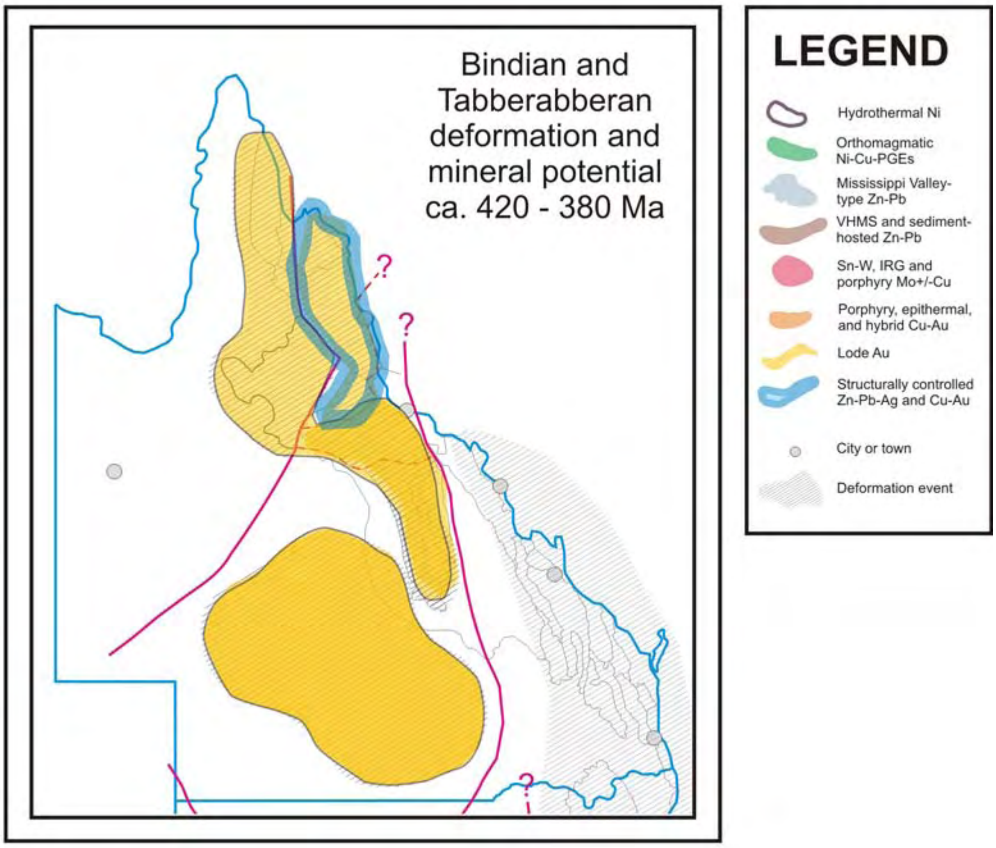

Figure 64. Mineral potential of the Bindian-Tabberabberan orogenies.

3.5. Kanimblan cycle (380-350 Ma)

The Kanimblan Cycle was marked by I-, S- and A-type magmatism associated with extension and rifting possibly related to a volcanic arc and subduction zone well off to the east. Although some lode gold deposits in the Victorian Goldfields and granite-related Sn-W and hydrothermal Ni deposits in Tasmania formed during this cycle (Champion et al., 2009), no significant deposits of this age are known in North Queensland. However, as geodynamic systems of this age extended into North Queensland, potential for Kanimblan-aged mineralisation is present

3.5.1. Mineral potential

Synthesis and analysis of geological and metallogenic data suggest that the Kanimblan cycle was characterised by two major geodynamic systems (Champion et al., 2009):

1. Connors-Auburn arc-backarc system (Figure 65); and
2. Kanimblan Orogeny (Figure 66).

Based on existing metallogenic data and the tectonic evolution model presented in section 2.5, predictions are made below about the existence and likely extent of mineral systems for both of these tectonic systems in North Queensland.

3.5.1.1. Connors-Auburn arc-backarc system

Figure 65 shows the mineral potential for the Connors-Auburn arc and related backarc and forearc systems based on the interpretation that the Kanimblan cycle was dominated by west dipping subduction offshore that extended along the eastern margin of Australia at that time (Champion et al., 2009). In this model, the arc is represented by I-type granites that extend inland from the Queensland coast from northwest of Brisbane to just south of Townsville. Basins that are located outboard of the magmatic arc, are interpreted as forearc basins, and blocks further outboard are interpreted as accretionary wedges. None of these tectonic units extend into North Queensland. Inboard of the magmatic arc, a backarc environment is interpreted for the early history of Drummond Basin to the north and sedimentary rocks of the Kanimblan cycle in the Lachlan Orogen (Champion et al., 2009).

3.5.1.2. Kanimblan Orogeny

The 360-340 Ma Kanimblan Orogeny is extensively developed through the Tasman Orogen as low-grade metamorphism and east-west shortening. Although this orogen affects older rocks to the east, in central and North Queensland, the Kanimblan Orogeny does not have a major effect on the Connors-Auburn arc-backarc system, with magmatism and sedimentation largely unaffected by this orogeny. The most significant effect of this orogeny in the Connors-Auburn system was termination of sedimentation in the Drummond Basin (Champion et al., 2009). Although Champion et al. (2009) considered this orogeny to have some potential through the Tasman Orogen for lode gold deposits, the highest potential was considered to be in the East Lachlan of New South Wales. In addition to lode gold potential, the Kanimblan Orogeny may also have potential for structurally controlled Zn-Pb-Ag and Cu-Au deposits, analogous to those in the Cobar district, within the Hodgkinson Province (Figure 66).

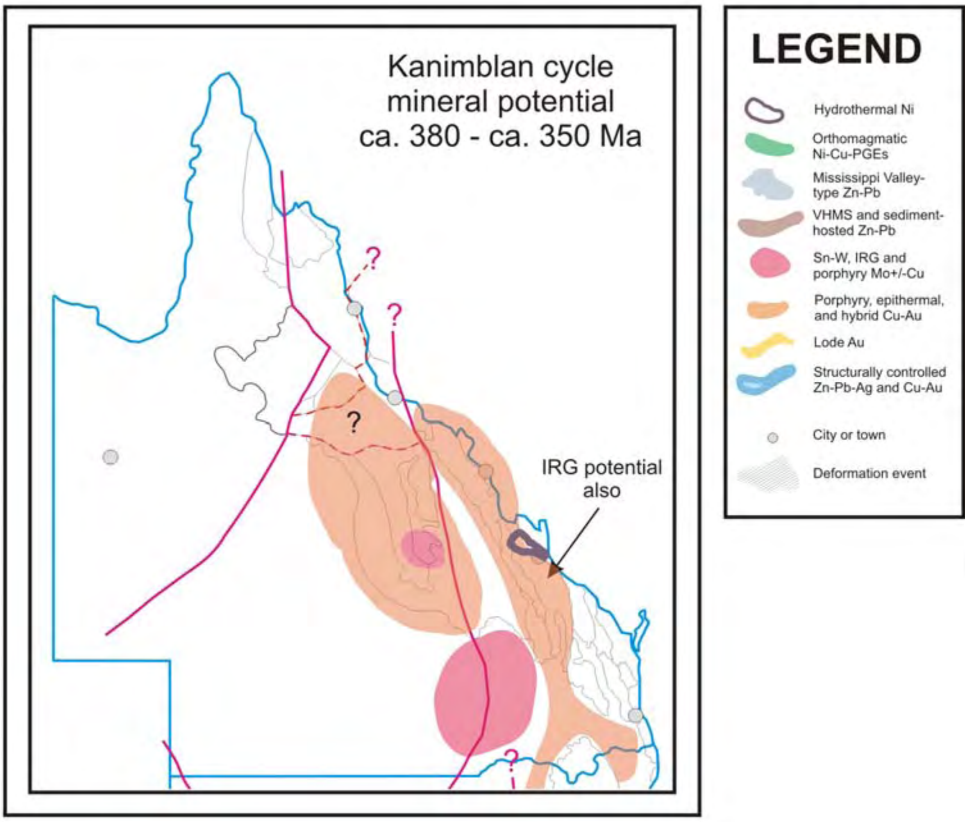

Figure 65. Mineral potential of the Kanimblan cycle.

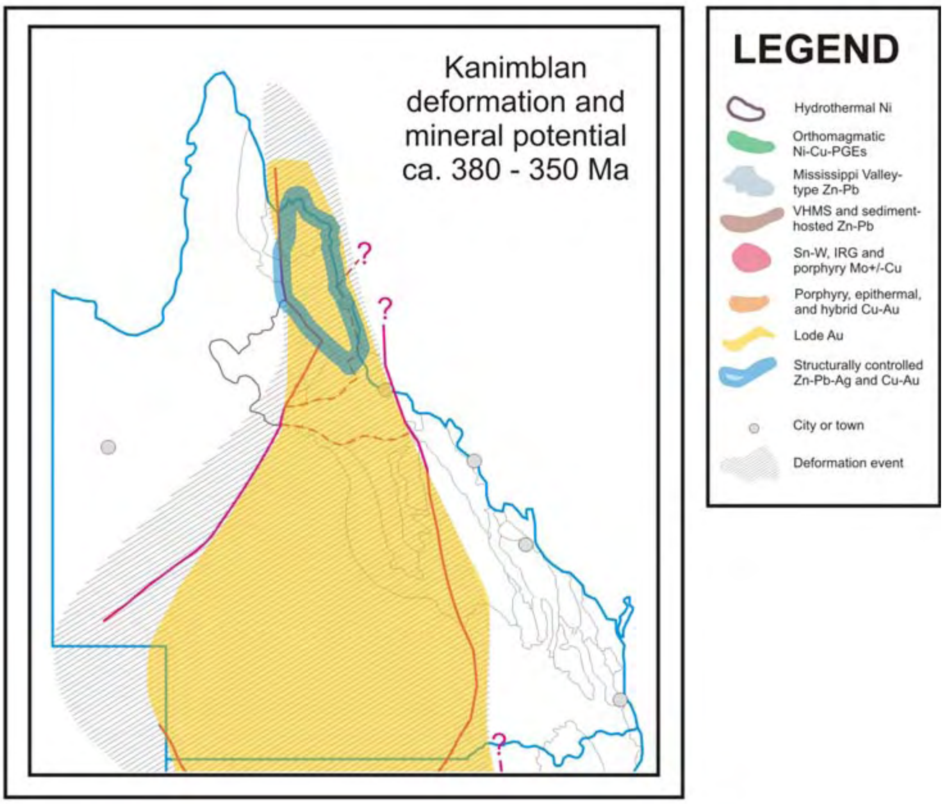

Figure 66. Mineral potential of the Kanimblan Orogeny.

3.6. Hunter-Bowen cycle (350 Ma-230 Ma)

Although relatively weakly mineralised in comparison with other cycles, the Hunter-Bowen cycle contains a very diverse assemblage of mineral deposits (Figure 67), many of which are granite-associated. Spatially, and to a certain degree temporally, most deposits of the Hunter-Bowen Cycle can be split into two groups: (1) deposits in northern Queensland associated with Permo-Carboniferous (345-280 Ma) magmatism, and (2) deposits located mostly in the New England Orogen, with ages mostly between 290 and 230 Ma. Deposits in the New England Orogen are described separately in Champion et al. (2009), and the North Queensland deposits are described below.

3.6.1. Permo-Carboniferous (345-280 Ma) intrusion-related deposits of North Queensland

Widespread mineralisation occurs associated with Kennedy Association felsic (mostly intrusive) magmatism in northern Queensland (e.g., Gregory et al., 1980; Murray, 1990; Morrison and Beams, 1995). The magmatism-related mineralisation encompasses a variety of styles, including Sn-W, intrusion-related gold (± Mo, Bi, W), porphyry Cu-Au and Cu-Mo ± base metals, as well as epithermal Au ± Ag, and perhaps U-F-Mo mineralisation. Although much of the mineralisation is of small size, significant deposits exist for most styles. Much research over the last 25 years has focussed on both the magmatism (e.g., Sheraton and Labonne, 1978; Richards, 1980; Champion and Chappell, 1992; Champion and Heinemann, 1994) and the related mineralisation (e.g., Morrison and Beams, 1995; Pollard and Taylor, 1983; Pollard et al., 1983; Witt, 1987, 1988; Blake, 1972). What is evident from the region is that deposit styles although varied, largely relate to the same tectonic and magmatic events, with mineralisation styles and commodity types more related to magmatic controls such as granite composition, redox state, and degree of fractionation, as elegantly pointed out by Blevin and co-workers (e.g., Blevin and Chappell, 1992, 1996; Blevin, 2004, 2005; Champion and Blevin, 2005), and also by Sillitoe (1991), Thompson et al. (1999), Lang et al. (2000) and Lang and Baker (2001). In addition to magmatic-related deposits there are also lode gold deposits such as the Hodgkinson goldfield.

3.6.1.1. Sn±W and W±Sn deposits

Extensive and widespread Sn-W mineralisation occurs throughout North Queensland. Most production (and current reserves) has been from four main regions: the Herberton-Mount Garnet-Georgetown region (Herberton Province of Solomon and Groves (2000), e.g., Mount Garnet; Herberton-Irvinebank, Sunnymount/Tommy Burns, Koorboora; the Cairns-Cooktown region (Collingwood Province of Solomon and Groves, 2000), e.g., Collingwood, Kings Plain; the Mount Carbine-Cannibal Creek region (Mount Carbine province of Solomon and Groves, 2000), e.g., Mount Carbine; and the Kangaroo Hills region (Province of Solomon and Groves, 1999), e.g., Sardine. Production figures for these regions are >150 000t Sn (~200000t of tin concentrate; Morrison and Beams, 1995) and 4000t W (Solomon and Groves, 2000). The vast majority of this has been derived from Herberton Province (140 000t of tin concentrate; Murray, 1990) and in particular the Herberton-Mount Garnet area, i.e., the eastern half of the Herberton Province, with recorded production (up to 1969) of ~110 000t of tin concentrate (Blake, 1972). Although extensive, total tin production from the region is relatively minor when compared with the larger Devonian tin deposits of Tasmania (e.g., see Solomon and Groves, 2000). Most of the W production in the region has come from the Mount Carbine deposit (Mount Carbine Province), though a number of relatively small W-Mo-Bi pipes, e.g., Bamford Hill, Wolfram Camp, have also been mined.

Much of the tin mined in North Queensland (as cassiterite) has been derived from alluvial and eluvial deposits, including deep leads, over the last 100+ years, within all regions (Withnall et al., 1997a, Bultitude et al., 1997). Significant production from lode deposits only occurred in the Herberton Province.

3.6.1.1.1. Herberton. Blake (1972), Taylor (1979), Pollard and Taylor (1983), Kwak and Askins (1981), Brown et al. (1984), amongst others, have documented a variety of Sn-W mineralisation styles in the Herberton Province, including:

- chlorite lodes – the most abundant type, occurring within granite or in host rocks. Assemblages include chlorite-quartz-cassiterite-sericite-sulphides± fluorite-topaz-garnet-tourmaline;
- greisen – either massive with disseminated cassiterite or as greisen lodes, with quartz-mica-cassiterite-fluorite ± wolframite-monazite-topaz-kaolinite-chlorite-sulphides;
- quartz-tourmaline lodes – mostly within host metasedimentary rocks;
- complex sulphide lodes – in both granite and host rocks; quartz-cassiterite-pyrite-chalcopyrite ± stannite-chlorite-fluorite-epidote-calcite-carbonate;
- fluorite-magnetite-garnet 'wrigglite' (F-Sn-W) skarns ± cassiterite – scheelite, e.g., the Gillian Prospect near Mount Garnet. Much of the tin appears to be within silicate phases such as garnet (Kwak and Askins, 1981; Brown et al., 1984);
- quartz lodes – minor;
- disseminated cassiterite or wolframite deposits in granites and pegmatites – minor.

As is typical of Sn-W systems, most of the mineralisation is either hosted within granite or close to the granite contact within the local host rocks, such as the metasediments (and locally carbonates) of the Hodgkinson Province. Blake (1972) showed that the tin deposits of the Herberton region exhibited well-defined district zoning, from an innermost W zone (within the granite), to Sn (granite and host rocks), to Cu, and an outer Pb zone (both within the host rocks). As stated above significant production came from the Herberton tin fields, and unlike other tin producing regions in North Queensland, much of this production was from lode deposits, although much of this was prior to 1930 (see Pollard and Taylor, 1983). Up to 1972 ~70 kt of a total ~110 kt tin produced was from lode deposits, mostly from numerous small deposits; the Vulcan Mine being the largest producer with ~14 kt (Blake, 1972). Sizeable reserves (greisen, stockwork and skarns) still exist within the region in a number of prospects, e.g., Sailor, Baalgammon, Gillian (Morrison and Beams, 1995; Garrad et al., 2000). The Sn±W mineralisation in the region is clearly related to granites (e.g., Pollard and Taylor, 1986; Witt, 1988), in particular to the granites of the various suites of the O'Briens Creek Supersuite (Champion and Chappell, 1992; Champion and Blevin, 2005). It is also clear that there is a strong host rock control. Granites of the O'Briens Creek Supersuite are widely distributed (e.g., Champion and Heinemann, 1994); Sn-W mineralisation, however, is strongly localised east of the Palmerville Fault, i.e., where the granites intrude the metasediments of the Hodgkinson Province.

3.6.1.1.2. Kangaroo Hills. Total production from this region was ~7500t of tin (mostly cassiterite, minor stannite) concentrates (Murray, 1990), from alluvial and lode deposits, with the most significant lode deposit being the Sardine Mine (Wyatt et al., 1970). Lode deposits, mostly veins and pipes, include chlorite (dominant), tourmaline and sulphide-rich lodes, greisens, pegmatitic segregations, and skarns (e.g., Wyatt et al., 1970; Gregory et al., 1980; Rienks et al., 2000), within the granites and local sedimentary country rocks. These comprise cassiterite ± base metals but also include stannite (Wyatt et al., 1970). Mineralisation appears to be mostly related to granites of the Oweenee Supersuite, but possibly also to the poorly outcropping S-type Dora Supersuite (Champion and Heinemann, 1994).

3.6.1.1.3. Cooktown. The Cooktown tin province, has historically been a minor producer – about 14 kt of tin concentrate – largely alluvial (Murray, 1990). Significant reserves, however, exist, including Collingwood (currently in production – 28 kt Sn) and Jeanie River (54 kt Sn) – both lode deposits and Kings Plain (alluvial - ~6 kt tin concentrate); e.g., Morrison and Beams, (1995), Garrad et al. (2000). Mineralisation at Jeannie River, described by Lord and Fabray (1990), is hosted within the metasediments of the Hodgkinson Formation, and is dominated by complex sulphide lodes, i.e., cassiterite-sulphides (including pyrite-pyrrhotite-sphalerite-galena-chalcopyrite-arsenopyrite). Zoning is evident, from an outer Pb-Zn±Sn zone to an inner pyrrhotite-rich, Cu-As-W±Sn stockwork vein swarm zone (Lord and Fabray, 1990). Alteration includes silicic, sericitic and propylitic assemblages (Lord and Fabray, 1990). Although thought to be intrusion-related, the granites responsible for the mineralisation have not been unequivocally identified. Lord and Fabray (1990) favoured porphyry dykes that occur near some of the prospects.

Mineralisation at Collingwood, south of Cooktown, has been described by Jones et al. (1990). The deposit occurs within an area of Hodgkinson Formation metasediments intruded by S-type granites of the Cooktown Supersuite. Mineralisation is largely hosted within various flat-lying phases of the Finlayson Batholith. Jones et al. (1990) document three mineralisation styles:

- steep siliceous sheeted greisen veins, and associated siliceous (quartz-muscovite-biotite-tourmaline) alteration haloes, which host most of the ore;
- albitic veins (albite - cassiterite - chlorite - fluorite± biotite – muscovite - sulphides assemblages) with siliceous alteration haloes. These veins have high tin grades and cross-cut the sheeted veins, and
- sub-horizontal mineralisation and silica, tourmaline and sericite alteration, along the granite-sediment contact, associated with topographic highs in the granite.

Tin mineralisation increases in grade towards the granite contact but is minor outside of the granites (Jones et al., 1990). Mineralisation in the Cooktown tinfield is related to the Permian S-type granites of the Cooktown Supersuite (Bultitude and Champion, 1992; Champion and Blevin, 2005).

3.6.1.1.4. Mount Carbine Province. This province is characterised by Sn-W and W-Sn mineralisation, with a number of significant W deposits, of which the Mount Carbine tungsten deposit is the most important. The province is largely delineated by the distribution of the S-type Whypalla Supersuite (Bultitude and Champion, 1992; Champion and Bultitude, 1994) to which mineralisation is spatially and probably genetically related (e.g., Higgins et al., 1987). Total production includes alluvial and lode Sn-W and W mineralisation, mostly from veins and alluvial deposits but also skarns (Solomon and Groves, 2000). The province differs from the others in the presence of significant W mineralisation, e.g., Mount Carbine, Watershed. It has been delineated as a W corridor.

Mount Carbine, northwest of Cairns, is a wolframite deposit hosted by the Silurian to Devonian metasediments of the Hodgkinson Formation. As described by Forsythe and Higgins (1990), mineralisation occurs as multiple vein zones comprising early, steep-dipping, quartz - apatite ± wolframite ± K- feldspar ± biotite ± muscovite ± molybdenite ± bismuth veins with strong tourmaline-biotite alteration selvages and later (partly overprinting) fluorite-chlorite-tourmaline-albite-scheelite-cassiterite-sulphide-calcite vein and fracture-fill assemblages (Forsythe and Higgins, 1990). About 16.4 kt of wolframite concentrate was produced from the deposit (Murray, 1990). Mineralisation is thought to be largely genetically related to intrusives, most probably the nearby Permian S-type Whypalla Supersuite granites in the Mossman Batholith (Bultitude and Champion, 1992), consistent with ages of ca. 280 Ma for the local granite and greisen alteration (see summary in Forsythe and Higgins, 1990).

The Watershed tungsten prospect, northwest of Mount Carbine, contains scheelite mineralisation hosted by the Silurian to Devonian metasediments of the Hodgkinson Formation. Scheelite is present as disseminations within altered metasediments including calc-silicates, and within quartz-feldspar veins (Pertzel, 2007). The deposit has been interpreted as a quartz-vein swarm (Pertzel, 2007). Current resource estimates are ~44.1 kt contained WO_3 (http://www.vitalmetals.com.au /projects/watershed.phtml [accessed December, 2008]), although mineralisation is apparently open along strike and at depth.

Tin-tungsten mineralisation in all regions is clearly related to the associated granites, i.e., granites of the O'Briens Creek Supersuite in the Herberton-Mount Garnet-Georgetown region; the Kangaroo Hills region – granites of the Oweenee and Dora Supersuites largely (Rienks et al., 2000), the Cooktown region (including Collingwood) – granites of the Cooktown Supersuite, and the Mount Carbine region (including Mount Carbine) – granites of the Whypalla Supersuite (Blake, 1972, Richards, 1980; Champion and Bultitude, 1994; Champion and Heinemann, 1994). As shown by Champion and Blevin (2005) there is a clear strong relationship in North Queensland between Sn mineralisation and strongly fractionated, reduced I- and S-type granites. Records for alluvial production are not comprehensive (e.g., Withnall et al., 1997a) but include >>3900 tonnes (cassiterite concentrate) west of the Palmerville Fault and 2260 t in the Cannibal Creek area.

Other tungsten deposits occur in the region, most notably W-Mo-Bi mineralisation, which occur as pipe-like bodies and associated greisens within granites in the Herberton region, e.g., Bamford Hill and

Wolfram Camp, and in the Kangaroo Hills region (Rienks et al., 2000). Deposits were mostly small, e.g., Wolfram Camp and Bamford Hill together, produced ~9.3 kt wolframite concentrates and <2 kt molybdenum concentrates (Murray, 1990). In the Herberton region the W-Mo-Bi mineralisation is associated with granites of the Ootann Supersuite (e.g., Blevin, 2004). One feature of these deposits is the large sizes of many of the ore minerals within the pipes.

3.6.1.2. Porphyry Cu-Mo-Au and intrusion-related gold deposits

A variety of styles of Carboniferous to Permian intrusion-related gold mineralisation exist in North Queensland. Morrison and Beams (1995) included these all together under a broad 'Porphyry' category, but subdivided them into breccia, stockwork, vein and skarn subtypes. Recent work on intrusion-related gold deposits, chiefly in north America, has led to the recognition of an intrusion-related gold (IRG) mineral system with a wide variety of deposits styles and types (e.g., Thompson et al., 1999; Lang et al., 2000; Lang and Baker, 2001), that include all the sub-types listed by Morrison and Beams (1995). Additional work in Australia (e.g., Blevin, 2004, 2005) and by the original proponents of the IRG model, have resulted in identification of two end-members for intrusion-related gold deposits, i.e., porphyry Au, Cu-Au deposits associated with primitive oxidised magmas largely in primitive tectonic settings (e.g., Macquarie Arc deposits in NSW), and the IRG end-member with more evolved, more reduced magmas, largely in continental settings. In a North Queensland context the majority of intrusion-related gold deposits belong to the IRG end-member (e.g., Blevin, 2005). The only change to the Morrison and Beams (1995) grouping is the inclusion of Mount Leyshon as a porphyry Cu-Mo deposit style, i.e., an end-member of the porphyry Cu-Au porphyry-style (P.Blevin, cited in Champion, 2007). This subdivision is followed here. It should be noted, however, that many IRG deposits in Australia have associated early high temperature molybdenum (Mo-W-Bi) mineralisation with, typically, more distal gold (Blevin, 2005, written commun., 2008).

3.6.1.2.1. Intrusion-related gold (IRG) – Kidston, Red Dome and Mungana. Significant IRG mineralisation occurs with North Queensland associated with the Carboniferous-Permian granites of the Kennedy Association, and most of the more significant gold producers in the region fall into this category, e.g., Kidston, Red Dome, Ravenswood. As with other granite-related mineralisation in the area, specific granite supersuites appear more conducive to this style of mineralisation, in particular the Ootann and closely related Glenmore Supersuites (Champion and Heinemann, 1994; Withnall et al., 1997a), largely reflecting the intensive parameters of the granites in these supersuites (e.g., Blevin et al., 1996). Recorded ages of mineralisation (e.g., Perkins and Kennedy, 1998) range from 330 Ma (Kidston) to ca. 280 Ma (Ravenswood/Mount Wright), consistent with the ages of associated magmatism and Kennedy Association magmatism in general. The mineralisation ages also young to the east and north-east as does the magmatism (see section 1).

The *Kidston* gold deposits, south of Georgetown, is a breccia pipe deposit thought to be related to Carboniferous magmatism (see Baker and Tullemans, 1990; Baker and Andrew, 1991; Morrison et al., 1996; Bobis et al., 1998). The breccia pipe occurs within the Mesoproterozoic Einasleigh Metamorphics but close to various intrusives phases of the Silurian Oak River Batholith (Withnall and Grimes, 1995), and clasts of these units occur within the breccia. The breccia pipe is of significant size – up to a kilometre-wide at surface, and continuing at depth up to 1.4 km (Bobis et al., 1998) as shown by drilling. Studies by Morrison and others (e.g., Morrison et al., 1996; Bobis et al., 1998) have shown that the breccia pipe is zoned from carbonate-pyrite-±pyrrhotite at the top, through a number of zones (including gold-basemetals), to quartz-fluorite-molybdenite-Bi phases-pyrrhotite±base metals±scheelite±wolframite at depth. The deposit becomes more porphyry-Mo like at depth (Bobis et al., 1998). Gold apparently overprints (postdates) molybdenum mineralisation, but both are suggested to be intrusion-related (e.g., Morrison et al., 1996; Bobis et al., 1998). As indicated by Baker and Tullemans (1990), both the brecciation and mineralisation are temporally and spatially associated with the intrusives. Perkins and Kennedy (1998) suggest ca. 332 Ma ages for mineralisation and post-ore dykes at Kidston confirming this relationship. Mineralisation, therefore, is thought to be related to the Carboniferous intrusive phases which occur within the breccia and outcrop nearby (e.g., Withnall and Grimes, 1995; Baker and Tullemans, 1990). The Carboniferous intrusives range from mafic to felsic, and appear to form a largely co-magmatic fractionated suite (Blevin, 2005) – originally placed in the

Ootann Supersuite by Champion and Heinemann (1994) and Blevin (2005), but reassigned by Withnall et al (1997a) to the Glenmore Supersuite.

The *Red Dome* gold deposit, northwest of Chillagoe, is a skarn deposit related to intrusion of Carboniferous rhyolite dykes, at high crustal levels (e.g., Ewers et al., 1990, Nethery and Barr, 1998) into steeply-dipping limestone and other sediments of the Chillagoe Formation, Hodgkinson Province (Bultitude et al., 1997). The deposit falls at the eastern end of a west-northwest trending belt of deposits – the Mungana Group (Nethery and Barr, 1998). Within the deposit two separate episodes of rhyolite intrusion and associated magnetite-bearing skarn development have been documented (Ewers et al., 1990), as well as an intermediate phase of wollastonite-bearing skarn and retrogressive alteration after each skarn phase (Ewers and Sun, 1988; Ewers et al., 1990). Nethery and Barr (1998) also indicate a late epithermal phase perhaps related to A-type intrusions. The deposit also comprises an upper post-mineralisation breccia zone, thought to be a collapse breccia (Ewers et al., 1990). Recorded sulphide minerals include bornite-chalcocite (with wollastonite) and chalcopyrite-arsenopyrite-pyrite-sphalerite elsewhere (Ewers et al., 1990). Gold appears to be largely associated with the wollastonite-bearing skarn and first phase of post-skarn-retrogression (Ewers et al., 1990; Nethery and Barr, 1998), as well as in quartz-arsenopyrite-molybdenite +/- gold stockwork mineralisation spatially associated with the intrusives. The second rhyolite phase appears not to have introduced additional gold but only remobilised existing mineralisation (Ewers et al., 1990) though Nethery and Barr (1998) appear to indicate gold introduction (and base metals) with the second retrogressive phase also. Fluid inclusion data indicate temperatures to 380°C and the presence of high salinity fluids (Ewers and Sun, 1989). According to Kagara Zinc (2008 figures) the Red Dome mine produced over 30 t Au and 70000 t Cu, and has a current resource of ~8.5 Mt at 1.61g/t Au, 0.4% Cu and 13 g/t Ag (http://www.kagara.com.au [accessed December 2008]). Kagara Zinc also report the presence of molybdenum mineralisation at depth. Nethery and Barr (1998), largely on the basis of the widespread nature of intrusive-related alteration in the region suggested that the porphyries at Red Dome, and in the Mungana group deposits and environs in general, were related to a larger pluton(s) at depth. These authors indicate similar mineralisation to Red Dome also occurred within other deposits in the region, such as Mungana. As pointed out by Nethery and Barr (1998), however, the latter also appears to contain earlier Besshi-style VMS mineralisation, which has been overprinted by the later Carboniferous-Permian intrusive activity, skarn development and subsequent retrogression. Like Red Dome, quartz-arsenopyrite-molybdenite±gold mineralisation occurs spatially associated with intrusives, as well as younger epithermal overprinting and acid leaching (Nethery and Barr, 1998). The combined current inferred Au and Ag resources at Red Dome and Mungana are 43 t Au, 426 t Ag and 79 kt Cu (http://www.kagara.com.au). Available geochronology (Perkins and Kennedy, 1998; Georgees, 2007) suggests intrusives are ca. 320 Ma in age, though chemical and field considerations suggest a range of intrusive ages from ca. 317 Ma to 307 Ma, and perhaps younger, to ca. 290 Ma (see Nethery and Barr, 1998). Alteration at Mungana and Red Dome, lies around ca. 310 Ma (Perkins and Kennedy, 1998). Georgees (2007) reports a Re-Os molybdenum age of ca. 207 Ma for Mungana.

The *Ravenswood area*, south of Townsville, has had a long history of gold mining, with some 28 t Au produced from the area prior to 1968 (Collett et al., 1998), from alluvial and lode deposits. Lode gold production was mainly from quartz-sulphide (pyrite-sphalerite-chalcopyrite-arsenopyrite-pyrrhotite) veins, often with high grade gold (up to 30-100 g/t), with minor but intense sericite, calcite and chlorite alteration selvages (McIntosh et al., 1995). Collett et al. (1998) suggested these veins record multiple events with up to eight alteration events and brecciation recognised. Locally the veins form stockworks such as at the Nolans Deposit (McIntosh et al., 1995; Collett et al., 1998). Additional gold has been derived from older, low-grade, chlorite-silica shear zone hosted, locally brecciated, quartz (buck) reefs with pyrite-sphalerite-pyrrhotite-chalcopyrite-gold and a wide biotite/chlorite alteration halo (McIntosh et al., 1995; Collett et al., 1998). All mineralisation is hosted within older Devonian mafic and felsic intrusives of the Ravenswood Batholith. Renewed production since 1987 (11.2 t Au produced for the period 1987-1996; Collett et al., 1998) has been from extensions of old deposits and a number of new deposits such as Nolans (5.1 t Au). Significant reserves (17.85 t Au) and resources (inferred 33.6 t Au) exist in the Nolans and Sarfield deposits (Collett et al., 1998).

The *Mount Wright* deposit, ~10km from Ravenswood, comprises a brecciated Carboniferous-Permian rhyolitic intrusive, which occurs as a pipe-like deposit within older intrusives of the Ravenswood

Batholith. Both the rhyolite and host granites have been brecciated (Harvey, 1998). Both brecciation and gold mineralisation, which has a significant vertical extent (up to a kilometre at depth; A-Izzeddin et al., 1995) appears to be closely associated and related to the rhyolitic intrusives (Harvey, 1998). Mineralisation occurs dominantly as quartz-carbonate (siderite) -sericite-sulphide (arsenopyrite-pyrrhotite-sphalerite-chalcopyrite-molybdenite) -gold breccia infill and minor veins (A-Izzeddin et al., 1995; Harvey, 1998). Alteration assemblages, which extend into the older granite wall rocks, include sericite, silica, chlorite and carbonate (siderite). Historic production, centred on the mother lode, total some 0.5 t Au (Harvey et al., 1998). The inferred resource (at 1998) was 10 Mt at 3 g/t Au (30 t Au: Harvey, 1998). Total production figures are uncertain, although over 8 t Au have been produced from Ravenswood and Mount Wright (combined) in the last 2 years, with reserves of 5.6 t Au and indicated/inferred resources of over 21 t Au (http://www.resolute-ltd.com.au [accessed December 2008]). Geochronology by Perkins and Kennedy (1998) suggests vein mineralisation at Ravenswood and breccia mineralisation at Mount Wright was largely coeval, with ages of ca. 310-305 Ma. Buck reef mineralisation appears to have been earlier – ca. 330 Ma (Perkins and Kennedy, 1998).

3.6.1.2.2. Porphyry style Cu±Mo±Au and Mo±Cu±Au deposits. Despite the great abundance of granites in North Queensland, porphyry-style mineralisation only occurs sporadically, e.g., Horton (1982). This is particularly true for Cu-rich porphyries. Where mineralisation is known, e.g., Mount Turner, Ruddygore, alteration is often well developed, extensive, and zoned (like porphyry Cu deposits elsewhere), but does not appear to have significant metal endowment (Richards, 1980; Baker and Horton, 1982). The lack of significant Carboniferous-Permian porphyry Cu mineralisation in North Queensland is expected given the general relationships between intensive granite parameters and mineralisation styles (e.g., Blevin et al., 1996; Lang et al., 2000). In general, the great majority of Carboniferous and Permian granites of northern Queensland are too evolved (too felsic) and not oxidised enough to generate significant porphyry Cu ± Mo deposits (e.g., Champion and Blevin, 2005). Similarly, the interpreted tectonic setting (mature continental and probably distal from arc, especially in the Georgetown region; see section 2) is not consistent with such deposits (Champion, 2007). It is noteworthy that the most significant porphyry-style Cu-Mo deposit in the region is Mount Leyshon (south of Charters Towers), which was mined for its gold. It should be noted that there is some significant Cu-Zn mineralisation in the region. These occur in skarns, the best example of which is Mount Garnet (Hartley and Williamson, 1995). These skarns are distinct from the F-Sn-W skarns (Brown et al., 1984). The Cu-Zn skarns appear to be typically related to Almaden Supersuite granites (the same supersuite responsible for the Ruddygore porphyry mineralisation). Some of the base metal mineralisation in the Mungana region may also relate to Almaden Supersuite granites.

The nature of the Carboniferous-Permian intrusives in North Queensland does not rule out porphyry Mo mineralisation. Although no significant porphyry Mo deposits are known (e.g., Horton, 1982), it is evident that some of the intrusion-related gold deposits, such as Kidston, become porphyry Mo-like at depth (e.g., Bobis et al., 1998).

The *Mount Leyshon* gold deposit represents an intrusion-related, hydrothermal breccia-pipe – the Mount Leyshon Breccia Complex - up to 1.5 km in diameter (e.g., Paull et al., 1990; Orr, 1995; Morrison and Blevin, 2001; Allan et al., 2004). Like Kidston, the breccia pipe is located in older rocks, near the (complex) contact between Cambrian-Ordovician metasediments of the Puddler Creek Formation and the Ordovician Fenian Granite (Hutton and Rienks, 1997; Allan et al., 2004). Numerous Carboniferous-Permian porphyries and dyke swarms as well as four breccia phases have been delineated around and within the deposit (e.g., Paull et al., 1990; Orr, 1995; Morrison and Blevin, 2001; Allan et al., 2004). Alteration at Mount Leyshon is largely chlorite and biotite-magnetite (early propylitic) with later feldspar-phyllic alteration, associated with gold, and apparently related to some of the porphyries (Paull et al., 1990; Orr, 1995; Morrison and Blevin, 2001; Allan et al., 2004). Allan et al. (2004) report fluid inclusion data, with early quartz-molybdenite-pyrite-chalcopyrite veins, quartz-K-feldspar-chlorite-carbonate-fluorite-pyrite-sphalerite breccia infill, and subsequent sphalerite-pyrite-quartz-gold veins (ore). Fluids associated with the ore are of low to moderate salinity with temperatures of 350-400°C (Allan et al., 2004). According to Morrison and Blevin (2001) mineralisation extends over some 700m vertical extent, containing over 90 t Au (~70 Mt at 1.43 g/t Au). The deposit is zoned from an outer Zn±Au zone, through a Cu-Pb-Zn±Au zone to a pyrite-rich, base metal-poor core (Morrison and Blevin, 2001). Mineralisation at Mount Leyshon has been dated at ca. 290-280 Ma by Perkins and Kennedy (1998), and Paull et al. (1990) report ages of ca. 280 Ma for alteration. Lead model ages (J.A. Dean and G.R. Carr, cited in Paull et al., 1990) also suggest ca. 280 Ma ages. As pointed out by numerous authors (e.g., Paull et al., 1990) these ages are contemporaneous with associated magmatism in the region, supporting intrusion related gold models for the deposit. Morrison and Blevin (2001) suggest Mount Leyshon is a gold-rich porphyry Cu-Mo system. These authors document a co-magmatic suite of andesitic to rhyolitic intrusive phases that appear to be associated with phyllic alteration and gold mineralisation. These intrusives form part of, and lie along, north-east striking corridors of Carboniferous-Permian intrusive and extrusive magmatism which have been considered important in localising gold mineralisation in the region (e.g., Paull et al., 1990).

3.6.2. Middle Carboniferous (~340 Ma) epithermal gold-silver deposits, North Queensland

Although epithermal deposits occur in various places within North Queensland and the Thomson Orogen, e.g., Anastasia (SW of Chillagoe; Nethery, 1998), they are best developed south of Charters Towers in the northern Drummond Basin (Thomson Orogen), where significant deposits occur including Pajingo and Vera-Nancy, Wirralie, and Yandan. These and other deposits in the basin have been recently summarised by Denaro et al. (2004). All are hosted by Cycle 1 Upper Devonian volcanic rocks and sediments of the Drummond Basin (Denaro et al., 2004), though the hosts for the Pajingo deposits may be Upper Devonian to Lower Carboniferous (Richards et al., 1998). They all comprise low-sulphidation quartz-adularia epithermal vein and/or replacement deposits (Porter, 1990; Richards et al., 1998; Seed and Ruxton, 1998; Ruxton and Seed, 1998). At Pajingo and Vera Nancy, (Pajingo epithermal system of Mustard et al., 2003), mineralisation occurs as veins. These comprise chalcedonic or cryptocrystalline quartz, clay (illite-kaolinite), carbonate and pyrite, and contain gold and silver (Porter, 1990; Richards et al., 1989). Veins dip at moderate to steep angles, and mineralisation at Vera-Nancy is recorded to 400+ m depth (Porter, 1990; Richards et al., 1998). Alteration envelopes around veins vary from distal chlorite-dominant propylitic (chlorite-calcite ± pyrite) to proximal, higher temperature, silica-pyrite-sericite-clay (illite, illite-smectite, local kaolinite) phyllic or argillic assemblages (Porter, 1990; Richards et al., 1998; Mustard et al., 2003). Late stage alteration assemblages include carbonate (ankerite, dolomite, siderite) and overprint earlier assemblages (Porter, 1990; Mustard et al., 2003). Mustard et al. (2003) suggested the propylitic alteration, at least in part, represents an earlier, basin-wide alteration event. A variety of quartz vein textures are present in the deposits but most gold (in the Vera-Nancy system) is apparently associated with early-formed banded quartz veins (Mustard et al., 2003). Available fluid inclusion data – summarised in Richards et al. (1998) - suggest low salinity fluids, with evidence for fluid boiling. Brecciation is also recorded (Richards et al., 1998). Location of veins appears to be structurally controlled, which Richards et al. (1998) interpreted as a strike-slip fault. Sericite (K-Ar) ages for the Scott lode suggest middle Carboniferous ages (342 ± 3 Ma) for the mineralisation (Richards et al., 1998). Scott and Cindy lodes yielded 12 t Au and 38.9 t Ag (Richards et al., 1998). Reserves, in 1998, for Vera and Nancy (at 1998) were 33.5 t Au and 30.9 t Ag (Richards et al., 1998). Current (2008) reserve and resource estimates for the area are 15.1 t Au (http://www.nqm.com.au [accessed December 2008]).

Mineralisation at Wirralie comprises quartz-chalcedony-pyrite ± breccia veins and stockworks of such veins, as well as silica replacement zones of volcaniclastic hosts (Fellows and Hammond, 1990; Seed, 1995b; Seed and Ruxton, 1998). Alteration includes illite-pyrite and adularia (associated with gold) and overprinting quartz-kaolinite assemblages (Seed and Ruxton, 1998). Sulphides are largely pyrite but include marcasite, chalcopyrite, arsenopyrite, and sphalerite (Fellows and Hammond, 1990; Seed, 1995b). Mineralisation at Wirralie is suggested to have a strong structural control, particularly by reactivated early graben structures (Seed and Ruxton, 1998). Mining at Wirralie, up to 2001 produced 14.85 t Au from oxide ores (http://www.ashburton-minerals.com.au [accessed December 2008]), although Denaro et al. (2004) indicate that 17.3 t of bullion were produced. Current remaining gold resources (measured, indicated and inferred) at Wirralie (at 2004) are 4.7 t Au in oxide zones and 12.35 t Au in sulphide zones (http://www.ashburton-minerals.com.au [accessed December 2008]).

Mineralisation at Yandan comprises silica-adularia-illite-pyrite or kaolin-illite-adularia-quartz replacement deposits, largely replacing calcareous sandstone (Ruxton and Seed, 1998). Subordinate, locally brecciated, chalcedonic and quartz-adularia-calcite veins also host ore. Alteration (for the bulk of the ore) comprises a quartz-adularia core with pyrite±chalcopyrite (and gold), through illite-smectite, adularia and kaolinite assemblages to a propylitic celadonite-carbonate-chlorite-clay halo (Seed, 1995a; Ruxton and Seed, 1998). Mineralisation appears to be both structurally and lithologically controlled (Ruxton and Seed, 1998). Mining figures for Yandan are variable. Ashburton Minerals reports production of 11.4 t Au from 1992 to 1998 (http://www.ashburton-minerals.com.au), whereas Denaro et al. (2004) report 7.03 t of gold bullion for 4.64 t of Au from the period 1993-2001. Delta Gold Ltd (2000; cited in Denaro et al., 2004) report a measured resource of 0.83 t Au at a grade of 0.4 g/t.

As summarised by Denaro et al. (2004), epithermal mineralisation has a strong structural control, though lithology (e.g., Yandan) can also be important. Denaro et al. (2004) suggest north, north-east and south-east structures are most dominant. Fluid boiling appears to have been the most important mechanism for depositing gold (Richards et al., 1998; Ruxton and Seed, 1998; Seed and Ruxton, 1998, Denaro et al., 2004). Although geochronology is sparse most evidence suggests an early (to mid?) Carboniferous age for mineralisation, during the end of Cycle 1 magmatism in the Drummond Basin (e.g., Denaro, et al., 2003).

3.6.3. Lode gold deposits, North Queensland

Minor Carboniferous to Permian lode gold deposits occur in North Queensland. The most significant of these are in the Hodgkinson goldfield, to the northwest of Cairns, which produced about 9 t of Au and over 3 t of Sb (Murray, 1990). This goldfield comprises a number of separate mineralised zones – Beaconsfield, Union, Thornborough, Kingsborough and Northcote – hosted by metasedimentary rocks of the Hodgkinson Formation and localised close to major north-west trending structures (Vos and Bierlein, 2006). Gold mineralisation is vein hosted with sulphide-poor (arsenopyrite-pyrite±sphalerite-galena-tetrahedrite-stibnite) Au-Sb quartz veins, with earlier gold-quartz veins and later gold-antimony (stibnite)-quartz veins (Peters et al., 1990; Vos and Bierlein, 2006). Fluid inclusion data (Peters et al., 1990; Vos and Bierlein, 2006), indicate low salinity fluids with minor CO_2, and temperatures of 150-400°C, consistent with lode/orogenic gold mineralisation styles, though Peters et al. (1990) did not rule out a distal magmatic contribution. The timing of mineralisation is uncertain. Morrison and Beams (1995) a suggested Carboniferous age of ~ 328 Ma, whereas Davis et al. (2002) suggested much of the lode gold in the Hodgkinson was Permian in age, and Vos and Bierlein (2006) proposed two episodes of mineralisation related to successive deformation events in the Late Devonian-early Carboniferous and the middle Carboniferous. In proposing young (Permian) gold, Davis et al. (2002) have suggested that whilst quartz veins are of multiple ages, the gold mineralisation is one age, related to the last major orogenic deformation event in the province. What is not in dispute is the structural control and relationship of the gold mineralisation to major deformation events, so multiple gold events within a region or within the one deposit are perhaps not surprising. The best example of this is the Amanda Bel goldfield in the Broken River Province which in addition to gold mineralisation in the Early and Late Devonian also apparently contains a mid to Late Carboniferous mineralising (Sb±Au-As) event (e.g., Teale et al., 1989; Vos et al., 2005).

The Palmer River goldfield (northwest of Cairns) produced over 40 t Au, but this was dominantly alluvial, with only minor lode gold (Murray, 1990). Like the Hodgkinson goldfield, the sources of the Palmer River alluvials may be of Permo-Carboniferous age (Morrison and Beams, 1995; Davis et al., 2002), but they could be related to Devonian deformation (Murray, 1990).

3.6.4 Uranium deposits of uncertain age and origin, North Queensland

Numerous small, U-F-Mo prospects and two significant deposits (Maureen and Ben Lomond) occur, in the Townsville to north Georgetown region, associated with felsic volcanics and sediments of the Kennedy Association. According to Morrison and Beams (1995) and Mega Uranium (http://www.megauranium.com, accessed December 2008), mineralisation includes U-bearing phosphates, sulphates and molybdates in veins or shear infill, as well as replacement zones, closely associated with unconformities. Although mineralisation (U especially) is most likely ultimately sourced from the Kennedy Association felsic magmatism, it is not clear whether these deposits are Carboniferous-Permian in age, representing hydrothermal mineralisation related to the magmatism (Bain, 1977; Morrison and Beams, 1995) or reflect younger, low-temperature, unconformity-related mineralisation (Wall, 2006). Morrison and Beams (1995) suggested the possibility that the deposits may represent the distal portions of polymetallic Sn-W deposits. Ewers (1997) indicated that the deposits are generally small in size. Current (2008) indicated and inferred resource (Canadian NI43-101 compliant) estimates are 2.88 kt U_3O_8 at Maureen and 4.86 kt U_3O_8 at Ben Lomond.

Mathison and Hurtig (2009) recently described the Maureen deposit as being localised near the unconformity between Mesoproterozoic sedimentary rocks and dolerites and Paleozoic sedimentary rocks that grade upwards into volcaniclastic sandstone, tuffaceous rocks and rhyolitic ignimbrite. Mathison and Hurtig (2009) interpreted these rocks to be part of the Late Carboniferous to Early Permian Maureen Volcanic Group rather than the Devonian Gilberton Formation. The mineralised zones are roughly bedding parallel but also form vertical zones that extend to the unconformity. The mineralised zones are characterised by replacement of the host rock by fluorite, clay and sulphide minerals. The sulphide minerals are dominated by molybdenite, with additional arsenopyrite, arsenian pyrite and minor sphalerite. The alteration assemblages are characterized by fluorite, dickite, chamosite and disseminated pyrite. Goyazite, anatase, carbon are also associated with sulphide minerals as is very-fine-grained uraninite (Mathison and Hurtig, 2009).

3.6.5. Mineral potential of Hunter-Bowen cycle

Synthesis and analysis of geological and metallogenic data suggest that the Hunter-Bowen cycle was characterised in North Queensland by two geodynamic systems:

1. Kennedy magmatic system; and
2. Hunter-Bowen Orogeny.

3.6.5.1. Kennedy magmatic system

As described in section earlier, magmatism in the Kennedy magmatic association spans the period from 340 to 260 Ma, with an apparent younging in ages from west to east, possibly associated with the eastward retreat of the related subduction zone. The granites are mostly I-type with lesser A- and S-types. The A-type granites are relatively young, mostly between 290 and 275 Ma. Compositionally, the granites are dominantly felsic with lesser intermediate and mafic compositions. Despite the strong crustal input into the magmatism, these granites are interpreted to be arc-related, possibly in an extensional backarc position relative to the continental arc to the east in the New England Orogen.

The Kennedy magmatic association is extensively mineralised, with the age of mineralisation decreasing from west to east like the associated granites. Three styles of intrusion-related deposits are associated with the granites: (1) skarn, greisen and vein-hosted Sn and W deposits; (2) IRG-style vein, skarn-hosted and breccia-pipe hosted Au(Mo-Bi) deposits; and (3) porphyry Cu±Mo±Au and related deposits. Of these three deposit styles, only the Sn-W and Au(Mo-Bi) groups contain significant deposits. The Kennedy magmatic association has significant potential for further discoveries of these two deposit styles (Figure 68), but much lower potential for the discoveries of porphyry Cu and related deposits as this latter deposit type is more closely associated with oxidised, intermediate intrusions, which are not abundant in the Kennedy magmatic association. Moreover, these deposits tend to be formed in magmatic arcs, and not in a backarc position as interpreted for the Kennedy magmatic association.

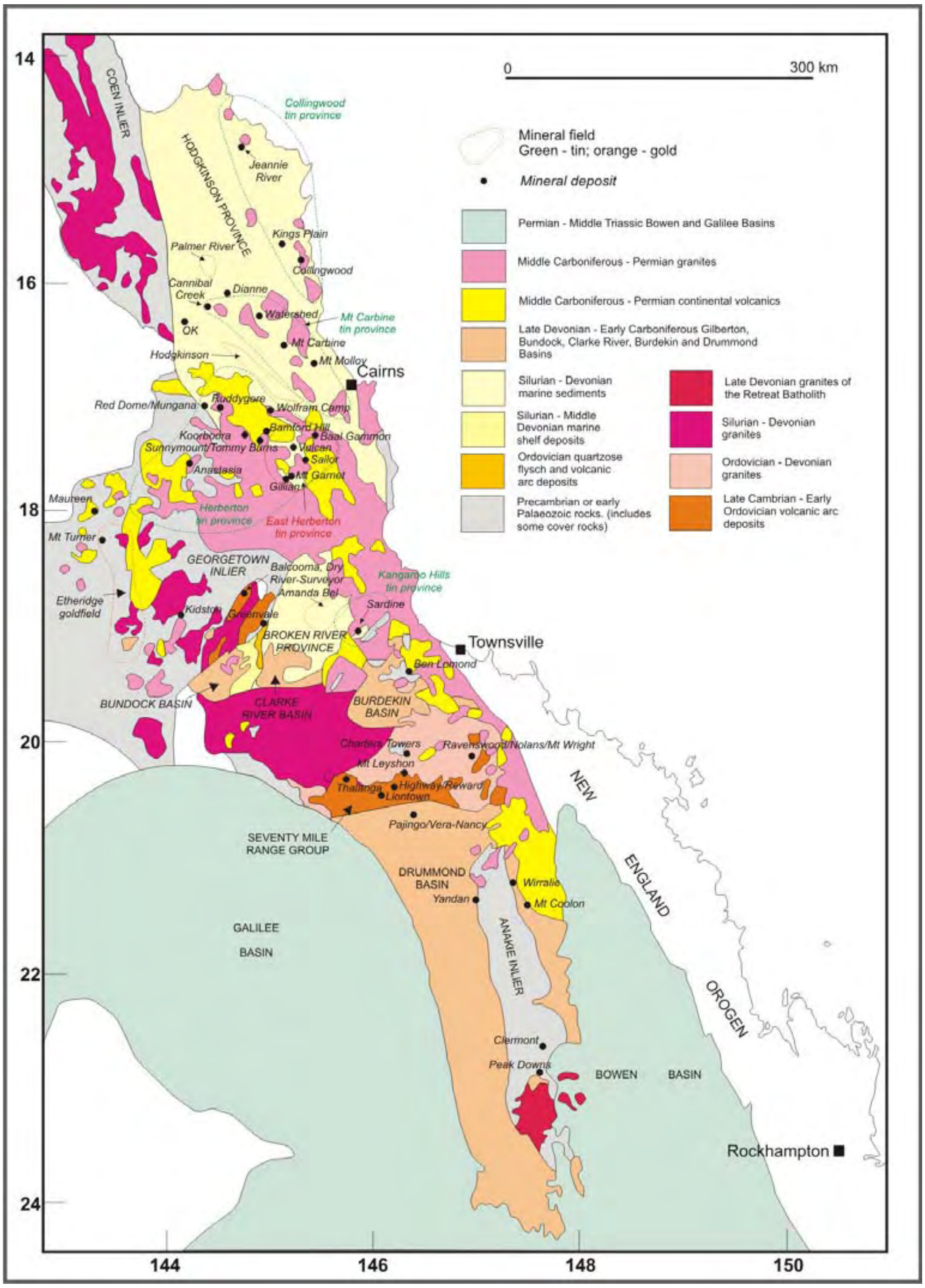

Figure 67. Distribution of Sn-W and Au-Mo-Cu-Bi mineral provinces and major individual deposits in North Queensland. Modified after Murray (1990).

The potential for these deposits may not be uniform across the Kennedy Association. Tin-tungsten deposits are largely localised in the east, particularly associated with granites that intrude metasedimentary rocks of the Hodgkinson Province. Intrusion-related gold deposits, in contrast, are more widely distributed. The simplest explanation for this distribution is the oxidation states of the ore-related granites. As demonstrated by Blevin and Chappell (1995), Sn-W mineralisation is related to reduced to strongly reduced granites – their predominance in the Hodgkinson Province suggests that the local sedimentary rocks are intrinsically reducing the magma.

3.6.5.2. Hunter-Bowen Orogeny

At ~265 Ma, the New England Orogen went from extension into contraction when a magmatic arc was re-established on the eastern margin of the Australian continent. As a consequence, a west verging fold-thrust belt developed in the former extensional basins to the west of the developing magmatic arc, and the Sydney-Gunnedah-Bowen system changed from a backarc extensional to a foreland setting, which it retained until the Middle Triassic (Korsch et al., 2009a). The Hunter-Bowen Orogeny mostly affected the NEO and parts of North Queensland.

Metallogenically, one of the earliest effects of this tectonic change was the deposition of lode Au deposits in the Hodgkinson goldfield (section 3.6.3). The Permian age combined with the close association with structures suggests that these deposits formed during initial contraction associated with the Hunter-Bowen Orogeny. The Hunter-Bowen Orogeny is developed widely through the NEO, suggesting potential for lode Au deposits through this orogen and its hinterland, and into North Queensland (Figure 69). This concept is possibly supported by the presence of small lode Au deposits in the Berserker Group near the Mount Chalmers VHMS deposit (Crouch, 1999) in central Queensland.

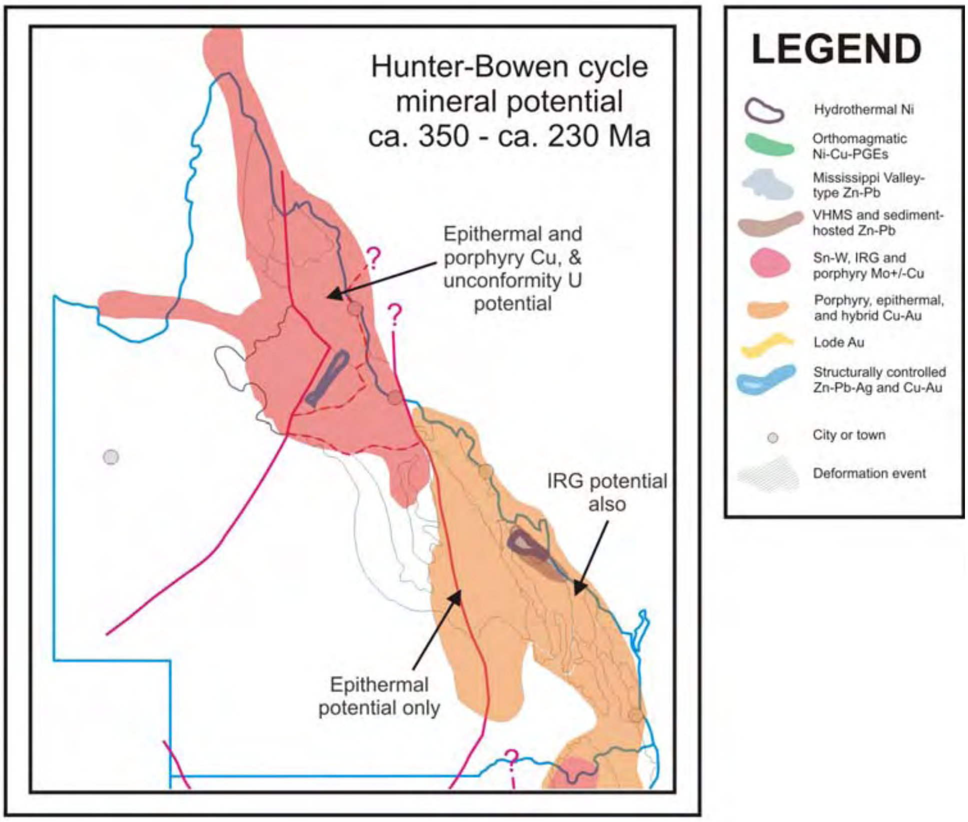

Figure 68. Mineral potential of the Hunter-Bowen cycle.

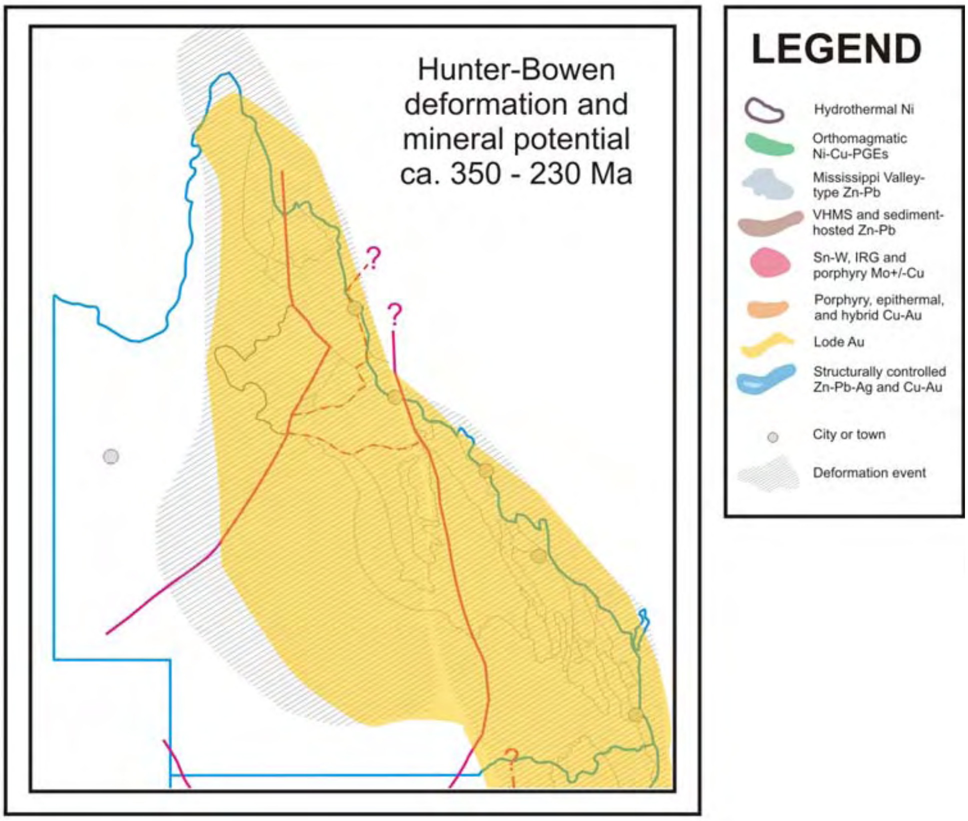

Figure 69. Mineral potential of the Hunter-Bowen Orogeny.

3.7. Mesozoic

This time interval is dominated by sedimentary basins, dominantly the continental sediments of the Carpentaria, Eromanga and Laura basins. Overall, these basins are poorly mineralised, although known mineral resources of the Carpentaria, Laura and Eromanga basins include groundwater and oil shale. The Toolebuc Formation of the Eromanga Basin is rich in kerogenous material (Smart and Senior, 1980) and hosts significant oil shale and vanadium resources (Garrad et al., 2000).

3.7.1. Mineral potential

As discussed by van der Wielen (in prep.), the Eromanga and Carpentaria basins have potential for sandstone-hosted uranium deposits. In addition, Mesozoic intrusions along the Whitsunday coast may have potential for Sn and intrusion-related gold (Fig. 70).

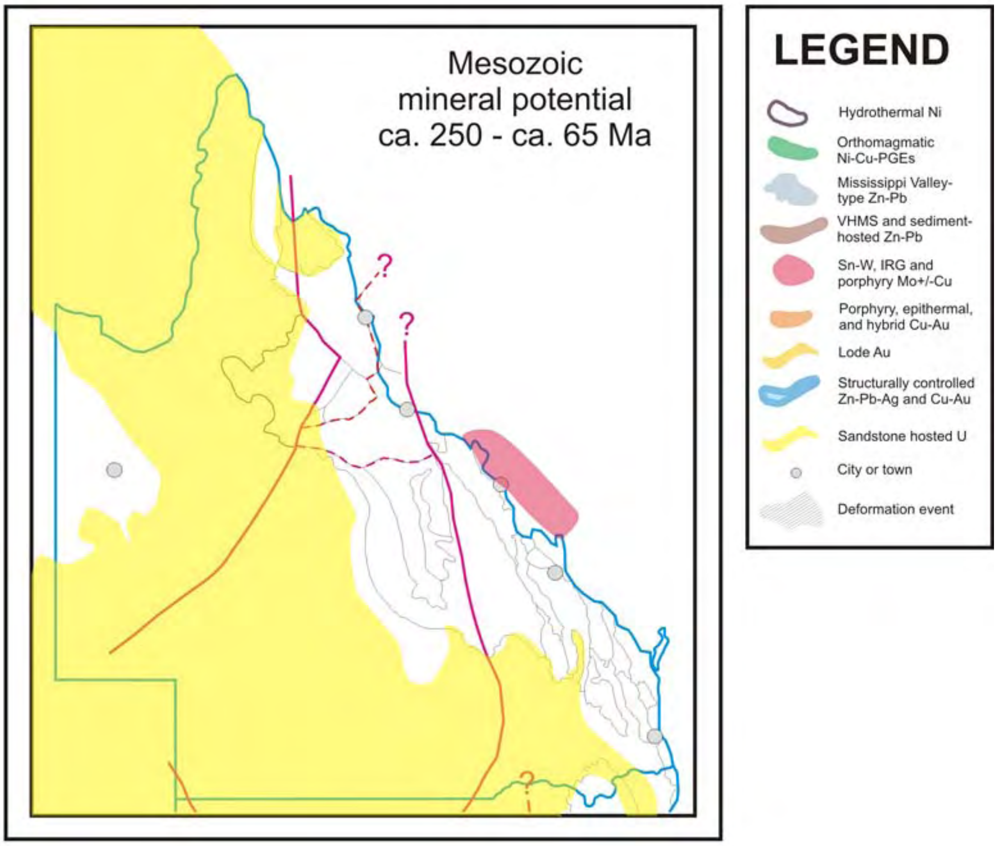

Figure 70. Mineral potential of the Mesozoic interval.

3.8. Cenozoic

The Cenozoic rocks, sediments and weathering profiles of North Queensland have yielded a number of important economic minerals, which occur predominantly as placers, and deposits that were upgraded by deep weathering processes (Grimes, 1985). Examples include alluvial/eluvial placers of gold and cassiterite, colluvial, eluvial and alluvial placer gems (i.e., sapphire, topaz, diamond), lateritic nickel-cobalt ores developed on ultramafic bodies, bauxite deposits developed on heavy mineral sands in coastal deposits, and oil shale deposits in sedimentary basins.

3.8.1. Alluvial/eluvial gold

Alluvial placer gold deposits occur in Cretaceous, Tertiary and Quaternary stream channels, and as colluvial/eluvial deposits across North Queensland, the main areas being the Palmer River drainage system of the Palmer River Goldfield (Yambo Subprovince), and the drainage systems of the Etheridge Goldfield (Denaro et al., 1997). The Palmer River drains areas of mesothermal metamorphic related gold mineralisation of the Hodgkinson Province and has an estimated alluvial gold production in excess of 33t (Garrad et al., 2000). Alluvial gold placer deposits are also associated with some mesothermal gold deposits in the Coen, Ebagoola, Hayes Creek, Whites Creek, Skae Creek and Leo Creek areas of the Savannah Subprovince (Ewers, 1997).

3.8.2. Alluvial Tin deposits

A significant proportion of Queensland's tin production has been derived from Cainozoic alluvial and eluvial tin deposits associated with primary deposit styles (Garrad et al., 2000). In the Stanhills tinfield, cassiterite occurs in shallow, generally narrow, alluvial deposits in creeks and gullies near areas with cassiterite lodes (e.g., Hans Gully, Grenners Creek and Ten Mile Creek). Tin deposits of the Herberton-Mount Garnet area include some ‘deep leads’ which have been preserved beneath late Cainozoic basalt flows (Sutherland, 1977; Denaro et al., 1997). Gem-quality topaz occurs with cassiterite in alluvial and eluvial deposits in the Elizabeth Creek and O’Briens Creek areas (Ewers, 1997).

3.8.3. Alluvial and placer gems

Sapphires in Queensland are mainly associated with Tertiary and Quaternary alluvial deposits derived from the weathering and erosion of Tertiary basaltic lavas, pyroclastics and volcaniclastics of the Eastern Australian Cainozoic Igneous Province (Grimes and Withnall, 1995). Tertiary aged sapphire bearing palaeodrainage systems have been reworked to form the main sapphire bearing alluvium at Anakie. Sapphires of the Anakie area were carried to the surface in the plugs of the early to mid-Tertiary Hoy Basalt (Garrad et al., 2000). The sapphire is typically found as xenocrysts in both lava and pyroclastic flow deposits, and as placer accumulations within a variety of Pliocene to Pleistocene fluvial, colluvial and alluvial deposits (Pecover, 1996). The Anakie province is noted for its association with alluvial gem deposits, which yield not only abundant sapphire, but zircon and rare diamonds (Grimes and Withnall, 1995).

Gem quality blue sapphires also occur in shallow colluvium, eluvium and alluvium adjacent to and within current watercourses at Lava Plains, between Greenvale and Mount Garnet in northeast eastern Queensland (Withnall et al., 1997). Sapphires occur in the modern eluvium, colluvium and alluvium derived from eruptive volcanics in the vicinity of a limited number of vents. Associated minerals include zircon, ilmenite, olivine, hematite and feldspar. The Subera mine has an indicated-inferred resource of 689 tonnes of sapphire (Garrad et al., 2000), and is the largest producer of sapphires in North Queensland.

Sapphires, zircon, olivine, garnet and other gems have been documented within Cenozoic basalts and associated sediments of North Queensland (Robertson, 1976a, b; Stephenson et al., 1980), mainly supporting amateur prospectors. Basaltic flows belonging to the McBride and Chudleigh Subprovinces are suspected to be the source of minor sapphire, zircon and olivine occurrences in basaltic soils derived from these subprovinces (Robertson, 1976a, b; Stephenson et al. 1980; Ewers, 1997).

The O’Brien’s Creek topaz field northwest of Mount Surprise is the source of most of Australia’s gem-quality topaz. Topaz and small amounts of beryl and aquamarine have been recovered from Cainozoic alluvial gravels derived from pegmatites and greisens of the Carboniferous and Permian granites of the Kennedy Association, and are also produced as a by-product of small-scale alluvial tin mining (Bain and Withnall, 1980).

Diamonds are found where Late Cretaceous to Cainozoic volcanism has occurred and at several locations diamonds have been recovered from deposits containing sapphire and zircon (Robertson, 1996). The main locations are at Stanthorpe, the Anakie Sapphire fields and the Elizabeth Creek area northwest of Mount Surprise (Robertson, 1996). Alluvial diamonds of unknown age are found throughout North Queensland, but their origin is uncertain (Bain and Withnall, 1980; Ewers, 1997)

3.8.4. Lateritic nickel – Greenvale

Nickeliferous laterites cover much of the surface of known outcrops of Proterozoic ultramafics along the eastern edge of the Georgetown Province (Bain and Withnall, 1980). Ni-Co mineralisation occurs within lateritic profiles developed above ultramafic (peridotite) units within mafic-ultramafic bodies such as the Boiler Gully Complex which hosts the Greenvale deposit (Fletcher and Couper, 1975; Burger, 1995). Greenvale (now closed) produced 39 Mt at 1.5% Ni and 0.1% Co (Burger, 1995). Metal enrichment, from low contents of ~0.28% NiO and ~0.01% CoO in fresh serpentinite of the Boiler Gully Complex (Fletcher and Couper, 1975) resulted from weathering and development of a laterite profile. Successive laterite development appears to have occurred within the deposit. Ni is hosted within hydrous silicates (nepouite) and within goethite and smectite as well as manganese oxides (Fletcher and Couper, 1975; Burger, 1995). Best Ni grades are reported to be within the upper saprolitic horizon, decreasing upwards in the overlying limonitic horizon (Fletcher and Couper, 1975). Best Co grades are in the latter (Fletcher and Couper, 1975; Burger, 1995).

3.8.5. Kaolin and bauxite

The west coast of the York Peninsula has a major kaolin and bauxite deposit at Weipa, with a resource in excess of 3 Gt of bauxite. This deposit is developed through lateritic weathering of the Weipa beds, quartz-rich sandstone and conglomerate, which is overlain by sandy clay and clay lenses. This unit overlies the early Cretaceous Rolling Downs Group, and both are part of the Carpentaria Basin (Schaap, 1990).

3.8.6. Mineral sands

Rutile, ilmenite and zircon are the major economic components of Queensland's heavy mineral sands and occur in the Pleistocene and Holocene coastal beach and dune systems along the coastline (Garrad et al., 2000).

3.8.7. Tertiary oil shale deposits

Tertiary oil shale deposits occur in basins near Queensland's eastern coastline from Proserpine to Bundaberg and west to Duaringa (e.g., Duaringa Basin, Nargoorin beds, Lowmead Basin, Yaamba Basin) (Garrad et al., 2000).

3.8.8. Mineral potential

Potential for placer deposits is greatest in drainages that source existing hard rock sources of gold, tin and gems. Potential for both lateritic nickel and bauxite is restricted by both the exposure of suitable protoliths (particularly in the case of nickel) and by the extent of tropical, particularly monsoonal weathering (including palaeo-weathering). The distribution of mineral sands in Queensland is restricted to coastal areas. Paleo-strand lines, such as those in the Murray and Eucla Basins in southeastern Australia are not known in Queensland. The known distribution of units that host Tertiary oil shale deposits is well known and restricted to central coastal areas from Proserpine to Bundaberg.

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