Basin architecture and crustal evolution in the Paleoproterozoic–earliest Mesoproterozoic sequences of Mount Isa, northern Australia: a record of supercontinent assembly and breakup

NOTES FOR AN IGCP 648 FIELD EXCURSION IN THE MOUNT ISA REGION

Prepared and compiled by

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Executive Summary

Paleoproterozoic–earliest Mesoproterozoic sequences in the Mount Isa region of northern Australia preserve a 200 Myr record (1800–1600 Ma) of intracontinental rifting, culminating in crustal thinning, elevated heat flow and establishment of a North American Basin and Range-style crustal architecture in which basin evolution was linked at depth to bimodal magmatism, high temperature-low pressure metamorphism and the formation of extensional shear zones. This geological evolution and record is amenable to investigation through a combination of mine visits and outcrop geology, and is the principal purpose of this field guide.

Rifting initiated in crystalline basement ≥1840 Ma old and produced three stacked sedimentary basins (1800–1750 Ma Leichhardt, 1730–1670 Ma Calvert and 1670–1575 Ma Isa superbasins) separated by major unconformities and in which depositional conditions progressively changed from fluviatile-lacustrine to fully marine. By 1670-1655 Ma, a deep marine, turbidite-dominated basin existed in the east and basaltic magmas had evolved in composition from continental to oceanic tholeiites as the crust became increasingly thinned and attenuated. Except for an episode of collision-related deformation and basin inversion from 1650-1640 Ma, sedimentation continued across the region until onset of the Isan Orogeny at ca. 1620 Ma.

A near-identical record of crustal thinning and basaltic magmatism accompanied basin formation (lower Willyama Supergroup) in the formerly contiguous Broken Hill region from 1730–1670 Ma. This was followed by further extension and a second phase of basin development that lasted until at least 1640 Ma. Modern-day rifted continental margins preserve a comparable record of crustal thinning and near-continuous basin formation over 100–200 Myr timescales, supporting suggestions that the late Paleoproterozoic–early Mesoproterozoic rift basins of Mount Isa and Broken Hill similarly evolved to continental breakup and formed part of a continental margin sequence no later than 1650 Ma and possibly as early as 1670 Ma.

This rifted margin predates assembly and breakup of the Neoproterozoic Rodinia supercontinent to which Australia once belonged and best accords with a pre-Rodinia, SWEAT-like supercontinent (Nuna) that matches the east-facing late Paleoproterozoic–early Mesoproterozoic rift sequences of eastern Australia against rocks of pre-1800 Ma age in western Canada. Subsequent to 1800 Ma, the two continental margins evolved independently of each other until reunited during continent-continent collision commencing around 1620 Ma (Isa and Racklan orogenies). Reconstructions of Rodinia (AUSWUS) based on the distribution of Grenville-age orogenic belts that coincidently position the continental rift sequences of Broken Hill along strike from more juvenile 1700–1650 Ma accreted terranes in the SW United States (Yavapai and Mazatzal provinces) are only possible if the proposed alignment of terranes is not original but an artefact of Neoproterozoic supercontinent assembly. The SWEAT hypothesis avoids this complication but, like AUSWUS, presupposes that eastern Australia and western Laurentia remained juxtaposed throughout the Mesoproterozoic until onset of Rodinia breakup after 830 Ma.

Introduction

The Mount Isa region (Figure 1) is host to several world class ore bodies (e.g. Mount Isa, Cannington, Century) and constitutes the world's single largest repository of Pb-Zn mineralisation (Leach et al., 2010), the great bulk of which is contained within rocks of late Paleoproterozoic-early Mesoproterozoic age. The region is also known to harbour an exceptionally well preserved rift basin geometry although there is as yet no consensus about whether this geometry evolved in an entirely intra-continental setting (Betts, 1999; Betts et al., 1998; Derrick, 1982; O'Dea et al., 1997) or a tectonic environment more reminiscent of a passive continental margin in which crustal thinning and rifting had advanced to the point of seafloor spreading (Gibson et al., 2012; 2017). Notwithstanding such uncertainties, most researchers agree that the Mount Isa region serves as an excellent natural laboratory for the study of continental rifting and extensional tectonics in general. Moreover, with more than a century of mining activity and mineral exploration in the district, much of the extensional geology is now accessible by road and track (Figure 2), and within easy reach of the main towns (Mount Isa and Cloncurry). High quality regional gravity and aeromagnetic datasets, combined with recently published deep seismic reflection profiles that have imaged the crust all the way down to the Moho (Queensland, 2011), have further ensured that this record of continental rifting and extension is amenable to investigation at all scales and crustal levels (Murphy et al., 2011).

This excursion guide combines elements of the regional datasets with mine visits and outcrop geology to give an account of basin architecture and crustal evolution in the Mount Isa region, and the manner in which this architecture evolved over a 200 myr period from 1800-1600 Ma. No particular emphasis is placed on mineralisation style or the associated ore-bodies although it will be obvious that many of the basin structures and characteristics described here must have exercised some degree of control over fluid flow and mineralisation in the Mount Isa region (Murphy et al., 2011; Southgate et al., 2006). Mineralised sequences of comparable age have been identified in other parts of the world, including western North America (western Laurentia) against which the Proterozoic rocks of northern Australia may once have been joined (Figure 3). If so, the Proterozoic sequences of Mount Isa and western Laurentia are potentially analogues of each other and should not be considered in isolation (Barovich and Hand, 2008; Betts et al., 2011; Gibson et al., 2012; Gibson et al., 2008; Giles et al., 2002; Karlstrom et al., 2001).

Excursion Objectives and Content

1. Introduction to late Paleoproterozoic-early Mesoproterozoic sedimentary and magmatic rocks of the Mount Isa region, basin stacking patterns, and their correlation at local and regional basin scales
2. Basin architecture and geometry of the structures that controlled basin formation and evolution, and served as fluid and magmatic conduits during initial crustal extension and subsequent basin inversion
3. Summary of the geochronological constraints on basin formation and evolution, and the manner in which these geochronological data have been used to improve regional sequence correlations, timing of fluid migration, and development of a chronostratigraphic framework for the Mount Isa region
4. Synthesis and geodynamic evolution of the Mount Isa region, including the role played by magmatism and detachment faulting at different crustal levels
5. Examination of key outcrops and geological sections, and through mine visits better understand how field observations combined with theoretical considerations have been used to derive a predictive model for Pb-Zn mineralisation in the Mount Isa region
6. Derivation of a tectonic model for basin formation and evolution in the Mount Isa region that serves as a basis for comparison with equally well-endowed basinal sequences elsewhere in the world but more particularly in western North America (Laurentia).

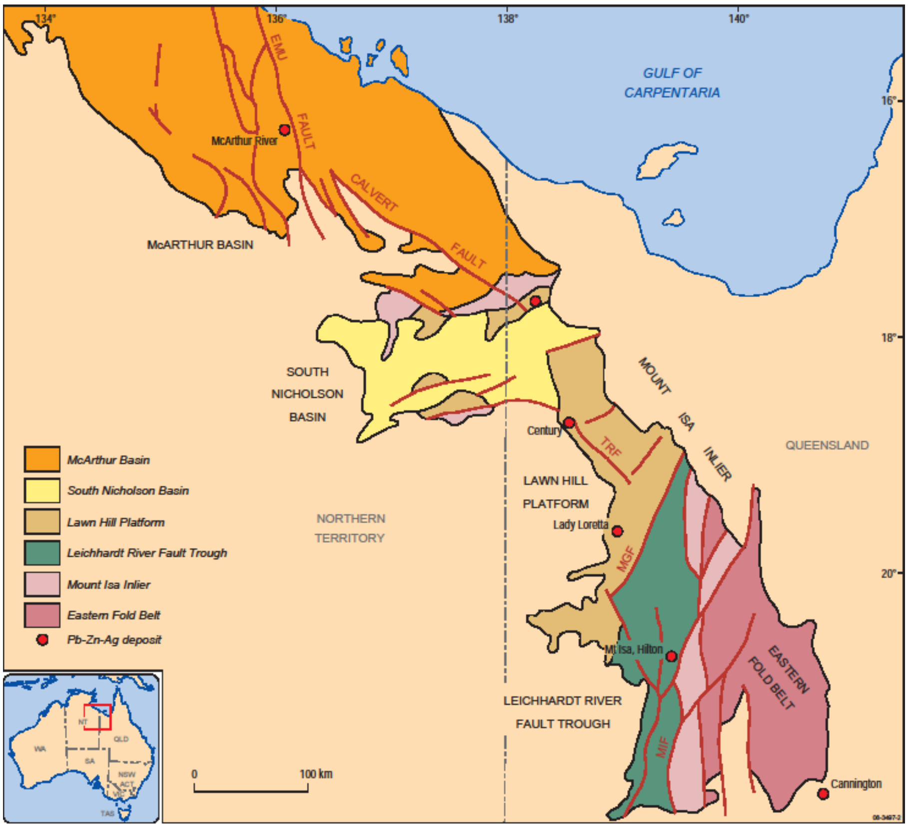


Figure 1. *Principal tectonic elements within the Mount Isa terrain and the Pb-Zn mineral deposits hosted by these different elements. TRF = Termite Range Fault; MGF = Mount Gordon Fault Zone.*

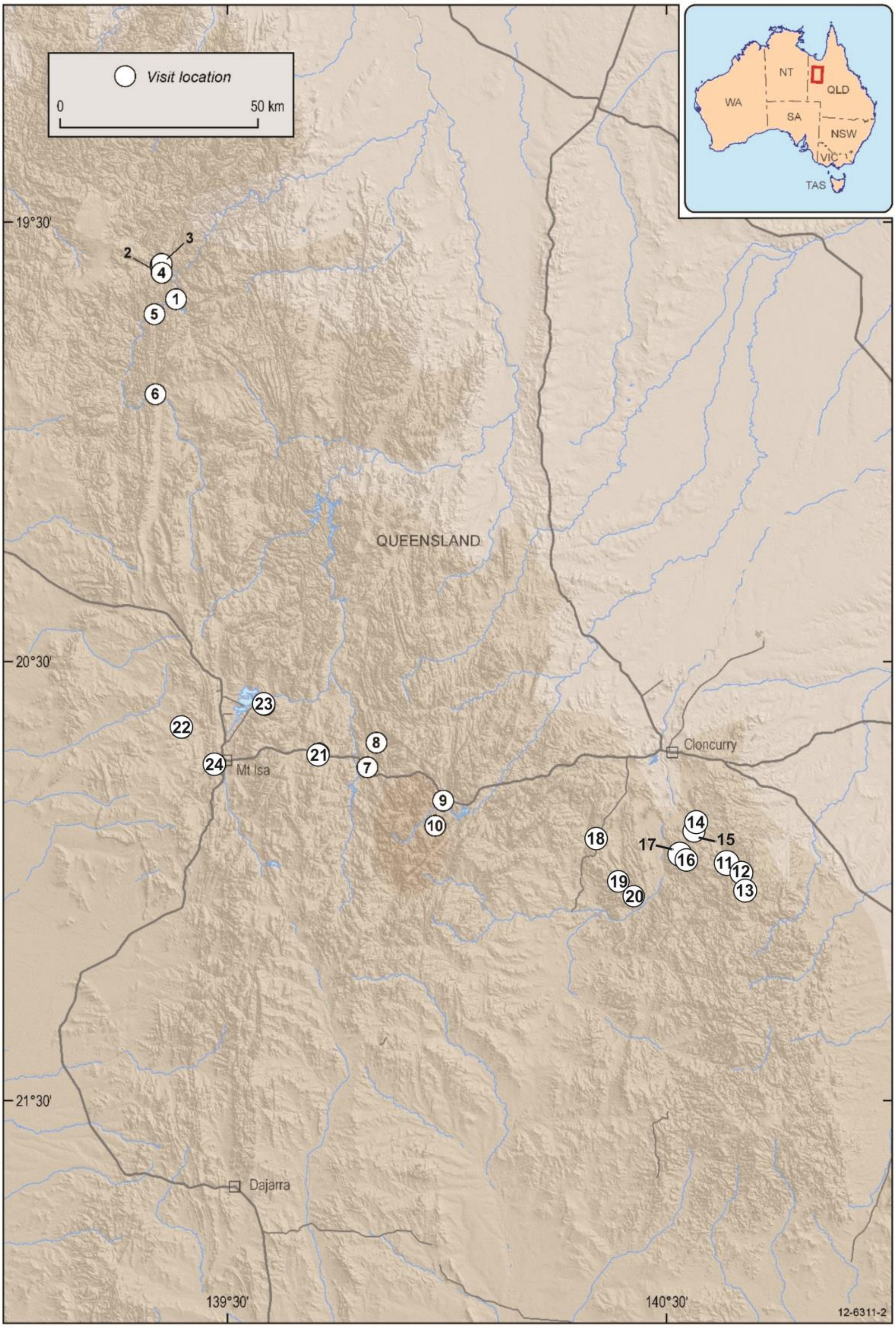


Figure 2. *Digital elevation image showing major roads and tracks, and localities to be visited.*

Excursion Organisation

Excursion Leaders: Dr George Gibson, Australian National University; Dr Ian Withnal, Queensland Geological Survey

Venue: Capricorn Mine at Mount Gordon (Gunpowder) and environs, Mount Isa & Cloncurry

Dates: Friday June 16 - Wednesday 21, 2017 (6 days)

Arrival in Mount Isa

The excursion will depart Mount Isa airport at 1:00pm on Friday June 16, giving participants plenty of time to get to Mount Isa from Townsville or Brisbane after conclusion of the conference on Wednesday June 14. Upon arrival at the airport, participants should congregate outside the terminal where the excursion leaders and vehicles for the excursion will be waiting. The journey to Mount Gordon takes about 1.5 hours. Lunch will be picked up in town en route to Mount Gordon.

Accommodation & Logistics

Participants remain at Mount Gordon for two nights (June 16-17) until the morning of day 3 (Sunday June 18). All meals and accommodation will be provided on site. A packed lunch is included for days 2 & 3. Accommodation is in individual cabins.

Following departure from Mount Gordon, and several outcrop visits, the party arrives at Cloncurry and remains there for two nights in motel accommodation (Sunday June 18 & Monday June 19). Continental breakfast is included; cooked breakfast is optional and by arrangement with the motel managers. Evening meals will be provided at the motels and adjacent pubs. Lunches and drinks can be obtained at the local bakery or supermarket.

From Cloncurry, the party returns to Mount Isa. The remaining two nights (Tuesday June 20 - Wednesday 21) are spent in single rooms but shared facilities-style accommodation in Mount Isa. All meals will be provided, up to and including breakfast on Wednesday, June 21.

The excursion officially ends on the evening of Wednesday June 21 (day 6).

Departure from Mount Isa

For those departing on the mid-day flight on Thursday June 22, taxis can be hired through the motel reception for the trip to the airport.

Outback Tourist Centre

Although not formally part of the Mount Isa excursion, it is recommended that delegates with time to spare avail themselves of the opportunity to visit the Outback Centre at 19 Marion Street where the Riversleigh fossil centre is housed and an excellent film on the history of mining in the region is on show courtesy of Glencore, the company that owns the local Mount Isa mines. Plan to set aside two hours for both the film and museum visit; cost per adult is ca. $20.

General Information

As with all Australian mines, visitors staying on site at Gunpowder (Capricorn Copper) will be required to adhere to all standard OH&S requirements laid down by mine management. This may include testing for alcohol or drugs. Such tests are routine on mine sites and nothing to be alarmed about. We will be advised by the camp medical officer in advance of our visit if any testing will take place. If so, medical details may be requested and a form made available to each registrant on the excursion.

As day-time temperatures (25-30°) and ultra-violet readings can be high even during the mid-winter dry season in northern Australia, it is recommended that you bring and/or wear the following:

- Good quality sunscreen (30+)
- Wide brimmed hat (not a baseball cap as the ears remain exposed)
- Long sleeved shirt (this is also a requirement for any mine visit)
- Boots or stiff walking shoes (best worn with decent pair of socks)
- Water bottle (even though water will be on hand each day from the vehicles)
- Small back-pack (for your water bottle, sunscreen and packed lunch)
- Gaiters or heavy jeans (in case of spinifex or other prickly grasses)

Shorts are OK during the day although it is advisable that knee or ankle-length socks be also worn to avoid being spiked by spinifex grass which occurs in a few of the localities to be visited.

Mount Isa geology and the supercontinent cycle

Reconstructions of the Neoproterozoic supercontinent Rodinia, and its Paleoproterozoic predecessor Nuna (or Columbia by which it is sometimes known) (Ernst et al., 2008; Rogers and Santosh, 2009; Zhao et al., 2002), are typically based on matching conjugate continental rift margins with similar geological histories and polar wander paths (Dalziel, 1991; Wingate et al., 2002). For the pre-Phanerozoic east Australian rift margin, potential matches have been sought in western Laurentia (Figure 3), South China and Mexico where basaltic dyke swarms, syn-rift sedimentary sequences and older basement rocks of the same age and isotopic composition are known to occur (Burrett and Berry, 2000; Karlstrom et al., 2001; Moores, 1991; Park et al., 1995; Thorkelson et al., 2001; Wang et al., 2011). Australian basement rocks for which Laurentian equivalents have already been proposed (e.g., Burrett and Berry, 2000; Karlstrom et al., 2001; Betts et al., 2008) include the late Paleoproterozoic–early Mesoproterozoic basin sequences of Broken Hill and Mount Isa (Figure 3a), both of which lie just inboard of the Tasman Line (Figure 3b) and east of which Proterozoic continental crust is thought not to occur. Although geographically distant from each other (Figure 3), these two regions exhibit strikingly similar geological histories and potential field signatures (Figure 4a) (Baker et al., 2010; Gibson et al., 2008; Giles et al., 2002; Henson et al., 2011; Laing, 1996). This has led many researchers to propose that their constituent rock sequences were formerly contiguous (Figure 4b) and originated through extensional processes in the same back-arc basin (Betts and Giles, 2006; Betts et al., 2008; Gibson et al., 2008; Giles et al., 2002).

More debatable is whether this back-arc basin evolved in the overriding plate of a subduction zone that dipped north (Betts et al., 2011; Betts et al., 2008; Giles et al., 2002) or west beneath conjoined north and south Australian cratons (Gibson et al., 2008). Proponents of the former point to a near-identical tectonic environment inferred for the late Paleoproterozoic–early Mesoproterozoic basins of interior North America (e.g., Thelon, Athabasca) north of the Cheyenne suture (Duebendorfer and Houston, 1987; Karlstrom et al., 2001; Karlstrom and Bowring, 1988; Rainbird et al., 2007; Thorkelson et al., 2005). In this interpretation, Laurentia did not separate from eastern Australia until long after 1800 Ma, in keeping with observations that the Paleo–Mesoproterozoic rocks of eastern Australia and western Laurentia share too many geological similarities to have developed in isolation of each other (Bell and Jefferson, 1987; Betts et al., 2011; Betts et al., 2008; Dalziel, 1991). In the second interpretation, continental breakup occurred much earlier and the two continental margins evolved independently of each other from 1800 Ma until 1650 Ma (Gibson et al., 2017). It has been further suggested that west-dipping subduction gave rise to an east-facing magmatic arc that once lay between Australia and Laurentia before being reaccreted to the east Australia margin at 1650 Ma (Gibson et al., 2008; 2017) ahead of continent-continent collision and obduction of this arc over the west Laurentian margin by 1600 Ma (Thorkelson, 2016 #1400). Thus, while there is a strong possibility that the basins of eastern Australia and western Laurentia are genetically related and share a common evolutionary history, this is best developed from 1650 Ma onward. Other researchers are of the opinion that a better match can be obtained between Laurentia and Serbia (Sears et al., 2004). Here, we give a brief account of basin evolution in the late Paleoproterozoic–earliest Mesoproterozoic sequences of the Mount Isa region along with a more tightly constrained kinematic and tectonic framework whereby the Paleoroterozoic rocks of eastern Australia might be further compared with their North American counterparts and used as a test of competing supercontinent reconstructions. Such comparisons have been carried out before but more usually in the context of Rodinia reconstructions, including AUSWUS (Australia-western United States)(Burrett and Berry, 2000; Karlstrom et al., 2001) and SWEAT

(SW United States - East Antarctica)(Dalziel, 1991; Moores, 1991) where the primary constraint on reconstruction was not the distribution of the Paleoproterozoic–Mesoproterozoic rift basins but the orogenic belts of Grenville-age along which supercontinent assembly is interpreted to have taken place (Figure 3).

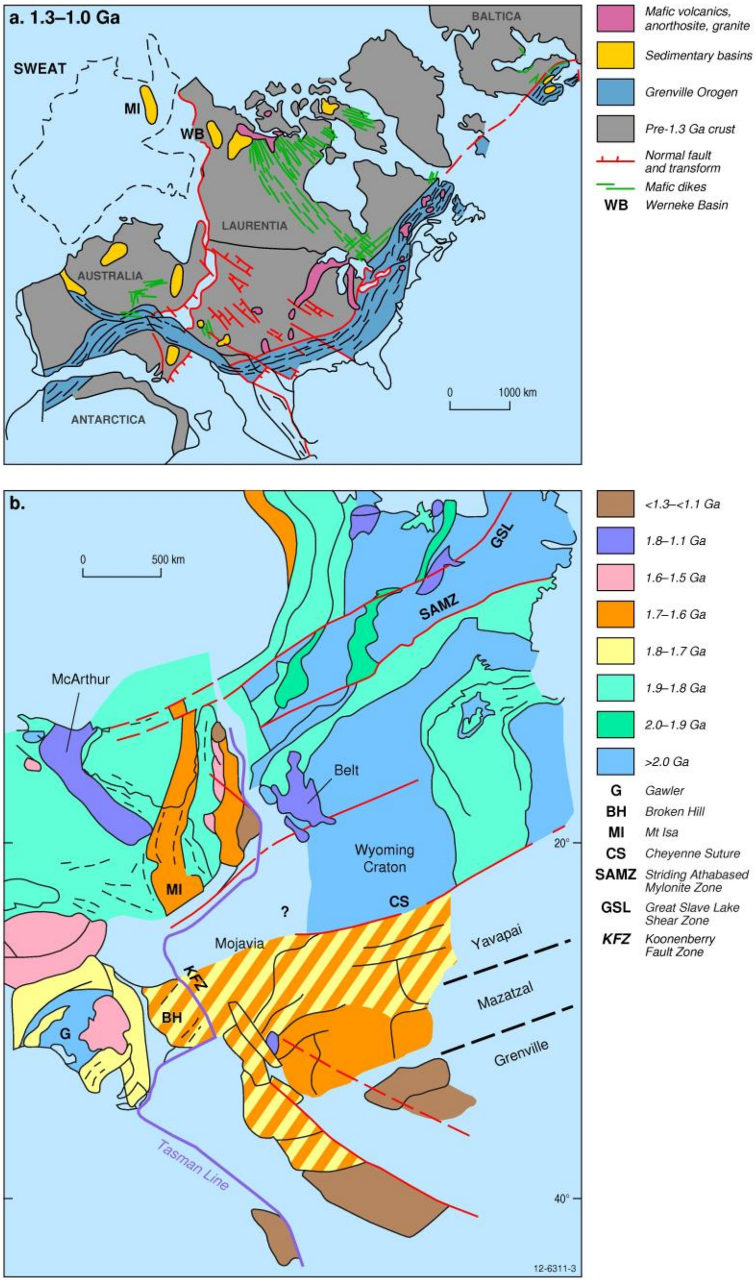


Figure 3. *(a) AUSWUS versus SWEAT reconstruction of Australian and Laurentian rifted margins for Neoproterozoic time. SWEAT restores Australia (dotted outline) and Mount Isa to much the same position opposite NW Canada as existed at the time of the Paleoproterozoic Nuna supercontinent. (b) More detailed AUSWUS reconstruction (Burrett and Berry, 2000) with Broken Hill Block juxtaposed against terranes of equivalent age and isotopic composition in southern Laurentia.*

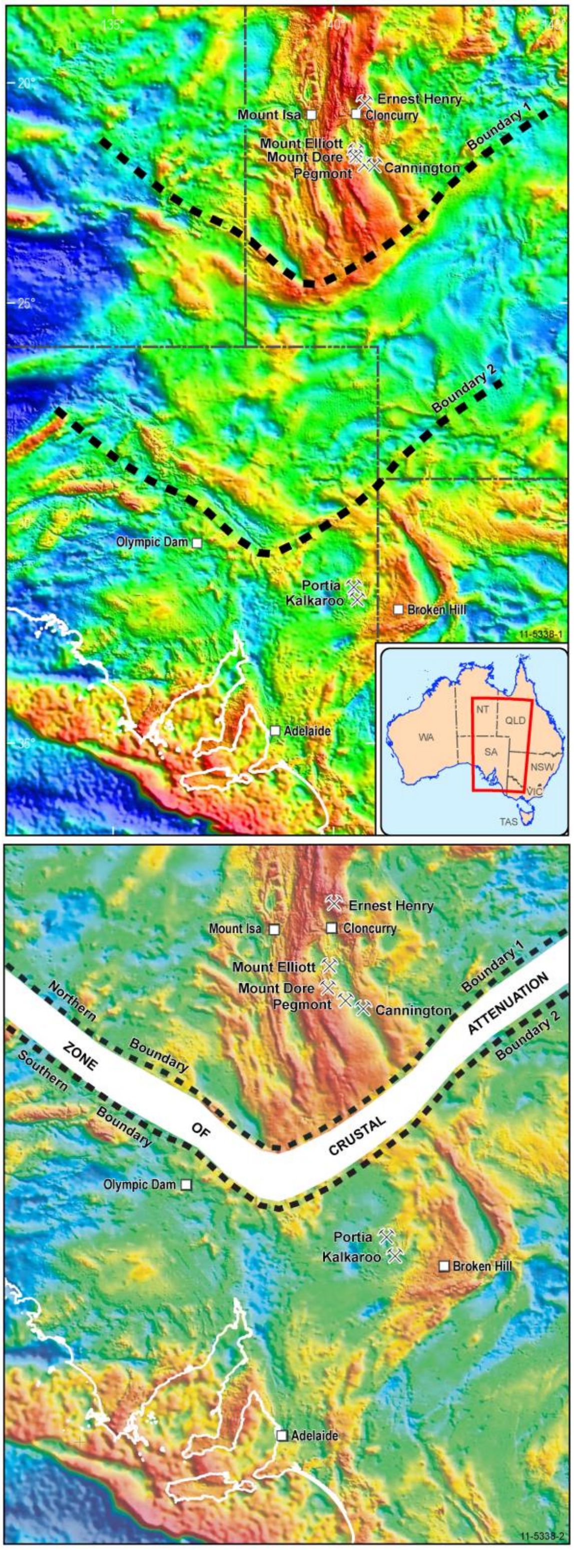


Figure 4. *(a) Uninterpreted gravity anomaly image with Mount Isa and Broken Hill in present-day configuration. (b) Gravity image with Broken Hill basement terrane restored to its pre-Rodinia breakup position opposite the Mount Isa region (after Henson et al., 2011). Note coincidence of Cloncurry-Cannington and Broken Hill gravity trends.*

Regional geology & tectonic setting

The Mount Isa region (Figures 1 & 5) combines an older crystalline basement (Kalkadoon-Leichhardt Block) affected by the ≥1840 Ma Paleoproterozoic Barramundi Orogeny with three variably deformed and vertically stacked superbasins ranging in age from 1800–1575 Ma (Leichhardt, Calvert and Isa superbasins). The Leichhardt Superbasin is best preserved in the Leichhardt River Fault Trough (Figure 1) whereas the other two superbasins are better exposed across the Lawn Hill Platform and neighbouring parts of the Western Fold Belt (western succession), and in the Eastern Fold Belt (eastern succession) on the eastern side of the Leichhardt-Kalkadoon Block (Figure 1).

Equivalents of the Kalkadoon-Leichhardt Block and Leichhardt Superbasin have yet to be identified in Broken Hill even though there are good geological and geophysical grounds for concluding that the two terranes were once continuous with each other (Figure 4b) and evolved in a common tectonic environment (Betts et al., 2011; Gibson et al., 2008; Giles et al., 2002; Henson et al., 2011). Orogenesis in both regions peaked around 1600–1585 Ma (Isa and Olary orogenies) and obscures an earlier history of syn-extensional magmatism, deformation and low pressure-high temperature metamorphism linked to basin formation and normal faulting at higher crustal levels (Conor and Preiss, 2008; Forbes et al., 2008; Gibson and Nutman, 2004; Gibson et al., 2008; Neumann et al., 2009a; Page et al., 2005).

Some researchers have also argued (Gibson et al., 2008; Holcombe et al., 1991; Passchier, 1986; Passchier and Williams, 1989) that basin evolution in the Mount Isa terrane was linked at depth to the formation of extensional shear zones best exposed east of the Kalkadoon-Leichhardt Block (Wonga Extensional Belt), inviting comparison with the North American Basin and Range Province where such linkages have been more comprehensively documented (Wernicke, 1985). Nevertheless, it is evident that such comparisons cannot be carried too far because the youngest extensional shear zones at Mount Isa formed no later than 1670 Ma (Gibson et al., 2008; Neumann et al., 2006) and thus relatively early in basin history. A further 70–80 Myr of predominantly deep water marine sedimentation followed, possibly linked to post-extensional thermal subsidence. This and other aspects of basin formation indicate that the Mount Isa terrane is not simply a deformed intra-continental rift or continental back-arc basin (Giles et al., 2002) but shares many similarities with present-day rifted continental margins and evolved almost to the point of sea-floor spreading. In the absence of any direct evidence for seafloor spreading in the Mount Isa region itself, rifting may have stepped further outboard and been re-established east of Georgetown (Baker et al., 2010) where continental breakup actually took place, possibly as late as 1650 Ma and no earlier than 1670 Ma (cf. Betts and Giles, 2006).

Basin history of Mount Isa region

The Leichhardt, Calvert and Isa superbasins each comprise several unconformity-bounded sedimentary packages or supersequences (Jackson et al., 2000; Southgate et al., 2000). These include both syn- and post-rift packages (Betts and Giles, 2006; Blake, 1987; Eriksson et al., 1993; O'Dea et al., 1997) although opinion remains divided about basin architecture and the kinematic framework in which successive

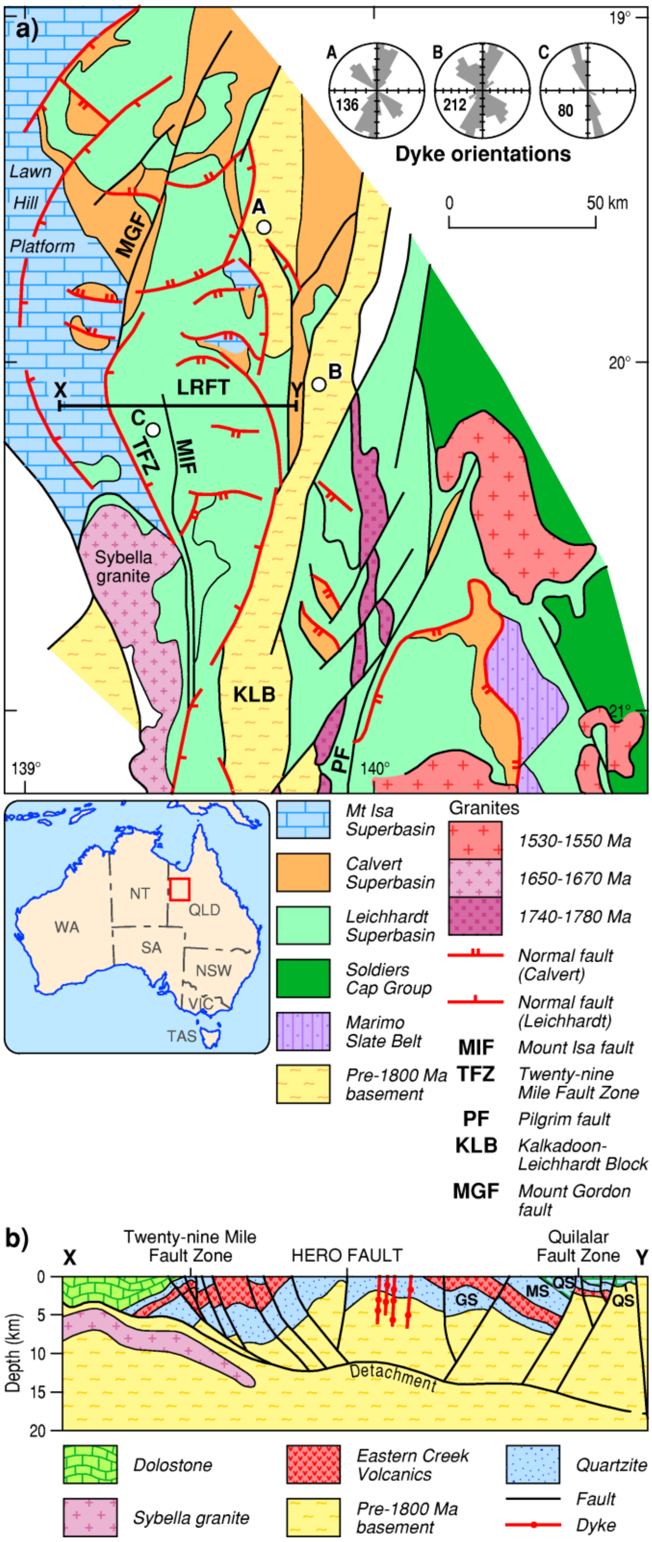


Figure 5: *Simplified geologic map and section for northern part of Leichhardt River Fault Trough (LRFT). Note switch in direction of stratal thickening into Quilalar and Twenty-nine Mile Fault zones at c. 1775 Ma, and parallelism between measured dike orientations (insets A, B and C) and normal fault trends in the LRFT and adjacent Kalkadoon-Leichhardt basement block. QS = Quilalar Supersequence (after Gibson et al., 2008).*

packages were deposited. Many of these same packages are recognised here (Figure 6) but with different conclusions drawn regarding basin evolution and tectonic history. Unlike some earlier studies, no definitive evidence was obtained for widespread basin inversion between deposition of the Leichhardt and Calvert superbasins (Betts, 1999; Betts, 2001). Instead, a major unconformity between successive extensional regimes is recognised across which there was a switch in the principal extensional direction from ENE- WSW to NE-SW (Figure 6). This switch brought about a major change in the pattern of sedimentation from c. 1730 Ma onward (Figure 6), and superimposed a differently oriented set of extensional structures on a pre-existing rift template (Leichhardt Superbasin). Deep seismic reflection profiles across Mount Isa support the case for a change in extensional direction between deposition of the Leichhardt and Calvert superbasins and show little evidence for significant basin inversion before c. 1640 Ma (Gibson et al., 2010; Queensland, 2011). Basin inversion at this time is further supported by a prominent 1640 Ma hairpin bend in the north Australia polar wander path (Idnurm, 2000) and corresponding change in sedimentation patterns (Southgate et al., 2000).

Further deformation and inversion of basin architecture occurred during crustal shortening and strike-slip faulting accompanying the polyphase 1600–1550 Ma Isa Orogeny but to different degrees on either side of the Kalkadoon-Leichhardt Block which trends N-S and subdivides the Mount Isa region into western and eastern successions (Figures 1 & 5). Eastern succession rocks preserve much less of the original basin architecture and have generally undergone deeper burial and more intense deformation than rocks of the same age farther west: peak metamorphism in these rocks occurred at c. 1585 Ma and ranges up to the amphibolite facies whereas greenschist to sub-greenschist facies conditions predominate in the western succession (Foster and Austin, 2008; Rubenach et al., 2008). Together, the eastern and western successions represent an oblique section through the crust whereby structures formed at mid-crustal depths (eastern succession) can be compared to structures formed at higher structural levels in the west.

Leichhardt Superbasin (1800–1750 Ma)

The Leichhardt Superbasin (Figure 6) developed between 1800–1750 Ma (Neumann et al., 2006) and is best known from the Leichhardt River Fault Trough (LRFT) and southern Lawn Hill Platform (Figure 5) where some 5–7 km of continental flood basalts (Eastern Creek Volcanics) and syn-rift sediments accumulated in an elongate, fault-bounded basin 50–80 km wide (Blake, 1987; Derrick, 1982; Eriksson et al., 1993; Jackson et al., 2000; Scott et al., 2000). Basin-bounding faults trend NNW and belong to a family of steep, mainly inward-dipping growth faults across which there has been appreciable vertical displacement resulting in half-graben formation (Gibson et al., 2008) and abrupt changes in sedimentary and volcanic thicknesses from the hanging to footwall (Figures 5, 7 and 8). Hangingwall displacements typically range from 100s of metres to a few kilometres (Figure 5) but despite such displacements, topographic relief appears to have been subdued with no evidence for the existence of deep water sedimentary basins. Rather, environmental conditions favoured the deposition of fluviatile to lacustrine sedimentary packages (Guide and Myally supersequences; Figure 6) in which cross- and trough-bedded quartzite and feldspathic sandstone are the dominant lithologies. Red beds with minor amounts of intercalated stromatolitic dolostone (Lochness Formation) commonly occur towards the top of the Myally Supersequence (Figure 6) and most likely represent local excursions into evaporitic or shallow marine conditions (Derrick, 1982; Jackson et al., 2000). Individual half-graben within the Leichhardt Superbasin have dimensions comparable to modern rift basins (Bosworth, 1992) and are up to 70 km long and 30–50 km wide (Figure 5).

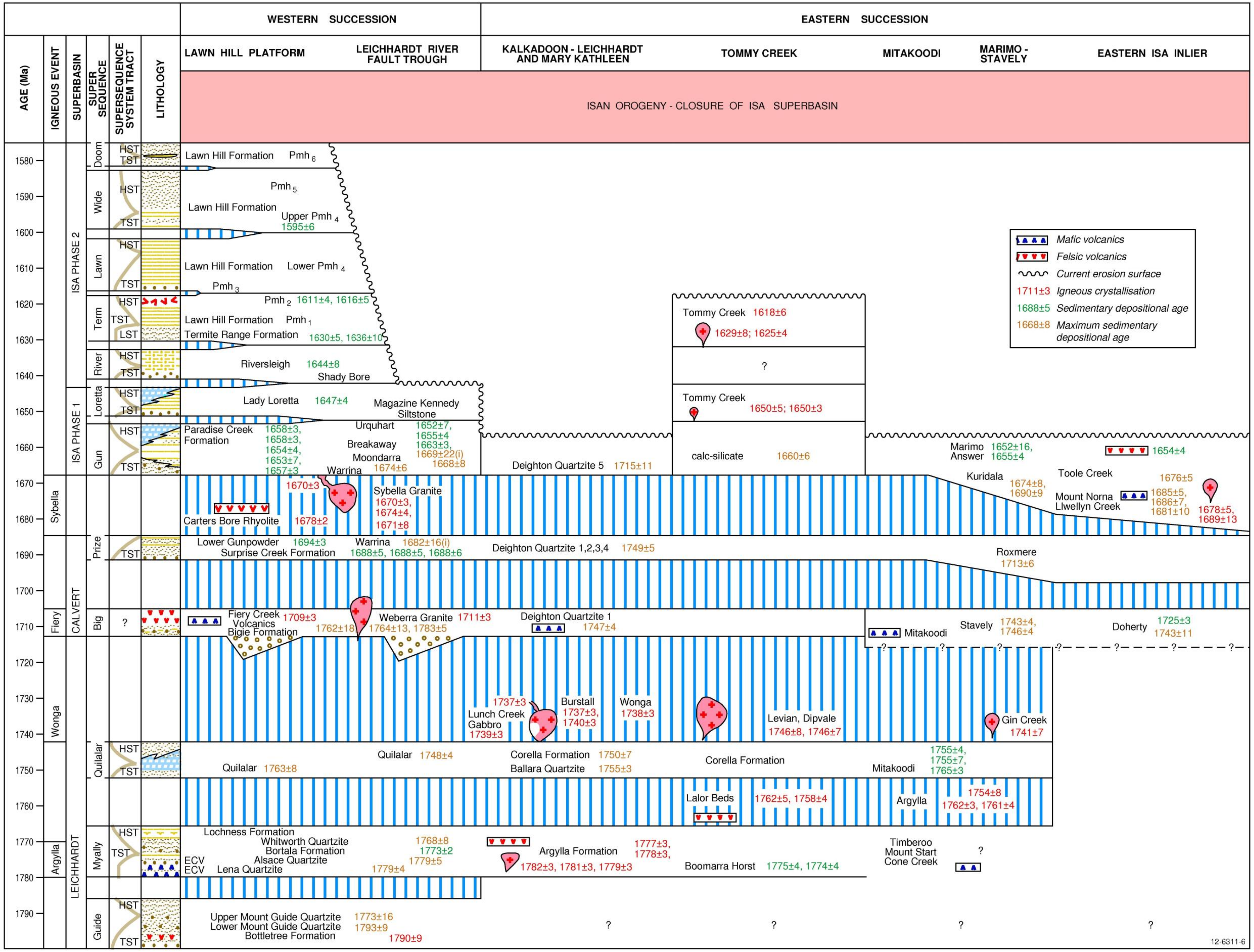


Figure 6: *Chronostratigraphy and interpreted kinematic history for Leichhardt, Calvert and lowermost part of Isa superbasins in Mount Isa region (after Neumann et al., 2006; 2009a; 2009b; Page et al., 2000).*

Basaltic rocks and interbedded siliciclastic sediments of the 1780–1775 Ma Eastern Creek Volcanics (Figure 6) thicken westwards in the LRFT (Bain et al., 1992; Gibson et al., 2008) and are not known to occur any farther west than the Twenty-nine Mile fault zone (Figure 5). The basalts were extruded under subaerial or shallow water conditions. Their inferred correlatives in the eastern succession are basaltic lava flows of the Marraba Volcanics which are similarly overlain by shallow water quartzite and sandstones (e.g., lower Mitakoodi Quartzite) and contain some layers of clastic sediment (Figure 6). A few interbeds of shallow marine stromatolitic dolostone have been observed within the Marraba Volcanics near its base although in most other respects the depositional environment in the eastern succession at this time does not appear to have been appreciably different to that in the western succession. Felsic volcanic rocks (Argylla Formation) with ages of 1760 and 1780 Ma (Neumann et al., 2009a; Page, 1983) at the base of the eastern succession have been widely interpreted as former ignimbrites (Blake, 1987) but have no obvious compositional equivalent in the Eastern Creek Volcanics farther west. Notwithstanding this important difference, both the Argylla Formation and older parts of the Leichhardt Superbasin (Guide Supersequence) have been extensively intruded by dolerite dikes (now metamorphosed) with orientations that match the inferred direction of extension in the Leichhardt Superbasin (Figure 5).

Deposition of the Myally Supersequence was followed (Figure 6) in the western succession by an episode of thermally-induced regional subsidence, leading to marine transgression and burial of the syn-rift sequences beneath a sheet-like cover of fluviatile-shallow marine sediments dominated by clean, well-sorted quartzite and well-bedded, stromatalitic limestones and redeposited calcareous sandstones (Quilalar Supersequence). The eastern equivalents of these rocks (Figure 6) are the Ballara Quartzite and platform carbonate sequences of the Corella Formation (Blake, 1987; Derrick et al., 1980). Detrital zircon ages and intrusion of this platform sequence by the 1740 Ma Burstall Granite (Page, 1983) constrain the age of this marine package to between c. 1755–1740 Ma (Figure 6).

Calvert Superbasin (1740–1670 Ma)

Onset of rifting and localised uplift in the Calvert Superbasin is marked in the western succession by a major regional unconformity, deposition of fanglomerates and coarse sandstones in fault-angle depressions and fluviatile environments (Bigie Formation), and a rejuvenation of bimodal magmatism (Figure 6), including extrusion of the 1710 Ma Fiery Creek Volcanics (Hutton and Sweet, 1982; Jackson et al., 2000) and intrusion of the 1710 Ma Weberra Granite (Neumann et al., 2006). This was followed by several cycles of upward-fining, mainly siliciclastic sedimentation (Prize Supersequence; Figure 6), during the course of which the depositional environment changed from near-shore to deltaic or shallow marine (Hutton and Sweet, 1982; Southgate et al., 2000). With further deepening of the sedimentary basin(s), increasingly greater amounts of thinly laminated carbonaceous shale or rhythmite were deposited. Stratal thickening of these sequences into E- or NE-trending growth faults points to a syn-rift origin for much of the Calvert Superbasin (Betts et al., 1998; Derrick, 1982; Gibson et al., 2008; O'Dea et al., 1997). Magmatic rocks emplaced during the later stages of rifting include the 1678 Ma Carters Bore Rhyolite and < 50 cm syn-sedimentary peperitic intrusions dated at c. 1690 Ma (Page et al., 2000a). These dates provide the best available age constraint on sedimentation in the Calvert Superbasin and are only marginally older than the 1670 Ma age obtained from the Sybella Granite (Neumann et al., 2006) which intrudes basement and/or the Eastern Creek Volcanics near the base of the underlying Leichhardt Superbasin (Figure 6).

Accompanying and/or immediately following the cessation of deposition in the Prize Supersequence (Figure 6), the main sedimentary depocentre shifted eastward into the region now occupied by the Soldiers Cap Group in the eastern succession. This group consists predominantly of metamorphosed deep water siliciclastic turbidites and intercalated carbonaceous sediments which have no direct lateral or temporal equivalent among the shallower water sedimentary facies preserved farther west in the LRFT (Figures 6 & 7). Rather, this sedimentary facies is restricted to the eastern succession where it has been intruded by basaltic dikes and sills, including variably metamorphosed 1685 Ma dolerite with highly evolved, Fe-enriched compositions (Baker et al., 2010). Compositionally, these mafic rocks resemble modern-day oceanic tholeiites or basalts extruded through thin sialic crust preceding continental breakup (Baker et al., 2010; Barberi et al., 1975; Sinton et al., 1983). Their magmatic age is identical to 1685 Ma detrital zircon ages obtained from their host rocks (Neumann et al., 2009b), indicating that sedimentation, crustal thinning and basaltic intrusion were all coeval in at least part of the Soldiers Cap Group (Figures 6 & 7). Turbidite deposition in Soldiers Cap Group is consequently viewed here as a response to the same syn-rift extensional processes that gave rise to accommodation space now preserved as Prize Supersequence deposits in the LRFT, despite the slightly younger age (Figure 6) and consequent stratigraphic position above preserved Prize Supersequence in the LRFT. The absence of a preserved temporal equivalent may indicate that parts of the Prize Supersequence have been removed through erosion at the break-up unconformity and now reside farther east in the Soldiers Cap Group (Figure 7).

Isa Superbasin (1670–1590 Ma)

The Isa Superbasin is best represented on the Lawn Hill Platform (Figure 5) where it comprises 8 km of rhythmically-bedded turbidites, carbonaceous shales and stromatolitic dolostone deposited in a shallow to deep water marine environment (Hutton and Sweet, 1982; Krassay et al., 2000). Farther south, the basal component of this supersequence comprises a transgressive package of fluviatile to shallow marine sandstones, siltstones and dolostones with subordinate amounts of black shale represented by the lower parts of the Gun Supersequence (Southgate et al., 2000). This transgressive package rests unconformably on rocks of the Calvert Superbasin and is widely considered to be of post-rift origin (e.g., Jackson et al., 2000). However, unlike the older Quilalar Supersequence with which it shares many similarities, this transgressive package also shows clear evidence of stratal thickening into the same E-W-trending structures that controlled deposition of the underlying Calvert Superbasin (Southgate et al., 2000). Either these structures continued to be active during the marine transgression or they were simply buried along with any remaining accommodation space during thermal subsidence and deposition of the fluviatile-shallow marine sequence. Possible correlatives of the Isa Superbasin in the eastern succession include thinly laminated carbonaceous slates and siltstones of the Marimo Slate Belt which, like its inferred western correlatives, lacks coeval igneous intrusions.

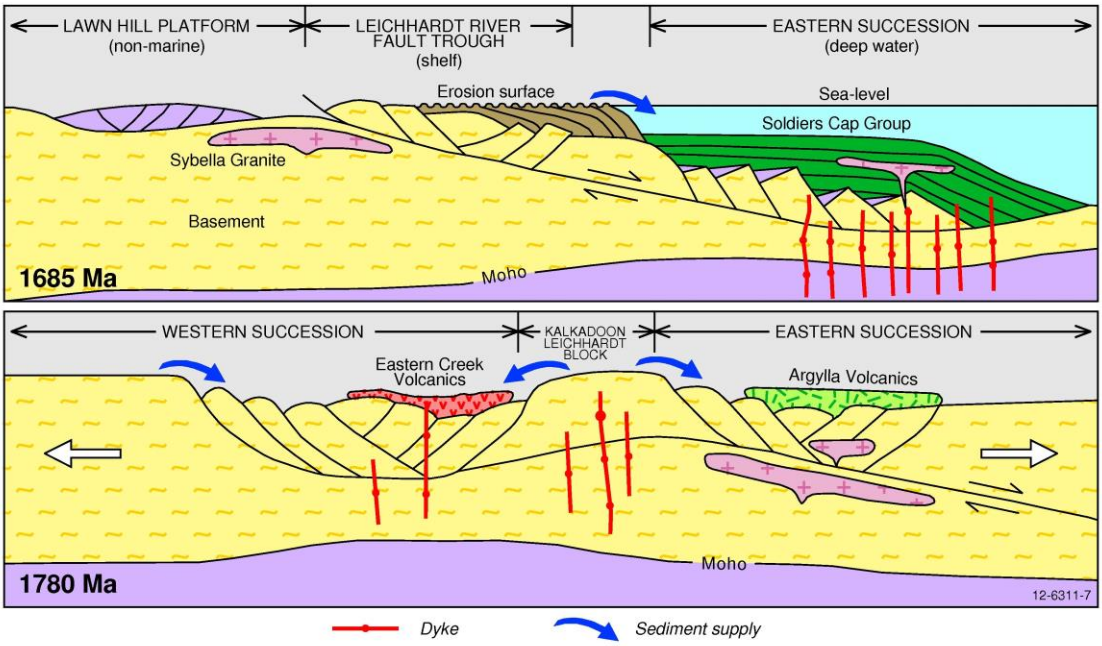


Figure 7: Generalised W-E crustal sections illustrating links between basin formation, magmatism and syn-extensional detachment faulting in Leichhardt (bottom) and Calvert superbasins (top). Note erosion and reworking of previously deposited platform and near-shore sequences (Prize Supersequence) to form deep water turbidites farther outboard (Soldiers Cap Group). Dolerite dikes are concentrated in region of greatest crustal thinning and deepest water sedimentation (after Gibson et al., 2012).

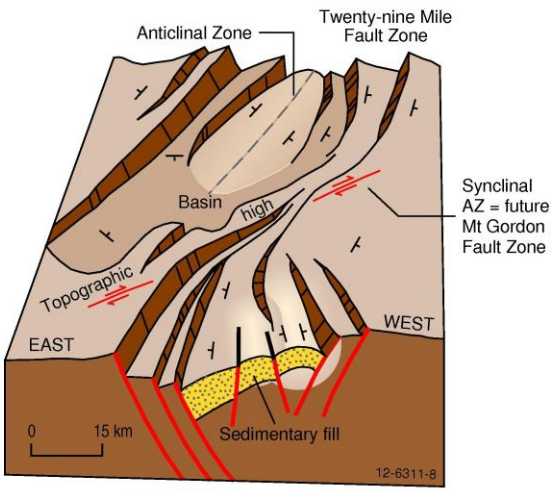


Figure 8: Schematic representation of basin architecture and fault geometry in the northern part of the Leichhardt River Fault Trough looking south. The future Mount Gordon Fault Zone formed along the accommodation zone (AZ) located between the two sub-basins (after Gibson et al., 2012).

Basin evolution and detachment faulting

Concomitant with initial basin evolution in the LRFT, mid-crustal extensional shear zones in the eastern succession (Figure 7) were intruded by bimodal magmatic rocks with ages ranging between 1740–1780 Ma (Gibson et al., 2008; Neumann et al., 2009a; Pearson et al., 1991).

These shear zones separate a locally exposed lower plate containing mylonitised 1780 Ma Argylla Formation from a brittle upper plate cut by normal faults that penetrate no higher than lowermost Corella Formation (Holcombe et al., 1991; Passchier, 1986). Footwall mylonites give a top-to-the-S or SW sense of shear (Pearson et al., 1991; Gibson et al., 2008) and are constrained by their magmatic host rocks to have formed no later than 1740 Ma and possibly as early as 1780 Ma (Neumann et al., 2009a). More importantly, these data indicate that the mylonites and their associated shear zones overlap in age with basaltic magmatism and basin formation at higher crustal levels in the Leichhardt Superbasin (Figure 7). A genetic as well as temporal relationship between half-graben formation, bimodal magmatism and development of these mid-crustal extensional detachments is indicated.

Half-graben formation, bimodal magmatism, and the formation of mid-crustal detachments beneath a brittle, extended upper plate are all features shared by other extensional terranes such as the North American Basin and Range Province (Wernicke, 1985). Particularly apt are comparisons with the Rio Grande Rift which shares a similar record of basaltic volcanism followed by fluviatile to lacustrine sedimentation in a narrow intracontinental rift (May and Russell, 1994). It serves as an excellent modern analogue for the Leichhardt Superbasin and, like the latter, comprises a series of half-graben bounded by normal faults that extend downward into a major detachment of extensional origin (Figure 8). Notwithstanding such striking similarities, there is no evidence that formation of the Leichhardt Superbasin was ever accompanied by uplift and the exhumation of metamorphic core complexes as was the case in the Basin and Range Province. Rather, the detachment and associated lower plate mylonites of the Leichhardt Superbasin (e.g., Double Crossing Metamorphics) remained buried until exhumed during a later phase of extension and/or by deformation accompanying the 1600 Ma Isa Orogeny.

By 1685 Ma, basin geometry in the Calvert Superbasin was well established, driven by NE-SW extension and accompanied in the eastern succession by intrusion of basaltic magmas (Figures 6 and 7) into deep marine basins filled by turbiditic sediments (Soldiers Cap Group) (Gibson et al., 2008). Farther west in the LRFT, near-shore, shallow water conditions persisted until arrested by a thermal perturbation at c. 1670 Ma accompanying intrusion and extensional unroofing of the Sybella Granite and its country rocks from mid-crustal depths (Gibson et al., 2008). Unroofing took place on an ENE-dipping detachment surface (Figure 7) that brought about erosion and reworking of rocks belonging to the Leichhardt Superbasin and older parts of the Calvert Superbasin, and their subsequent redeposition in half-graben elsewhere in the basin. Shear fabrics in the Sybella Granite and rotated tilt blocks in Calvert age rocks above the detachment on which unroofing took place further indicate that extension during this stage of basin evolution involved displacement of the upper plate towards the ENE (Gibson et al., 2008) and thus on a detachment that dipped oceanward in the same direction as overall deepening of the sedimentary basin (Figure 7). Less obvious is whether this detachment is the same (reactivated) structure that accommodated extension and normal faulting during formation the older Leichhardt Superbasin. Oceanward-dipping detachments such as these are thought to underlie all sedimentary basins formed in continental margin settings and are a predictable consequence of asymmetric crustal extension and basin development (Lister et al., 1991). The Calvert Superbasin would appear to be a case in point, leading us to conclude that by 1670 Ma basin geometry in the Mount Isa region had evolved beyond a simple intracontinental rift or Basin and Range-type setting into a fully-fledged back-arc basin in which the crust had become appreciably thinned and attenuated, possibly almost to the point of seafloor spreading. In keeping with this interpretation, basaltic rocks in the Leichhardt through to Calvert Superbasin (Eastern Creek Volcanics through Soldiers Cap Group) exhibit compositional changes consistent with extrusion through progressively thinner continental crust (Baker et al., 2010). Equally importantly, the Gun unconformity defining the base of the Isa Superbasin is markedly transgressive and bears a striking similarity to the continental breakup unconformities illustrated by Lister et al. (1991). This unconformity marked the onset of shallow marine conditions across much of the Mount Isa region and was followed by rapid deepening of the depositional environment with sedimentation thereafter dominated by open marine conditions and increasing deposition of turbidite sequences.

Implications for reconstructions of the Nuna and Rodinia supercontinents

Notwithstanding their obvious great difference in age, the Nuna and Rodinia supercontinents both assume that eastern Australia and western Laurentia represent conjugate rift margins (Betts et al., 2008, 2011; Dalziel, 1991; Karlstrom et al., 2001; Rogers and Santosh, 2009; Zhao et al., 2002). It follows that their constituent terranes were once contiguous and share a common geologic history. In this context, the 1800–1600 Ma history of intracontinental rifting and consequent rift margin formation outlined in this paper for Mount Isa and Broken Hill becomes important because the attendant events pre-date assembly of Rodinia and pertain only to the older Nuna supercontinent. This implies that the assumed longterm connectivity of 1800–1600 Ma orogenic belts between Australia and Laurentia inherent to the AUSWUS and SWEAT reconstructions of Rodinia is incorrect because the rocks in question are unlikely to have remained in their original pre-Rodinia configuration. Rather, following the breakup of Nuna, these rocks and their continental hosts would have dispersed before being reassembled in a different configuration during formation of Rodinia in the Neoproterozoic. A well constrained reconstruction of Rodinia based on matching events and orogenic belts of Grenville age need not work for older rocks such as those reported on here.

This is especially evident in the case of AUSWUS which provides a reasonable match between the Neoproterozoic rift basins of south-central Australia and the southern United States (Figure 3b) but positions the 1800–1600 Ma continental rift basins of eastern Australia, and Broken Hill in particular, along strike from more juvenile accreted terranes of near-identical age in southern Laurentia (Burrett and Berry, 2000; Karlstrom et al., 2001). As pointed out by Betts et al. (2008), the 1800–1600 Ma basins of eastern Australia are more analogous to the basins of interior North America and thus better accommodated in a pre-Rodinia SWEAT-like configuration (Figure 3a) that matches the rocks of Mount Isa against NW Canada (cf. Thorkelson et al., 2001). In this interpretation, the Mojave, Yavapai and Mazatzal terranes have no connection with Broken Hill (Figure 3) and lie much farther S with respect to Australia, occupying a position off the East Antarctic Shield where 1700 Ma eclogites and other collisional rocks have been reported (Goodge et al., 2002). These collisional rocks were interpreted to have formed through the same tectonic processes that accompanied terrane accretion in southern Laurentia and were originally continuous with terranes of the same age developed along the southern margin of the North Australian Craton. In effect, these terranes and their North American counterparts formed a broad continuous belt of 1700–1650 Ma accreted terranes passing from southern Laurentia through Antarctica (Mawsonland) into southern and central Australia. As with the basins of Paleo–Mesoproterozoic age north of the Cheyenne Suture in Laurentia (Figure 3b), the temporally equivalent rift basins in the Mount Isa and Broken Hill regions formed through extension in a back-arc position located above a north-dipping subduction zone (Betts et al., 2008, 2011; Giles et al., 2002). Subduction roll-back, followed by the accretion of continental ribbons and successive juvenile terranes and/or magmatic arcs, were identified as the major drivers of orogenesis along the respective southern continental margins (Barth et al., 2000; Betts et al., 2011; Betts et al., 2008; Karlstrom and Bowring, 1988).

Whether similar far-field stresses could have produced the basins of similar age in NW Canada is not entirely clear although it is interesting to note that the late Paleoproterozoic–early

Mesoproterozoic Wernecke Supergroup and Hornby Bay Group both developed on extended crystalline basement of similar age (≥ 1840 Ma) and magmatic character (MacLean and Cook, 2004; Thorkelson et al., 2005) to the Kalkadoon-Leichhardt Block of Mount Isa. As with Mount Isa, the Wernecke Basin (Figure 3a) also experienced basaltic magmatism at 1710 Ma (Fiery Creek vs. Bonnet Plume Intrusives) and orogenesis at 1600 Ma (Isa versus Racklan Orogeny). Further supporting a connection between the Paleoproterozoic sedimentary rocks of Mount Isa and NW Canada are strikingly similar detrital zircon (U-Pb) ages (Rainbird et al., 2007). Thorkelson et al. (2001) also suggested that the Quilalar Formation and Mary Kathleen Group at Mount Isa are sedimentary equivalents of basin fill in the Wernecke Basin although this makes no distinction between syn-and post-rift components and offers no explanation as to why the much thicker syn-rift sequences of the Leichhardt and Calvert superbasins are not more widely developed in western Canada. This may simply reflect the fact that much of the 1.8 Ga western edge of the North American craton lies buried beneath younger rocks of Late Neoproterozoic–early Paleozoic age (Cook et al., 2005) and is only occasionally sufficiently deeply exhumed to expose the underlying late Proterozoic–early Mesoproterozoic basins as in eastern Australia.

Recently published gravity images (Henson et al., 2011) indicate that the late Paleoproterozoic–early Mesoproterozoic sequences of Broken Hill and Mount Isa were not only originally continuous along strike (Figure 4) but formed part of a much more regionally extensive belt of similarly aged rocks that extended southward along the eastern margin of the Gawler Craton (upper Hutchison and Walleroo Groups) (Spzunar et al., 2011) into formerly adjacent parts of Antarctica (Peucat et al., 1999). This would imply that the rifted continental margins formed through the breakup of Nuna were oriented grossly N-S (present-day co-ordinates) and had a strike length of several thousand kilometres. Moreover, their orientation was almost orthogonal to the accreted terranes developed along the southern margins of Australia and Laurentia, ruling out any possibility that major Laurentian structures such as the Cheyenne Suture (Figure 3) originally extended into central Australia or has any correlative along the southern margin of the North Australian Craton (Gibson et al., 2008). Rather, the Laurentian terranes would appear to cut across the N-S trend of the Australian late Paleoproterozoic–Mesoproterozoic basins and possibly truncate them. The strike-length of these basins is such that any corresponding conjugate rift margin formed in western Canada at the time of Nuna breakup must be similarly well endowed in an impressive and regionally extensive set of late Paleoproterozoic–earliest Mesoproterozoic rift sequences over and above those currently known and exposed as inliers within the North American Cordillera.

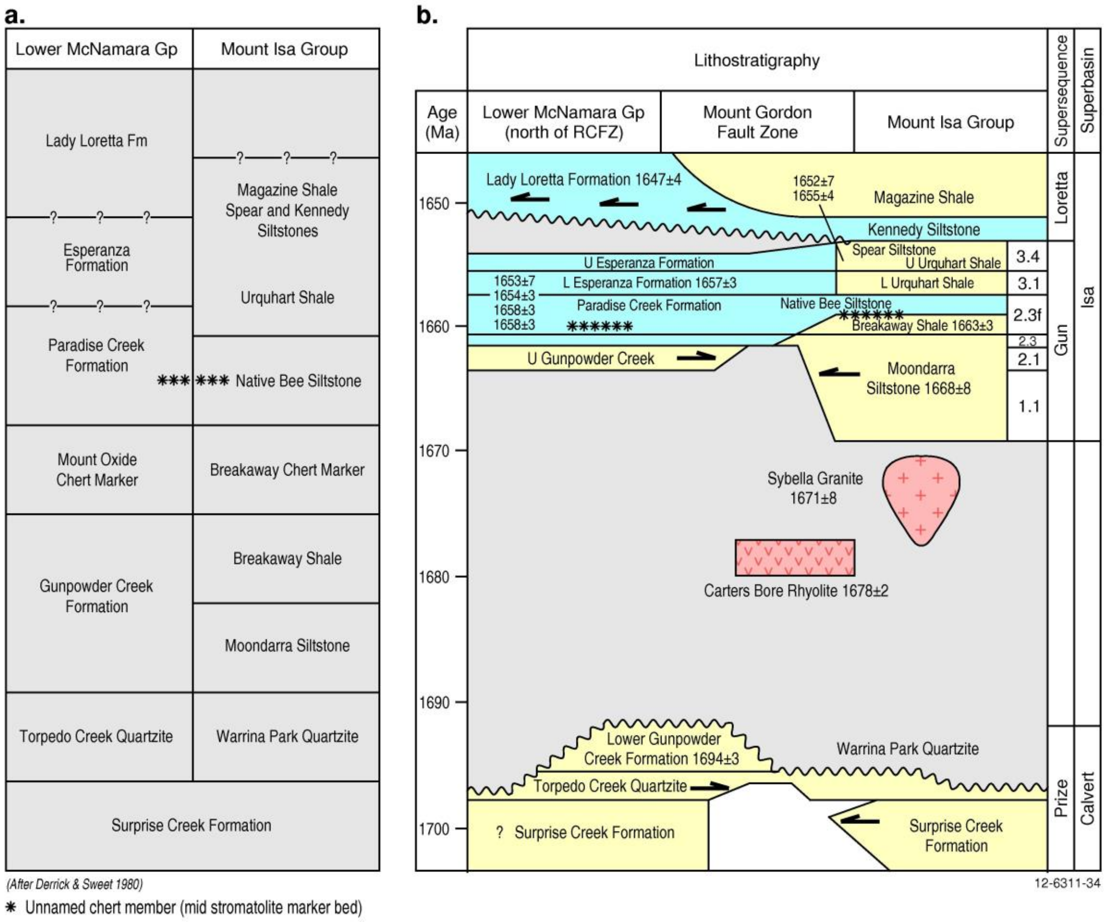


Figure 9: *(a) Correlation of lithostratigraphic units within the McNamara and Mount Isa groups (after Derrick and Sweet, 1980); (b) Alternative correlation of McNamara and Mount Isa groups based on sequence stratigraphy (after Southgate et al., 2000). The major transgressive surface and corresponding break in sedimentation between the lower and upper Gunpowder Formation equates to the Gun Unconformity. This same unconformity occurs within lowermost Moondarra Siltstone farther south in the Leichhardt River Fault Trough (see Figure 1).*

Day to Day Itinerary

A significant portion of the excursion deals with the examination and interpretation of outcrop geology and measured sections at various sites across the Mount Isa Inlier (Figure 2). Both sedimentary and magmatic rocks will be investigated during the excursion, along with a number of localities where basin architecture and fault geometries can be determined. Many of the localities and rock units to be visited have been sampled for geochronology and consequently have good ages attached to them (Figures 6 & 9) (Neumann et al., 2009a; Neumann et al., 2009b; Neumann et al., 2006; Page et al., 2000a).

Single-section logs at ca. 1:1000 scale (Figures 10 – 13) are supplied for several localities (Jackson et al., 2002; Southgate et al., 1999). These logs contain an outcrop-derived gamma-ray curve, grain size, lithology, sedimentary structure and lithostratigraphic information. The logs are useful as an aid to the interpretation of sedimentary facies, facies trends and stacking patterns, including subdivision of the sedimentary sequences into shallowing or deepening upward packages (sequence stratigraphy; see Figure 6). Logged sedimentary facies and sections from near-shore (western succession) to distal deep water (Soldiers Cap Group) depositional environments are included. By combining the information on sedimentary facies with other datasets on fault geometry, magmatic history and event timing, it is possible to arrive at a reconstruction of the geological evolution of the Mount Isa terrane that accords with the tectonic interpretation and basin evolutionary framework presented here (Figures 6 & 7).

The identification of isochronous surfaces (sequences boundaries, transgressive surfaces, maximum flooding surfaces) can be used to erect an internally consistent and mutually reinforcing stratigraphy. These surfaces enable more robust correlation of stratigraphy within the Mount Isa and McNamara groups (cf. Figures 9a & 9b) and can be extrapolated from the western succession eastward into other parts of the Mount Isa terrane. They also serve as a constraint on basin evolution by providing insights and clues into tectonic activity, including subsidence and subsidence rates, and the operation and proximity of growth faults and rift shoulders.

Measured sections include:

Figure 10: *Measured section/stratigraphic column for Gunpowder Magazine locality (Jackson et al., 2002). Bulk of section is through uppermost Surprise Creek Formation (Calvert Superbasin) and lower part of Isa Superbasin.*

Figure 11: *Stratigraphic column for Barr Hole section in Torpedo Creek (Southgate et al., 1999). Stratigraphy is same as in Gunpowder Magazine section.*

Figure 12: *Measured section for Esperanza Waterhole along strike from both the Barr Hole (Southgate et al., 1999) and Hole-in-Wall sections. The Gun Unconformity is well exposed in this section as is lowermost part of the Isa Superbasin.*

Figure 13: *Crocodile Waterhole and condensed section through Calvert Superbasin into lower units of overlying Isa Superbasin (Southgate et al., 1999). Conglomerates (Bigie Formation) at the base of the Calvert Superbasin are channelized and deeply incised into rocks of the underlying Leichhardt Superbasin.*

Friday, June 16
4.00pm - 6.00pm. Gunpowder Magazine section (Figure 10) and deeply incised unconformity between the Surprise Creek Formation and underlying Myally Subgroup. Evening talk: Introduction and overview of stratigraphy, regional geology & geodynamic model for Mount Isa region. O'night, Capricorn Mine.

Saturday, June 17
8.30am - 5.30pm. Barr Hole section (Figure 11): Lochness Formation and unconformity with Surprise Creek Formation. Thrust faults, basin inversion and mineralisation in Barr Hole and Hole-in-Wall sections (local duplex structure). Comparison of McNamara Group and Esperanza sections (Figure 12) on either side of the north-dipping Mammoth Fault. More general discussion on the importance of growth faulting in Mount Isa region and the application of geochronology to regional correlation problems. O'night, Capricorn Mine.

Sunday, June 18
8.30am – 5.30pm. Crocodile Waterhole (Figure 13): Eastern Creek Volcanics through Myally Subgroup into Calvert Superbasin; Bigie and Surprise Creek Formations; lowermost Isa Superbasin. East along Barkly Highway into eastern succession rocks and platform equivalents of post-rift Quilalar Formation (Ballara-Corella Formations); syn-rift magmatic rocks (Argylla Formation); Wonga Extensional Belt in Green Creek, including mylonitised, lower plate syn-extensional granites and deformed upper plate metasedimentary sequences (Ballara-Corella Formations). O'night, Cloncurry

Monday, June 19
8.30am – 5.00pm. Bouma sequences in deep water turbidite facies (Soldiers Cap Group) of equivalent age to the Surprise Creek Formation/Prize Superquence farther west on the Lawn Hill Platform, and intruded metadolerites; Answer Slate and carbonate rocks of Corella and Staveley Formations; brecciated and metasomatised components of the Staveley Formation. Mylonitised contact between Answer Slate and Staveley Formation. O'night Cloncurry.

Tuesday, June 20
8:30 – 5:00pm. Rocks of Mitakoodi anticlinorium and culmination in Leichhardt Superbasin.. Railway cutting exposing shallow water sediments of the Mitakoodi Quartzite and intercalated Wakefield Metabasalt; pillow basalts in the Marabba Metabasalt and variably deformed silicified sediments making up the Overhang Jaspilite (Mylonite); West along highway taking in basement gneisses of Kalkadoon-Leichhardt block. O'night, Mt Isa

Wednesday, June 21
8.00 - 5:30 Extensional shear fabrics in Sybella Granite along May Downs road and (if time permits) strongly lineated granites in Mica Creek section; growth faults, basin inversion structures and stratigraphy of Mount Isa Group in Lake Moondarra section. Comparison of stratigraphy and structure of Mount Isa and McNamara groups. O'night, Mt Isa.

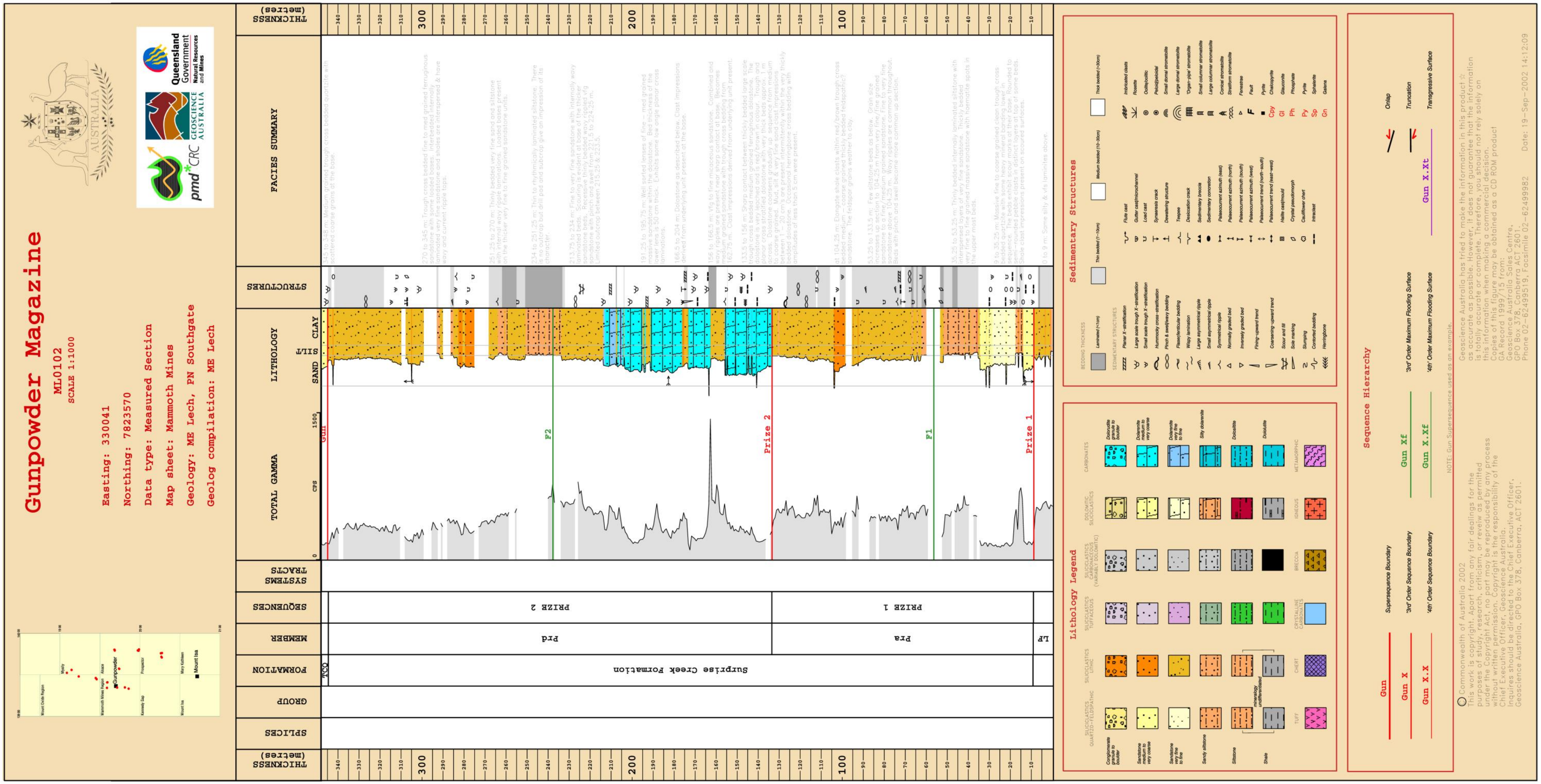


Figure 10: *Measured section/stratigraphic column for Gunpowder Magazine locality (Jackson et al., 2002). Bulk of section is through uppermost Surprise Creek Formation (Calvert Superbasin) and lower part of Isa Superbasin.*

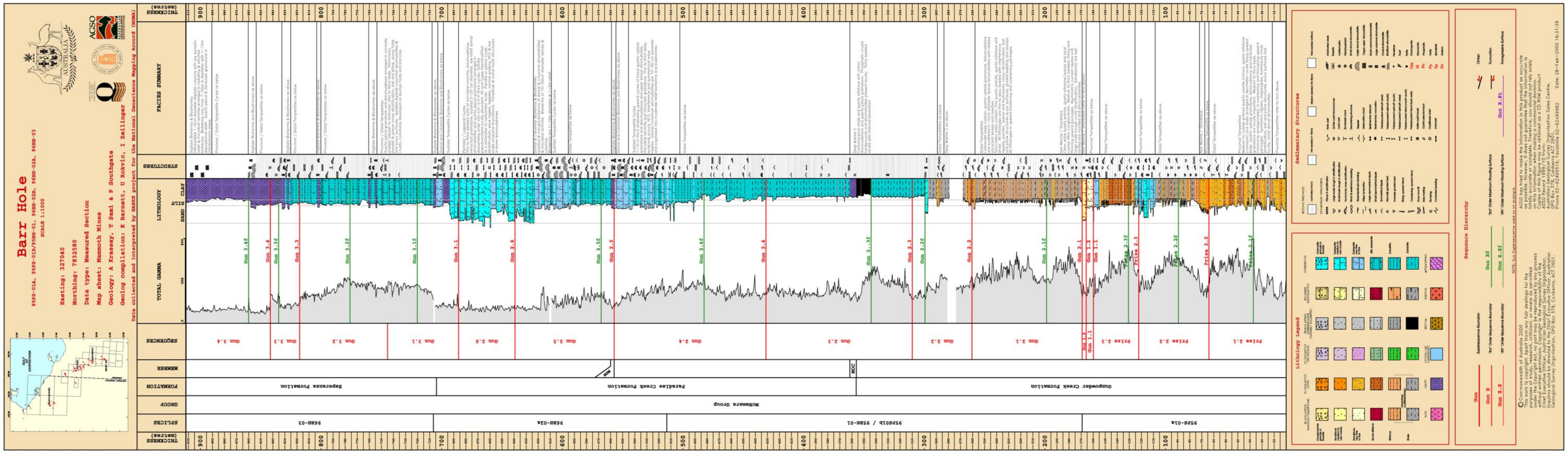


Figure 11: *Stratigraphic column for Barr Hole section in Torpedo Creek (Southgate et al., 1999). Stratigraphy is same as in Gunpowder Magazine section.*

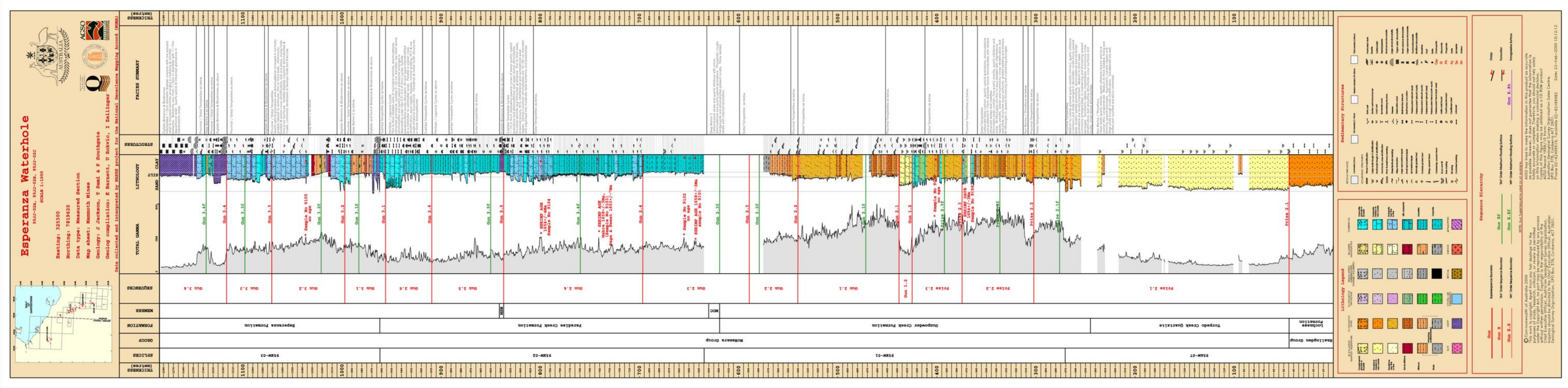


__Figure 12:__ Measured section for Esperanza Waterhole along strike from both the Barr Hole (Southgate et al., 1999) and Hole-in-Wall sections. The Gun Unconformity is well exposed in this section as is lowermost part of the Isa Superbasin.

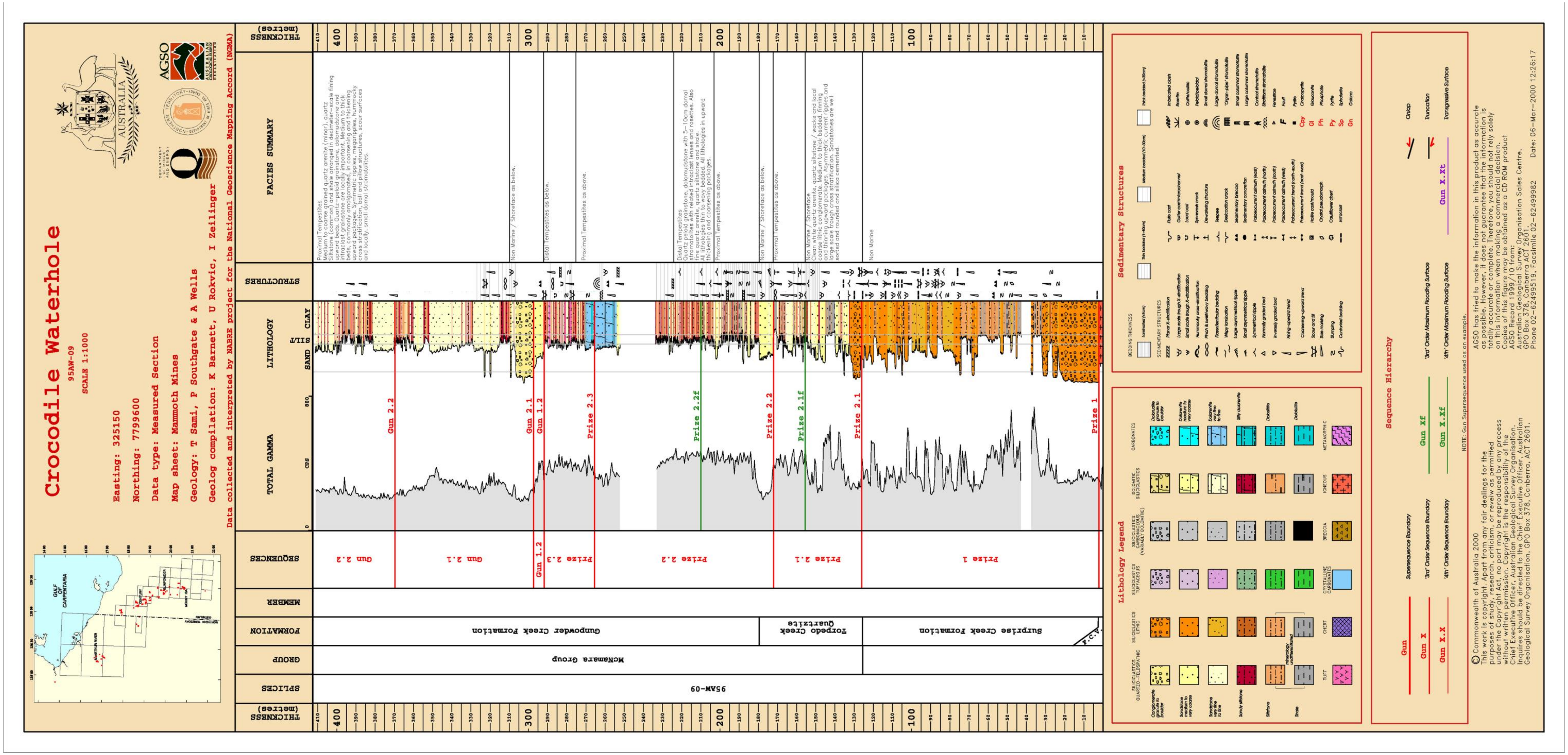


Figure 13: *Crocodile Waterhole and condensed section through Calvert Superbasin into lower units of overlying Isa Superbasin (Southgate et al., 1999). Conglomerates (Bigie Formation) at the base of the Calvert Superbasin are channelized and deeply incised into rocks of the underlying Leichhardt Superbasin.*

Localities, measured sections and outcrop geology

Day 1 – Magazine Section, Gunpowder Mine

Locality 1: Contact between Leichhardt and Calvert superbasins

This section (Figure 10) begins in the Calvert Superbasin, the lower part of which comprises conglomerates and sedimentary breccias belonging to Surprise Creek Formation. This formation rests unconformably on highly resistant white weathering feldspathic quartz arenites (Whitworth Quartzite) mapped as part of the Myally Subgroup in the Leichhardt Superbasin (Figure 14). The eroded surface between these two superbasins shows considerable topographic relief with pebble to boulder size conglomerates and sedimentary breccias filling channels and valleys in the underlying and deeply incised Whitworth Quartzite.

These conglomerates and breccias pass upward into cross-bedded, fluviatile sandstones and red-beds, and form part of a sequence ranging in thickness from a few 10s of metres up to several hundred metres (Surprise Creek Formation).

This sequence is in turn overlain by a white quartzite (Prc), also identified as part of the Surprise Creek Formation. This quartzite was deposited in a braided fluviatile to fluvial plain environment (Southgate et al., 2000). The measured section (Figure 10) commences in this fluviatile unit. Like many other rocks in this locality, this quartzite has a sharp erosional base and is heavily fractured and veined by reef quartz. It is overlain by thin-bedded siltstone and shale marking a rapid deepening of the sedimentary environment. These siltstones and shale are superseded by black-weathering ferruginous, cross-bedded dolostone (Figure 10) deposited in shallow water, possibly as a shoreline facies that was in part sourced from a carbonate reef.

Above this carbonate facies and nearer the top of the measured section (Figure 10) is the Gun unconformity (Southgate et al., 2000), a regionally significant transgressive surface that has now been recognised across the entire western succession. Some 20 Myr of missing rock record is inferred across this surface (Jackson et al., 2000; Southgate et al., 2000). The sedimentary succession (Figure 10) lying below this surface ranges in age from ca. 1695-1690 Ma and includes Surprise Creek Formation and lowermost Gunpowder Creek Formation (Prize Supersequence) whereas sediments above the unconformity at this locality are dated at between ca. 1670 Ma and 1655 Ma and encompasses the upper Gunpowder Creek, Paradise Creek and Esperanza formations (Jackson et al., 2005).

The very top of the measured section comprises white quartzite previously mapped as part of the McNamara Group (Torpedo Quartzite). It shares many of the characteristics of unit Prc and may be the same quartzite repeated across an east-directed, layer-parallel thrust. Alternatively, it may be a stratigraphically younger quartzitic unit. In this case, it is clearly younger than the ca.1655 Ma age obtained from the underlying sediments. Detrital zircons extracted from this unit along strike to the north (Figure 15) have ages ranging back to the Archean (Neumann et al., 2009b) but encompasses significant populations (peaks) of younger grains consistent with erosion of the ≥ 1840 Ma Kalkadoon-Leichhardt basement and underlying Leichhardt Superbasin (1800 -1750 Ma).

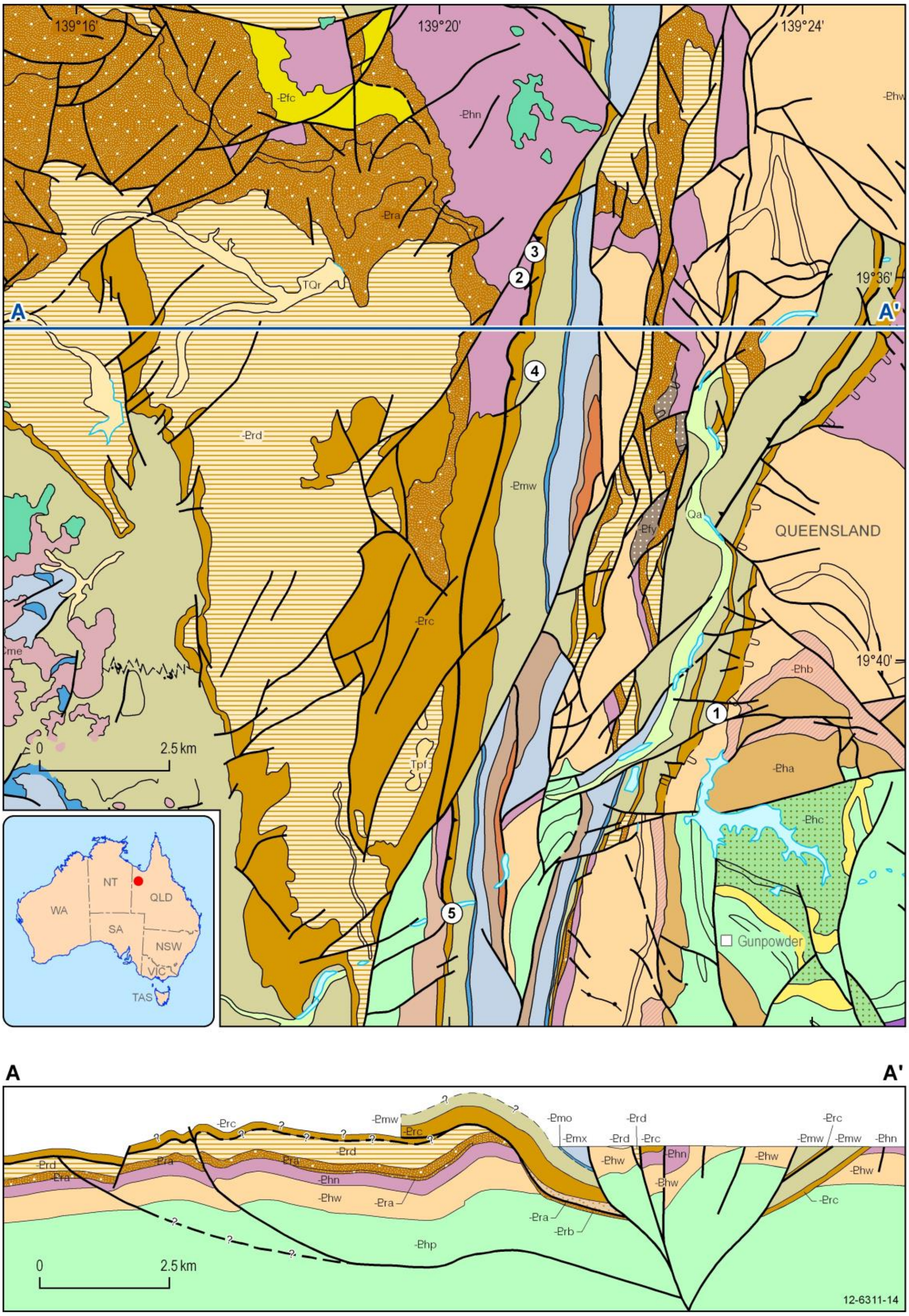


Figure 14: *Geological map and structural cross-section of region around Gunpowder Creek and Mount Gordon Mine.*

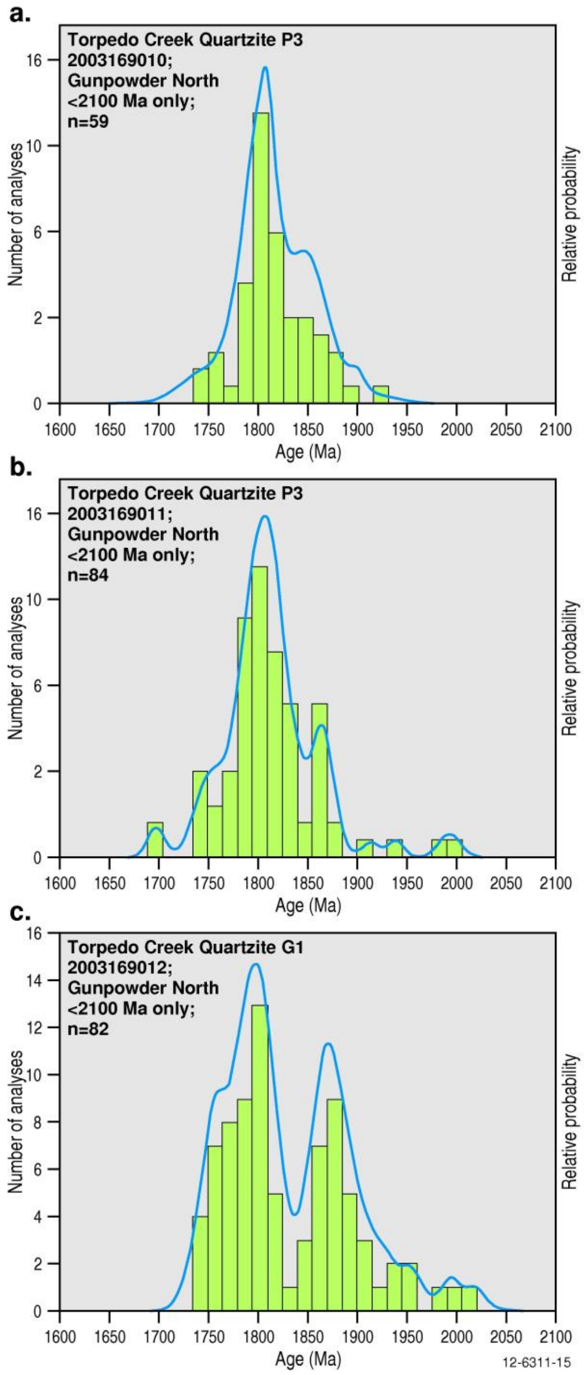


Figure 15: *Detrital zircon age spectra for three samples of quartzite mapped as Torpedo Creek Quartzite at base of Isa Superbasin (Neumann et al., 2009b).*

This quartzite was deposited under shallow water conditions (former beach sand) and forms part of the Isa Superbasin. Along with other quartzites in the immediate area, it has been mistakenly correlated with a similar looking white quartzite farther west in Torpedo Creek. The latter was originally included in the McNamara Group but has since been shown (Jackson et al., 2005) to be of equivalent age to the Surprise Creek Formation and for this reason has been reassigned to the Calvert Superbasin (Prize Supersequence).

Day 2 – Barr Hole section to Esperanza Waterhole

Depart Gunpowder Mine and head westward along gravel road to Mount Oxide (Figure 2), taking first right-hand turn onto road to Barr Hole Station after crossing Torpedo Creek at ford. After leaving the Mount Oxide road, the track recrosses Torpedo Creek before climbing steeply up to the skyline and a ridge formed of east-dipping white quartzite. The road affords excellent views back across Gunpowder Creek Formation and the ridge-forming quartzite shown on maps as Torpedo Quartzite. Beyond the ridge is a more subdued topography underlain by the same rock units observed yesterday in the Gunpowder Magazine section. Locally, creeks have cut down through rocks of the Isa and Calvert Superbasin to reveal rocks of the underlying Leichhardt Superbasin (Figure 14).

Locality 2: Unconformity between upper Leichhardt Superbasin (Lochness Formation) and Calvert Superbasin

The Whitworth Quartzite is not exposed at this locality and the Leichhardt Superbasin is instead represented by red-beds of the younger Lochness Formation (Figure 6). This unit dips moderately westward and, as elsewhere in the Mount Isa region, is dominantly made up of fine- to medium-grained, red-weathering hematite-cemented sandstone and siltstone. These characteristics are in keeping with earlier suggestions that this formation was deposited under sub-aerial to very shallow water conditions in an arid to semi-arid desert environment (Jackson et al., 2000). A shallow water origin for Lochness Formation at this location is indicated by the ubiquitous development of ripple marks on bedding surfaces (Figure 16).

Overlying Lochness Formation is a thin sequence of more gently dipping pebble conglomerates and grits representing the lowermost part of the Calvert Superbasin (cf Magazine section; Figure 10). This sequence passes upward through siltstone and sandstone into white quartzite dipping gently to the west, and forms part of a near-continuous clastic package that thins northward where it onlaps onto the eroded surface of the underlying Lochness Formation (Figure 14). This quartzite and associated coarse clastic rocks form part of Surprise Creek Formation.

The white quartzite at this locality is unit Pra which lies stratigraphically below unit Prc as shown on published 1:100 000 scale geological maps (Figure 14). Despite superficial similarities, this quartzite is not the same unit making up the ridge on the eastern skyline from which it is separated by an east-dipping thrust fault (Barr Hole Thrust) located along the western edge of the ridge. Quartzite west of the thrust has the same shallow westward dip as the rest of the Calvert Superbasin units whereas quartzite east of the ridge dips steeply eastwards and lies in the hangingwall of the thrust fault. This thrust fault formed during east-west shortening (D2) and is one of several east-dipping structures that disrupt stratigraphy in this area. The Barr Hole Thrust can be traced southward along strike into the Hole-in-Wall section where steeply dipping white quartzite (Prc) is again juxtaposed against more shallowly dipping rocks of the Calvert Superbasin and below which the Lochness Formation is again exposed.

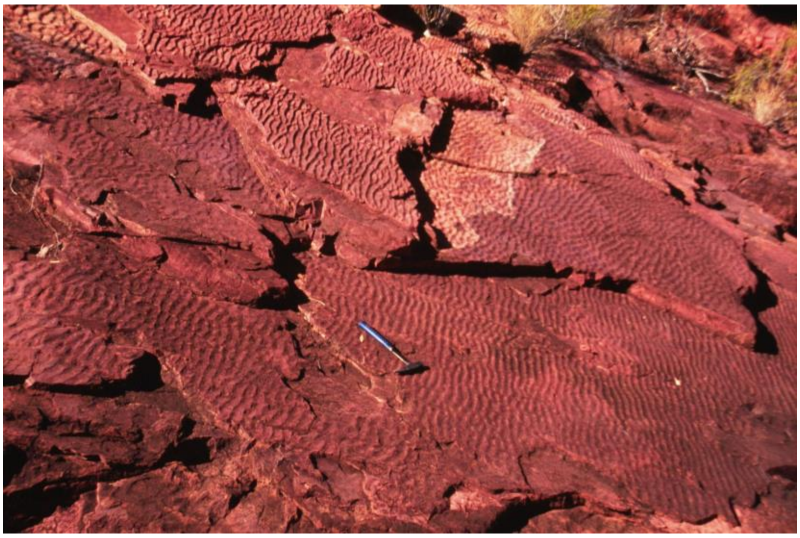


Figure 16: *Redbeds (former mud-flats) in Lochness Formation.*

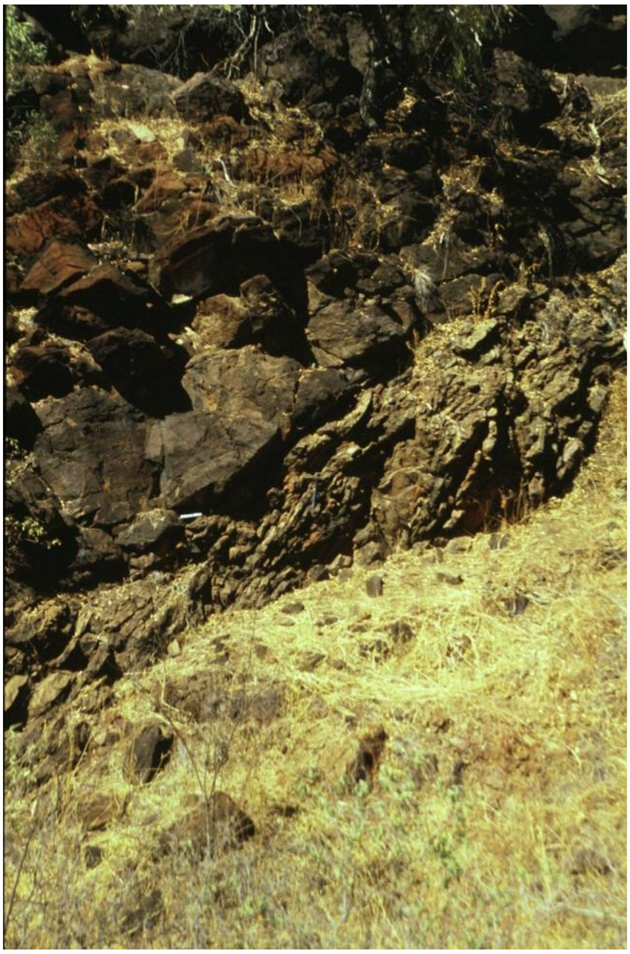


Figure 17: *East-dipping thrust contact between black-weathering gritty dolostone in hangingwall and thin-bedded sandstone and siltstone in footwall. Footwall rocks are deformed into series of variably plunging folds consistent with oblique reverse dip-slip on fault. Hangingwall and footwall rocks have both been mapped as part of the Gunpowder Creek Formation.*

Locality 3: Lower Calvert Superbasin (Surprise Creek Formation) at Barr Hole (Torpedo Creek Section)

The quartzite exposed in the waterfall at this locality (Figure 14) dips steeply east and is bounded on its western side by the Barr Hole Thrust. Although designated Torpedo Creek Quartzite (Figure 10) after the creek in which it is exposed, this is the same quartzite unit identified here and elsewhere in the district as unit Prc (Prize Supersequence). The quartzite has been erroneously assigned to the McNamara Group instead of Surprise Creek Formation where it rightly belongs. This is the same quartzite previously visited at locality 1, and will not be examined further here. It is enough to observe that Torpedo Creek Quartzite at this locality grades upward into several hundred metres of well bedded sandstones and siltstones (Gunpowder Creek Formation) before passing into black shale (Mt Oxide Chert) and dolostone (Paradise Creek Formation).

Some of the sandstones exhibit hummocky cross-stratification, indicating deposition in water depths that did not exceed storm-wave base (≤ 150-200 m). This is significantly greater than the shallow water depths in which the Lochness Formation and Torpedo Creek Quartzite were deposited and points to a progressive deepening of the depositional environment up section. Increased amounts of stromatolitic dolostone at higher stratigraphic levels (Paradise Creek Formation) support this interpretation and provide compelling evidence for a depositional environment that was by now fully marine.

A series of normal faults with throws of several metres cuts through these rocks and locally disrupts stratigraphy. A 10-20 cm thick silicic dyke, colloquially known as a pinkite, intrudes the dolostone unit just above the contact with the underlying black shale (Mount Oxide Chert).

Locality 4: Basin inversion structures (Hole-in-Wall Creek)

This short creek section exposes the same stratigraphic sequence observed at locality 3 but has undergone greater amounts of folding and thrusting as a result of basin inversion. At least two major episodes of folding and basin inversion are recorded in this creek section: an earlier episode related to north-south shortening (D1) and a second episode of basin inversion related to east-west shortening accompanying the Isan Orogeny (D2). D2 structures predominate and include both layer-parallel and oblique-slip thrust faults. These same structures are also present at Barr Hole (Locality 3) but because of their layer-parallel nature have previously gone unrecognised. Other than minor brecciation of the host rock along their traces, there is often little other evidence of their presence, particularly where the thrust faults occur within well bedded and lithologically homogeneous units. Late strike-slip faulting is also evident in a few places.

D2 oblique-slip thrust faults are generally located at the base of more competent dolostone units (Figure 17) which have been thrust eastward over a footwall of thin-bedded sandstones and siltstones in which variably plunging folds are developed (Figure 17). Fold axes seldom exceed 45°, except for one locality where the folds plunge vertically. These more steeply plunging folds point to a component of strike-slip faulting that accompanied or followed initial basin inversion. This is consistent with the observation that the regionally significant and nearby Mt Gordon Fault was reactivated in a strike-slip sense during the later stages of deformation associated with the Isan Orogeny.

Elsewhere along the creek, these same sandstones and siltstones are host to isolated anticlines that sole out into bedding-parallel detachments and seldom extend laterally and vertically along their axial planes for more than a few metres. Footwall mineralisation (Cu, Mn) is preserved locally in these rocks as are rare duplex structures in which the degree of bedding-parallel shortening in beds no more than 30 cm thick can exceed 20 metres!

Locality 5: Esperanza Waterhole and Gun unconformity

Unlike other localities to the north, the creek section at Esperanza Waterhole (Figure 14) is structurally undisturbed and devoid of any obvious thrust fault or inversion structure. It exposes a near complete and continuous section through the lower McNamara Group (Figure 12), commencing with unit Prc (but previously mapped as Torpedo Creek Quartzite) and deepening up section through sandstone and siltstone into black, gritty ferruginous dolostones in which mounded stromatolites are widely developed (lower Gunpowder Creek Formation). Gritty, dolomitic sandstone immediately overlying the stromatolitic sediments contains metre-scale cross-bedding consistent with deposition of this unit in a high energy beach or shallow marine environment. Its upper surface is the Gun unconformity (Figure 18).

A 20-30 cm-thick pinkite intruded into siltstone (Figure 19) just below the dolostone contact has been dated at ca. 1694 ± 3 Ma (Jackson et al., 2005), thereby providing a minimum depositional age for not only its siltstone host but the underlying quartzite (Prc). This quartzite and the other lower McNamara Group rocks at Esperanza waterhole are evidently no different in age to the Surprise Creek Formation and as such form part of the Calvert rather than Isa Superbasin (Figure 6).

Resting disconformably on the dolostone, but in sharp contact with them, is a upward-deepening sequence of thin-bedded siltstones and sandstones (Upper Gunpowder Creek Formation). The Gun unconformity at the base of this sequence marks the onset of a major marine transgression across the region (Figure 18). Bedding above and below the unconformity is parallel to the contact, but other than the abrupt change to deeper water sedimentary facies across this surface, there is little else in outcrop to suggest that this unconformity is of more than local significance.

As in the Barr Hole section, the sequence of thin-bedded sandstones and siltstones is overlain up section by black shale (unexposed) and dolostone (Paradise Creek Formation). A 1658 Ma age obtained from a 10cm-thick pinkite intruded into lowermost Paradise Creek Formation (Page et al., 2000a) constrains this part of the stratigraphy to be 20 Myr younger than rocks lying below the unconformity.

The rest of Paradise Creek Formation (Figure 12) is made up of dolostone with occasional horizons of stromatolitic rock and “cauliflower” chert. The latter are thought to be a replacement product of gypsum formed under hypersaline conditions in a peritidal or shallow-water, evaporitic environment. At the top of the section are spectacularly developed digitate stromatolites whose growth failed to keep pace with regional subsidence so that these organisms were ultimately drowned.

Figure 18: *Gun unconformity (broken yellow line) between siltstone-dominated upper Gunpowder Creek Formation and cross-beddded, dolomitic, gritty sandstone in lowermost Gunpowder Creek Formation*.

Figure 19: *Felsite (pinkite) interpreted here as a peperite unit intruded into wet, poorly consolidated thin-bedded sandstone and siltstone (Gunpowder Creek Formation). Note sharp base to pinkite and angular fragments of this lithology embedded in overlying host siltstone.*

Day 3 − Crocodile Waterhole, Kalkadoon-Leichhardt Block, Wonga Extensional Belt

Locality 6: Leichhardt through Calvert to Isa Superbasin (Crocodile Waterhole)

From Gunpowder Mine (Figure 2), follow the road south as far as the white cattle grid marking the start of the track into Crocodile Waterhole (right turn off road). The track first passes over a plain underlain by red basaltic soils derived from weathering of the 1780-1775 Ma Eastern Creek Volcanics before heading into a region of low hills where the first outcrops of this unit are encountered. Fresh exposures of Eastern Creek Volcanics can be found in the dry creek bed beyond the first cattle gate and before the first major waterhole (Crocodile Waterhole).

Basaltic rocks in these outcrops are typically massive or less commonly weakly foliated, and green in colour reflecting metamorphism up to the greenschist facies (chlorite ± epidote). Individual flows are not always evident although most of the sequence is demonstrably extrusive in origin, being interbedded with fluviatile-lacustrine sediments. Some flows are vesicular, particularly towards their tops. Other flows are brecciated or exhibit pillow structure consistent with extrusion into water. Quartz arenites (e.g. Lena Quartzite) and other interflow sedimentary rocks, including coarse-grained Fe-rich volcanogenic sandstones, occur throughout the volcanic pile. The basalts range in composition from alkaline through to tholeiitic and in this respect are not dissimilar to other basaltic large igneous provinces (LIPs) associated with continental rifting.

Overlying the Eastern Creek Volcanics (Figure 6) is a thick sequence of fluviatile to shallow marine sediments making up the Alsace Quartzite and Whitworth Quartzite (both in Myally Subgroup). Detrital zircon ages obtained from these two formations and other sedimentary units in the older Eastern Creek Volcanics are shown in Figure 20. Trough and cross-bedded quartzite is the dominant lithology in the Alsace and Whitworth formations and in some outcrops passes laterally and vertically into pebble beds or gritty sandstone. Fine to medium sandstones and siltstones also occur but red-beds, as developed elsewhere towards the top of the Leichhardt Superbasin, are missing or were never deposited. Instead, the Whitworth Quartzite is directly overlain by boulder conglomerates of the Bigie Formation (Calvert Superbasin; Figure 13) without any intervening Lochness Formation. Detrital zircons extracted from a sample of this conglomerate (Figure 21) yield an age spectrum consistent with derivation of this rock from the underlying Leichhardt Superbasin (cf Figures 20 & 21).

The Bigie Formation (Figure 13) is overlain by a sandstone- carbonate sequence that bears much similarity to the rocks exposed at Esperanza Waterhole (Gunpowder Creek Formation; Figure 12). In keeping with this interpretation, the carbonate rocks are intruded by pinkite that gives an identical 1693 ± 5 Ma zircon age (within error) to peperite emplaced into siltstone beneath the Gun unconformity at Esperanza Waterhole (Lambeck et al., 2012).

Detrital zircon ages from this younger package are not dissimilar to those from Torpedo Creek Quartzite farther north (Figures 21b & 21c).

Capping this sequence at Crocodile Waterhole is a 2m-thick pebble conglomerate (Figure 13). It is of equivalent age to the Torpedo Creek Quartzite and is immediately followed by an upward deepening sedimentary sequence that marks the onset of transgression in this particular part of Mount Isa. The Gun unconformity is located at the top of this capping conglomerate.

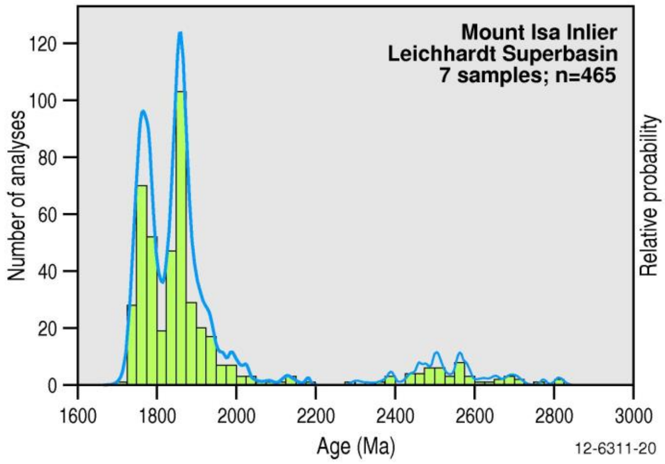


Figure 20: *Detrital zircon age spectra for seven sedimentary rocks in Leichhardt Superbasin. Note prominent peaks at ca. 1780-1760 Ma and 1860-1840 Ma consistent with a source region in both the 1780-1760 Ma Argylla Formation and 1860-1840 Ma granites of the Kalkadoon-Leichhardt block.*

transgression in this particular part of Mount Isa. The Gun unconformity is located at the top of this capping conglomerate.

Locality 7: Post-rift Ballara Quartzite, Barkly Highway

Return to Gunpowder-Mount Isa road and continue southward all the way to Mount Isa. Turn left into Marion Street and follow the Barkly Highway as far as the first prominent outcrops of white-weathering quartzite in cliffs overlooking the highway (Figure 2). The cliffs are made up of Ballara Quartzite, widely interpreted as an age equivalent of the Quilalar Formation which, along with the Corella Formation, is thought to form a post-rift transgressive package (sag phase) that once blanketed the whole region. The Ballara Quartzite has a maximum depositional age of ca. 1750 Ma age (Figure 6), based in part upon detrital zircon age patterns (Figure 22).

Locality 8: Syn-rift silicic magmatism (Argylla Formation) in Leichhardt Superbasin

The Ballara Quartzite at this locality (Figure 2) is underlain by a massive, mostly purplish pink to purplish grey silicic volcanic or hyperbyssal rock identified as the Argylla Formation. This magmatic rock has A-type characteristics and carries abundant phenocrysts of pink K feldspar. No contact with the overlying quartzite has been observed but is inferred to be of a concordant nature as might be expected if the younger quartzite had been deposited on the underlying magmatic rock.

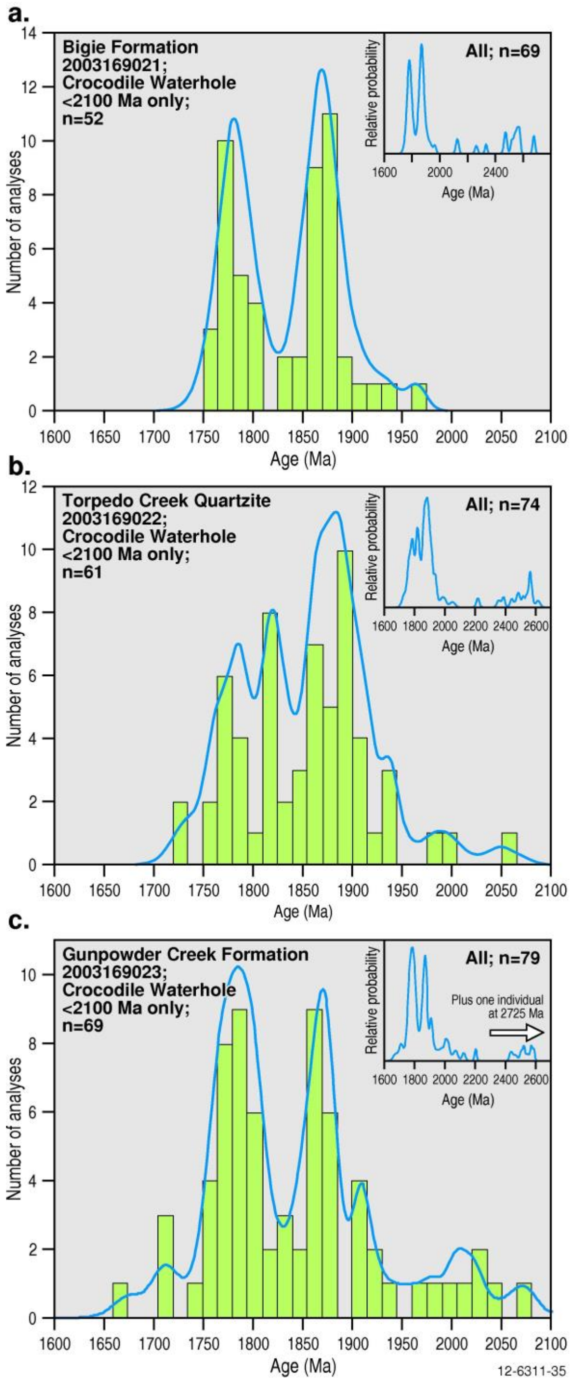


Figure 21: *Dominant peaks in detrital zircon age spectra for successively younger rock units at Crocodile Waterhole. (a) basal conglomerate at base of Calvert Superbasin (Bigie Formation); (b) "Torpedo Creek Quartzite" and (c) upper Gunpowder Creek Formation. Main peaks in each sample are the same peaks recoded in sediments of the underlying Leichhardt Superbasin. Insets show full age spectrum of all detrital grains in each sample.*

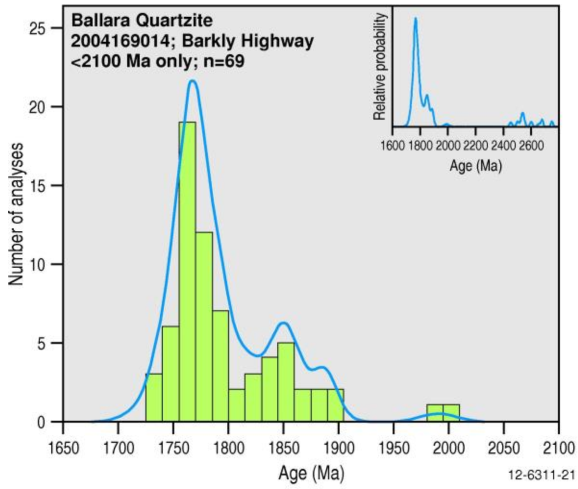


Figure 22: *Detrital zircon age spectrum for Ballara Quartzite, Barkly Highway*

Other than a crude banding developed locally, the Argylla Formation is unfoliated and lacks any structural features suggestive of magmatic flow. It could be interpreted as a sill or flow although the former seems more likely for a rock having the composition of rhyolite. In either event, the Argylla Formation was emplaced prior to deposition of the Ballara Quartzite. Towards its top, the Argylla Formation contains occasional xenoliths of sedimentary rock of a type not observed in the overlying sequence.

A 1778 ± 3 Ma age has been obtained from Argylla Formation at this locality (Neumann et al., 2009a). This age is identical within error to a ca. 1778 Ma tuffaceous layer contained within Bortala Formation in the Myally Subgroup farther west (Figure 6), supporting the notion that magmatism associated with development of the Leichhardt Superbasin was strongly bimodal as is expected of rocks formed in an extensional tectonic environment.

The Ballara Quartzite passes upward into thin-bedded sandstones and siltstones that appear to be in part dolomitic and belong to the Corella Formation (Figure 6).

Locality 9: Granitic rocks of Greens Creek (Wonga Extensional Belt)

Bimodal intrusive rocks making up the regionally extensive Wonga Batholith were emplaced into the Mary Kathleen Fold Belt between 1780 and 1740 Ma. This batholith and its mainly metasedimentary host rocks underwent tight, upright folding from 1585-1550 Ma, resulting in the exposure of different crustal depths through both the batholith and the extensional terrane into which the granitic rocks were intruded. Both upper and lower plates of this extensional terrane are exposed along Greens Creek. The detachment surface separating these two plates typically occurs within highly strained Ballara or Argylla Formation and has itself been locally intruded by granite and dolerite (Figure 23), the majority of which have been intensely deformed and/or mylonitised. Lower plate rocks have been uniformly metamorphosed under low P-high T amphibolite facies conditions whereas those in the upper plate range down to much lower grades.

Large pavements in Greens Creek (Figure 2) afford excellent exposures through lower plate intrusive rocks along the eastern upright limb of the Rosebud Syncline (Figure 23a). Lower plate granitic phases, including coarse biotite-hornblende granite intruded by aplite dykes, were emplaced contemporaneously with extension and commonly exhibit a variably developed gneissosity or mylonitic fabric in which a conspicuous stretching lineation is sometimes developed. A 1738 ± 3 Ma age has been obtained from the more weakly deformed biotite-hornblende granite host (Neumann et al., 2009a).

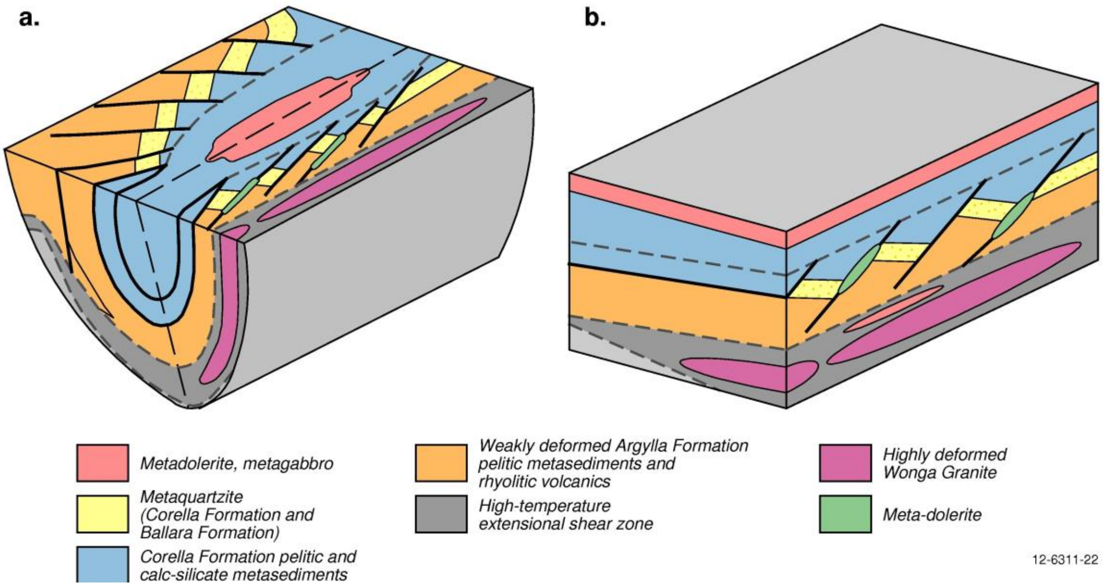


Figure 23: *(a) Schematic representation of folded rock units and stratigraphy in upper and lower plates separated by detachment surface in Rosebud Syncline; (b) Rosebud stratigraphy restored to pre-folding configuration. Note doleritic dykes intruded along normal faults.*

Figure 24: *Raft of strongly mylonitised 1780 Ma hornblende-biotite granite and intruded amphibolite dyke hosted by less strongly deformed 1740 Ma granite in which mylonitic fabrics are only weakly developed.*

Figure 25: *Corella Formation in which calc-silicate layers are conspicuously cut by two fabrics: a D2 crenulation cleavage trending NNE (clockwise wrt bedding) and a D3 spaced cleavage (anticlockwise wrt bedding) that overprints and crenulates the former. Less obvious is an earlier layer-parallel fabric thought to have developed during extension; it is locally accompanied by tight folding.*

Mylonitic fabrics are also widely developed in rafts of country rock that include 1780 Ma Argylla Formation and an even older deformed granite from which an identical 1780 Ma age has been obtained (Neumann et al., 2009). In a few places, mylonitisation has been accompanied by albitisation such that the granitic rocks have undergone a conspicuous bleaching along foliation planes.

An amphibolite dyke intruded into this older granitic gneiss is similarly mylonitised (Figure 24) and likely belongs to the same suite of basaltic dykes that served as feeder pipes to the Marabba Volcanics farther east. Significantly, these dykes and their granitic host rocks must have been intruded contemporaneously with normal faulting, basin formation and sedimentation at higher crustal levels in the Leichhardt Superbasin farther west because they share a common age (Gibson et al., 2008).

Locality 10: Upper plate rocks in Wonga Extensional Belt

This short section commences in Argylla Formation before passing upward into highly strained Ballara Quartzite which at this locality marks the location of the detachment surface between the two crustal plates. Calc-silicate rocks in the Corella Formation lying immediately above the quartzite are similarly highly strained but the amount of extensional strain rapidly diminishes up section and mylonitic fabrics are not especially well developed more than 50 metres into the Corella Formation. Instead, the more obvious feature in outcrop is compositional layering in which graded beds and facing directions are well preserved.

Structural fabrics of at least three generations (Figure 25)
are developed in these rocks: (1) a subvertical, spaced to weakly developed crenulation cleavage which overprints all other fabrics and trends north-south; (Milligan et al.) a steep, locally pervasive NNE-trending schistosity or crenulation cleavage related to D2 east-west shortening, and (3) a poorly preserved older fabric that appears to comprise two components which together seem to form an S-C fabric. This older fabric is tightly folded and interpreted here to be an extensional fabric developed in upper plate rocks during top-to-the-south shearing accompanying regional extension (see Figure 23).

As in other areas, extensional deformation appears to have been accompanied by metasomatism and the circulation of saline fluids as evidenced by the widespread occurrence of scapolite in many rocks, including metamorphosed dolerite dykes that locally intrude Corella Formation.

As in other areas, extensional deformation appears to have been accompanied by metasomatism and the circulation of saline fluids as evidenced by the widespread occurrence of scapolite in many rocks, including metamorphosed dolerite dykes that locally intrude Corella Formation.

Day 4 — Soldiers Cap Group, Staveley Formation and Answer Slate

The Soldiers Cap Group is one of the most dominant units in the eastern part of the Mount Isa region. Some of the best exposures occur in the Snake Creek area to the south-east of Cloncurry (Figure 26). Variably metamorphosed quartzofeldspathic psammite and pelite comprise most of the lowermost unit in the Soldiers Cap Group (Llewellyn Creek Formation). These rocks originally formed part of a turbidite succession and are locally host to sills of metamorphosed dolerite and gabbro. Overlying the Llewellyn Creek Formation is a 3000 metre-thick, upward-fining succession of quartzite and psammopelitic rocks (Mount Norna Quartzite), also intruded by mafic sills. The uppermost formation is a sequence of metabasalt and metadolerite intercalated with quartzite, pelitic schist, carbonaceous siltstone and ironstone (Toole Creek Volcanics).

The maximum depositional age of the Llewellyn Creek Formation is 1681 ± 10 Ma and that of the overlying Mount Norna Quartzite is 1685 ± 5 Ma (Figure 28) (Neumann, Gibson & Southgate, 2009). The age of the uppermost unit in the Soldiers Cap Group, the Toole Creek Volcanics, is constrained by a maximum depositional age on sandstone (Figure 28) and on a cherty tuff to about 1655–1660 Ma Ma (Carson et al., 2008; Page & Sun, 1998).

Mafic rocks in all three units, including the amphibolite and metadolerite sills as well as lavas of the Toole Creek Volcanics, are typically highly evolved, high Fe-tholeiites containing 11–20% $Fe_2 0_3$. Their compositions are consistent with emplacement into an extensional environment or a region underlain by thinned and highly attenuated continental crust (Baker, 2010 #937).

The structural and metamorphic history of the Soldiers Cap Group is best known from the Snake Creek area (Looseveld, 1989; 1992; Rubenach & Barker, 1998; Mares, 1998). Dominating structure in this area is the Snake Creek Anticline whose outline is delineated by the ridge-forming Mount Norna Quartzite whereas the Llewellyn Creek Formation forms the core, and the main closure plunging steeply to the north.

The Snake Creek Anticline is generally regarded as being a regional D_2 structure, but its axial trace curves clockwise to the north so that it parallels a series of roughly east-trending folds outlined by the stratigraphy in the Toole Creek Volcanics. This is interpreted as being due to refolding by subsequent events. The dominant foliation in the Snake Creek area is strongly penetrative and could easily be mistaken as S_1. Rare F_1 folds and an S_1 foliation overprinted by the dominant foliation provide evidence for the latter being S_2, but the best evidence is micro-structural with S_1 preserved as inclusion trails in porphyroblasts and in their strain shadows. Multiple sets of crenulations have been related to D_3, D_4 and D_5 events. However, based on micro-structural analysis of porphyroblasts, Mares (1998) identified shallowly dipping fabrics that he interpreted as due to gravitational collapse between the main shortening events, thus recognising seven deformation events.

Metamorphic isograds mapped by Rubenach & Barker (1998) and Foster & Rubenach (2006) transect the stratigraphy and range from a garnet zone through andalusite–staurolite into sillimanite and finally K-feldspar–sillimanite zones (Figure 27). The sillimanite and K-feldspar–sillimanite zones are syn-D_2 metamorphism, whereas the garnet and andalusite–staurolite zones relate to multiple growth episodes. Rubenach & Barker also recognised a syn-D_2 andalusite–kyanite isograd.

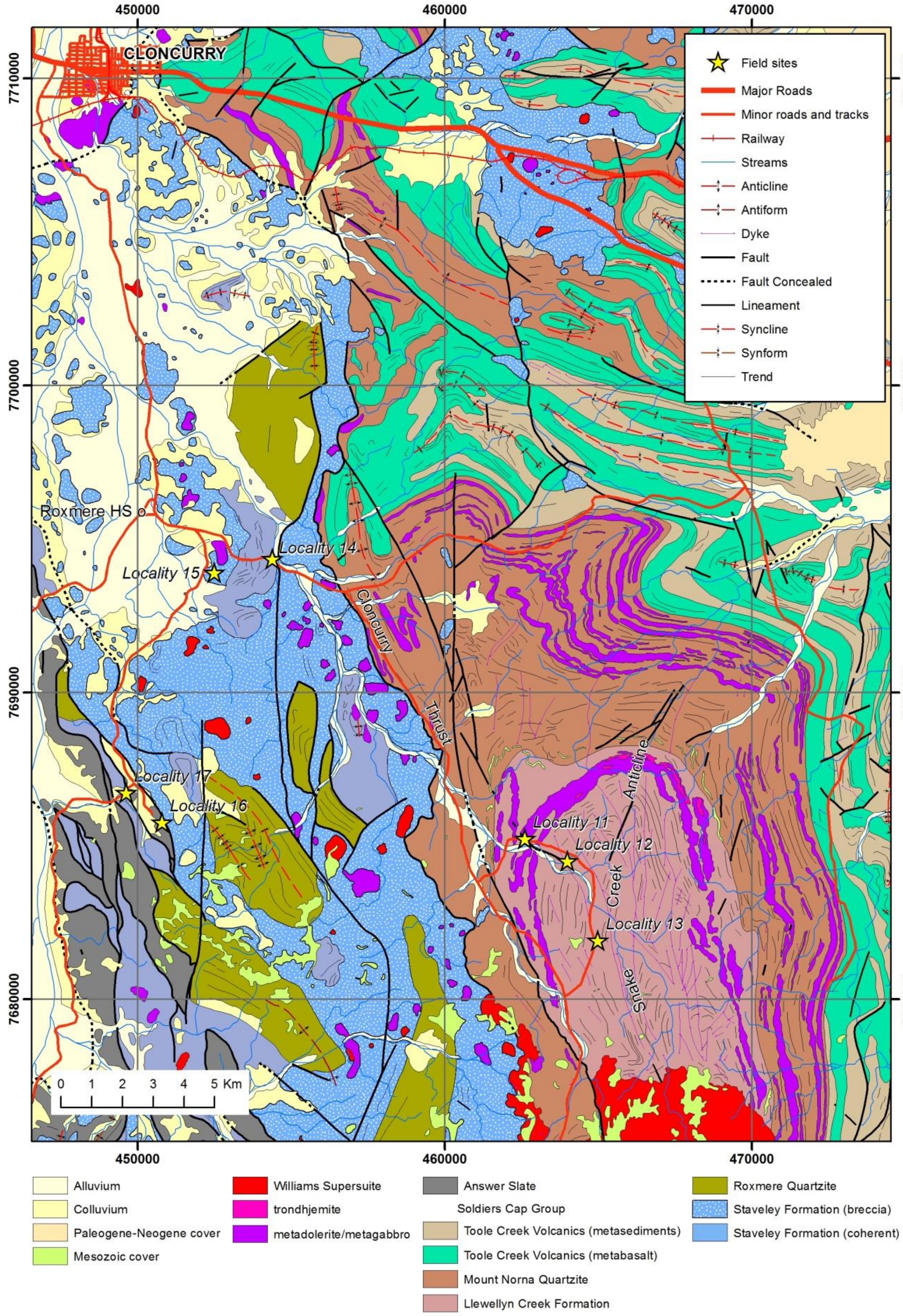


Figure 26: *Geological map of the Snake Creek area.*

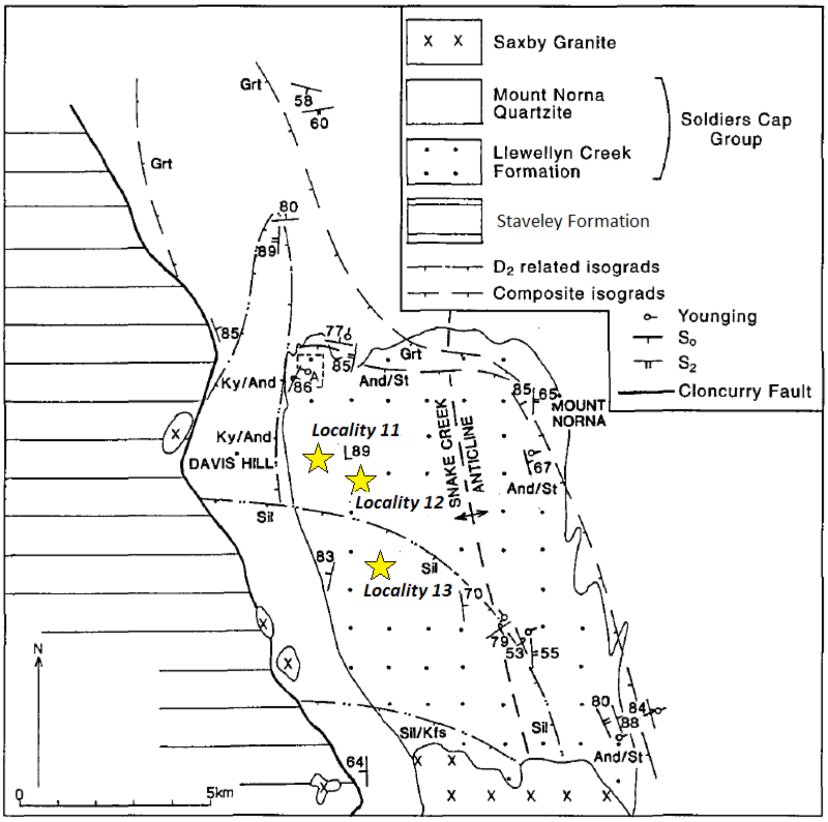


Figure 27: *Map of the Snake Creek Anticline after Rubenach & Barker (1998) showing pelitic isograds. The sillimanite (Sil), sillimanite–K-feldspar (Sil/Kfs) and kyanite/andalusite (Ky/And) isograds relate to syn-D_2 metamorphism, whereas the garnet (Grt) and andalusite-staurolite (And/St) isograds relate to multiple growth episodes from pre/early D_1 to syn-D_4.*

Soldiers Cap Group is best examined on the western limb of the Snake Creek Anticline, but only the Llewellyn Creek Formation and some of the mafic rocks that intrude it will be visited on this trip. The Mount Norna Quartzite is best exposed on the eastern limb, and the better outcrops of Toole Creek Volcanics are not easily accessible in the time available.

To reach the Snake Creek area, follow the Barkly Highway westward towards Mount Isa from Cloncurry, turning off to the south about 1.2 km from the centre of town between the anabranch and the main channel of the Cloncurry River. Follow the road south for about 16 km to the turnoff to Roxmere homestead. It will probably be necessary for everyone to sign in at Roxmere homestead. After signing in, return to the main track and continue south-east, crossing Snake Creek after about 5.5 km. Large outcrops of calcareous metasedimentary rocks of the Staveley Formation are passed on the way, but these will be examined on the way back. Continue southwards for another 12.5 km, crossing Snake Creek again, and then take a prominent track that turns off to the north-east. Follow it for 2.4 km, crossing the western and eastern branches of Snake Creek and stop on a scrubby ridge at coordinates UTM 54K 462627 7685227.

Locality 11: Metagabbro and trondhjemite emplaced into Llewellyn Creek Formation.

The ridge is formed by a 600 m-thick sill of metadolerite and metagabbro. The rock consists of dark greenish grey medium-grained metagabbro that has alternating plagioclase-rich and hornblende-rich layers 2 mm to 2 cm across (Figure 29). In thin section it consists of plagioclase laths to 1 mm and poikiloblastic bluish green hornblende as subequant crystals up to 3 mm (that have probably replaced clinopyroxene) as well as clusters of smaller prismatic grains. No relict pyroxene has been observed.

The sill also contains minor amounts of hornblende trondhjemite, some of which is exposed nearby. It is dark grey, medium-grained and hard to distinguish from the metadoleriite and metagabbro, except that close examination reveals the presence of quartz grains and very minor biotite.

A sample of trondhjemite from this site was dated by Rubenach et al. (2008) and gave a U–Pb SHRIMP age of 1686 ± 8 Ma, which is within error of the maximum depositional age of the host Llewellyn Creek Formation at 1681 ± 10 Ma and the overlying Mount Norna Quartzite at 1685 ± 5 Ma (Figure 29) closely constraining the age of deposition and almost contemporaneous mafic intrusion. Together with the age of the uppermost unit in the Soldiers Cap Group, the Toole Creek Volcanics at about 1655–1660 Ma Ma (Carson et al., 2008; Page & Sun, 1998), it indicates that episodic mafic magmatism was contemporaneous with deposition over about 20–25 million years.

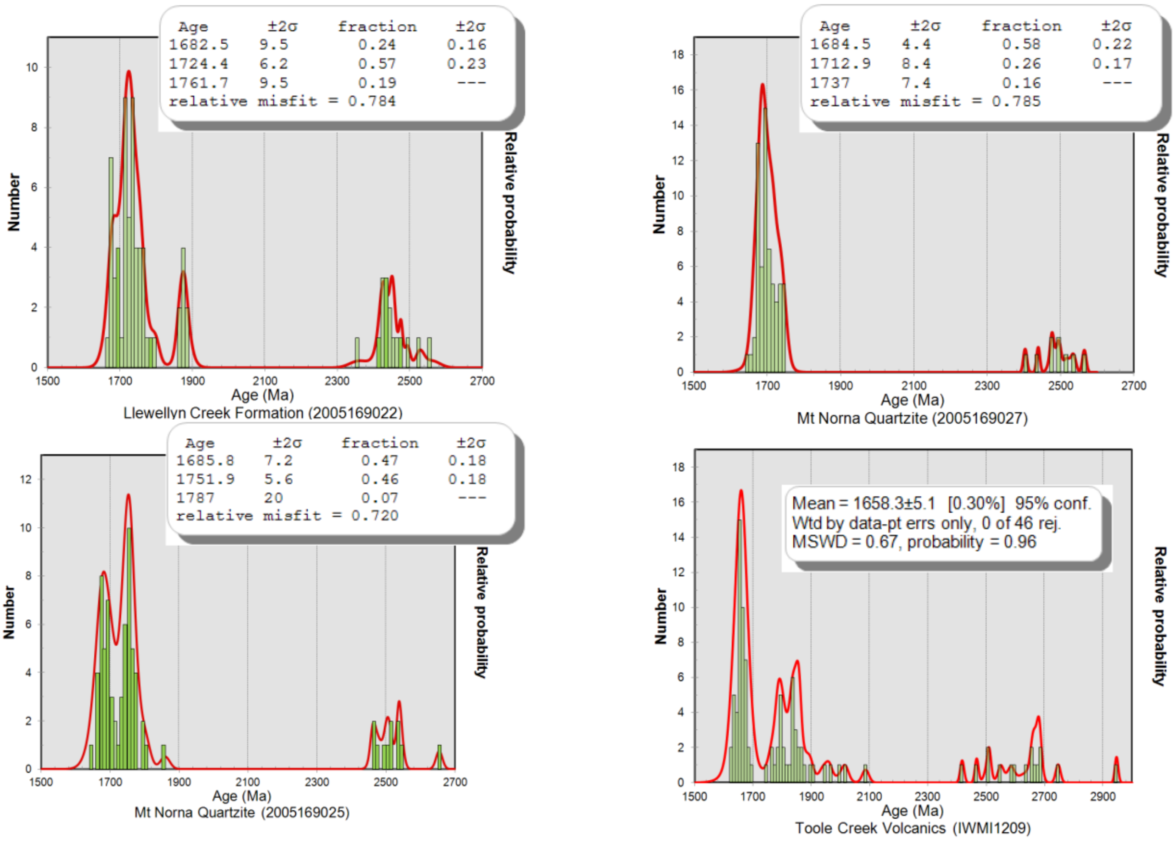


Figure 28: *Detrital zircon age spectra for four samples from the Soldiers Cap Group (Neumann et al., 2009b).The multiple ages in the boxes are the results of Gaussian deconvolution or 'unmixing' of the youngest, dominant age clusters*

Figure 29: *Layered metagabbro within a sill intruding the Llewellyn Creek Formation at Locality 11.*

Locality 12: Deep water turbidites metamorphosed to amphibolite facies (Llewellyn Creek Formation)

Continue east-south-east along the track for about 1.3 km, and then walk or drive about 400 m south-south-east to a small creek, where outcrops of typical Llewellyn Creek Formation are exposed. The rocks here are in the andalusite–staurolite zone and are psammitic to pelitic schists. In spite of the metamorphism, they preserve excellent sedimentary structures that are characteristic of turbidites (Figure 30). Thinner beds show planar laminae and ripple cross lamina as well as scoured bases. Thick beds are more massive and lack these finer structures, but have sharply-defined bases and original grading is indicated by the increasing abundance of andalusite porphyroblasts towards the originally finer, more clayey tops of the beds. In addition to andalusite porphyroblasts, which are up to 3 cm across, the rocks also contain garnet and rare staurolite. Both the younging indicated by these structures and the dip of the beds are to the west, consistent with position of the outcrop on the western limb of the Snake Creek Anticline. The schistosity is interpreted as the regional S_2, although here it appears to dip more shallowly westwards than the bedding suggesting that the structure is more complex.

Figure 30: *Llewellyn Creek Formation at Locality 12, showing laminated to cross-laminated psammite and thicker more massive, but graded psammite beds. Note the increasing abundance of large andalusite porphyroblasts in the tops of the graded beds reflecting the increasing clay content in the protolith.*

Locality 13: Deep water turbidites metamorphosed to amphibolite facies (Llewellyn Creek Formation)

Return to the track, and if time permits, continue to the south for another 3.6 km (otherwise backtrack across the two branches of Snake Creek and take the main track northwards to Locality 14). Locality 13 is still within the Llewellyn Creek Formation, but the grade has increased and is above the sillimanite isograd, which is marked by the first appearance of fibrolitic sillimanite (Rubenach & Barker, 1998). Progressive replacement of andalusite by coarse muscovite and pseudomorphism by sillimanite occurs upwards in the sillimanite zone.

In a gully on the eastern side of the track at UTM 54K 465000 7681920, thin to medium-bedded psammite and garnet-muscovite-biotite schist crop out (Figure 31). The schist still contains andalusite porphyroblasts to 1.5 cm, but they show partial replacement by coarse muscovite. Sillimanite is evident on the high ridge to the west of the track, but here it may be present in white streaky lenticles in the schist and also in strain shadows of the andalusite. The quartzite contains elliptical pods that were originally calcareous concretions.

Figure 31: *Llewellyn Creek Formation at Locality 13, showing large andalusite porphyroblasts partially replaced by coarse muscovite.*

Locality 14: Coherent metasediments of the Staveley Formation near Snake Creek crossing

Continue on for about 2.1 km, rejoining the main track again, and follow it back to the north towards Roxmere homestead for about 18.3 km stopping about 1 km west of the crossing of Snake Creek near UTM 54K 454400 7694340. For much of the route, the track runs alongside the Cloncurry Thrust, a major structure interpreted as east-dipping, that juxtaposes the Soldiers Cap Group against the Staveley Formation. The Staveley Formation forms low rocky knolls thickly vegetated with turpentine bushes (a species of *Acacia*) that contrast with the more open country on the Soldiers Cap Group.

The Staveley Formation is a unit of calcareous to ferruginous, feldspathic to quartzose sandstone and siltstone with minor impure limestone that grade into calc-silicate rocks and resemble the Corella Formation. The possibility that different areas of calcareous rocks in the eastern succession have different ages has been an ongoing controversy since it was hotly debated by Blake (1980, 1981, 1982, and 1983), Derrick & Wilson (1981) and Wilson (1983). As a compromise, rocks in the Selwyn–Kuridala area south of Cloncurry were assigned to two separate units the Staveley Formation and the higher-grade Doherty Formation, and the remainder were retained as Corella Formation (Blake, 1987). However, the relative ages were not known, and it led to inconsistencies, such as the Staveley and Doherty Formations passing northwards into Corella Formation across map sheet boundaries. In fact, the rocks at this locality were mapped as Corella Formation (or beds) by Ryburn et al. (1988) and this assignment has been followed by all subsequent authors (e.g. Marshall, 2003; Marshall & Oliver, 2008). However, there is no clear distinction or boundary with rocks to the south and west assigned to the Staveley Formation and Doherty Formation by Donchak et al. (1983). Therefore, the most recent mapping by the Geological Survey of Queensland has assigned all of the calcareous rocks east of the Mitakoodi Domain to the Staveley Formation (also re-assigning the Doherty Formation as a higher grade, more metasomatised part of the Staveley Formation).

The Corella Formation has not been dated directly, but constraints based on relationships with dated units suggest that it was deposited between 1755 Ma (the age of a tuff in the underlying Ballara Quartzite) and ~1740 Ma (ages from the Wonga–Burstall suites of plutons that intrude it). New isotopic dating of detrital zircon has shown that some rocks previously assigned elsewhere to the Corella Formation are indeed significantly younger and correlate with the successions in the Calvert and Isa Superbasins, but results on the Staveley Formation are somewhat equivocal (Carson et al., 2008, 2011; Geoscience Australia Online Geochronology Delivery System). In most samples, the youngest components of detrital populations in the Staveley Formation are suggestive of derivation from the Wonga–Burstall suites of plutons, but the error ranges for these populations extend into the age range for Corella Formation deposition. A possible exception is Sample 2006169013 in Figure 32, which has a component with an imprecise younger age of 1720 ± 27 Ma However, the most compelling evidence for a younger age is that it can be demonstrated at several localities that the Staveley Formation has a gradational and conformable relationship with the Roxmere Quartzite, for which reliable maximum depositional ages of ~1710 Ma have been obtained (Carson et al., 2011; Geoscience Australia Online Geochronology Delivery System; see Figure 32). Therefore the Staveley Formation is here tentatively regarded as equivalent to the Calvert Superbasin succession.

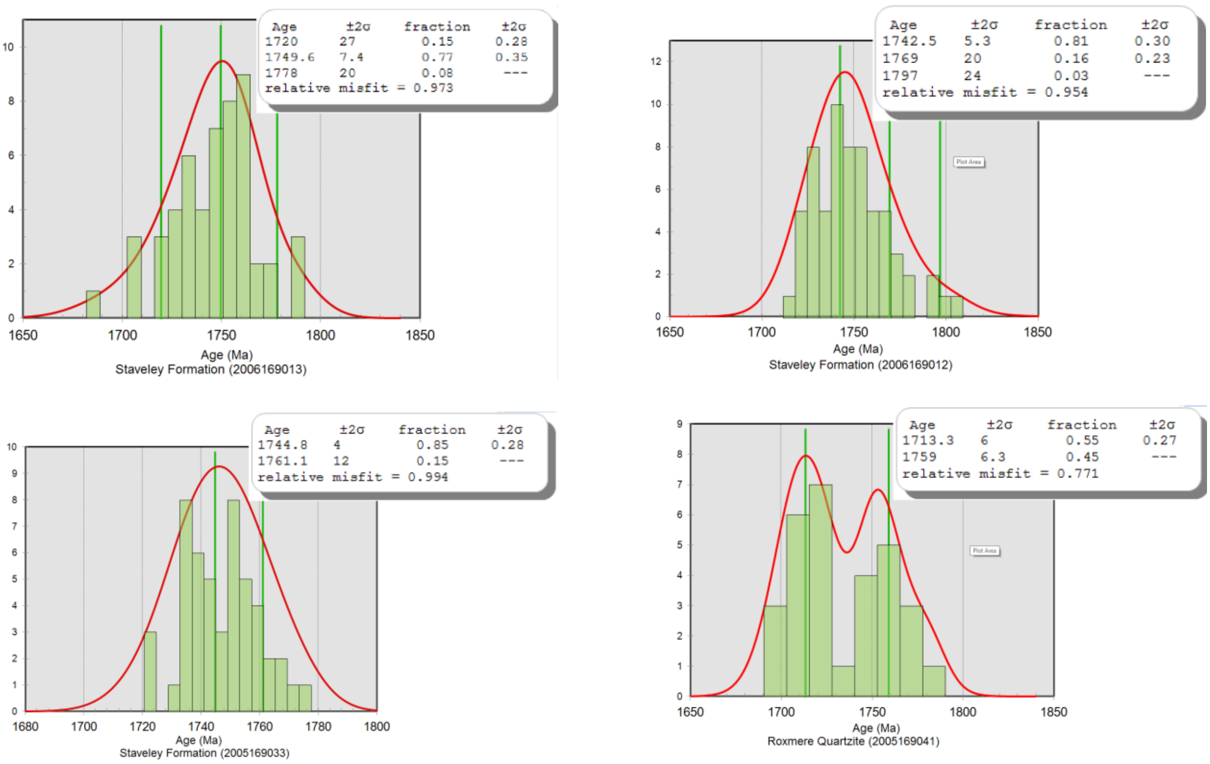


Figure 32: *Detrital zircon age spectra of the youngest zircon populations for three samples from the Staveley Formation and one from the Roxmere Quartzite (Neumann et al., 2009b). The multiple ages in the boxes are the results of Gaussian deconvolution or 'unmixing' of the youngest, dominant age clusters*

Much of the Staveley Formation as now mapped is regionally brecciated, but Locality 14 is an example of the relatively coherent rocks that are locally extensive. The outcrop consists of reddish brown, thinly bedded calcareous siltstone or very fine grained sandstone and some impure limestone. Small scapolite porphyroblasts to 3 mm are abundant in some layers. In thin section, the rocks are well-sorted consisting of feldspar and subordinate quartz and variable calcite (overall ~25%); some laminae rich in greenish-brown biotite are present.

A feature of this outcrop and almost characteristic of the Staveley Formation is the development of multiple sets of calcite filled fractures orthogonal to bedding (Figures 33 and 34). The calcite has been dissolved-out in weathered outcrop, so that on bedding surfaces, multiple fracture directions break the rock up into polyhedral segments (chocolate-block structure). They are interpreted as extensional fracture sets, and in some outcrops pass into small-scale, domino faults and then into breccias as the blocks separate.

Figure 33: *Coherent, thinly bedded calcareous siltstone or very fine grained sandstone and some impure limestone of the Staveley Formation. Note the abundant, small porphyroblasts of scapolite and also the orthogonal fractures (weathered-out calcite veins).*

Figure 34: *Bedding plane of calcareous siltstone or very fine grained sandstone of the Staveley Formation at Locality 14, showing the multiple weathered out calcite-filled fracture sets.*

Locality 15: Regionally brecciated Staveley Formation south of Roxmere homestead

Continue back towards Roxmere for 3.1 km and then turn off on a less distinct track that heads south-west across an open plain and follow it for 1.3 km. The locality is about 300 m from the track in an east-south-easterly direction, but the country is fairly open, so it should be possible to drive almost to the outcrop which is on a low rocky hill at 54K 452510 7693900.

The outcrop consists of chaotically brecciated Staveley Formation, typical of the rocks that constitute 70% or more of the outcrop of the unit east of the Cloncurry River. The breccia is matrix-supported with angular fragments of reddish brown siltstone or fine-grained sandstone as at Locality 14, mainly from granule to boulder size (Figure 35). Locally, as here, entrained within the breccia are large blocks up to 20 m across of relatively coherently bedded, although highly fractured or crackle-brecciated rocks. The matrix consists of calcite, albitic plagioclase and biotite or amphibole.

The origin of the breccias in the ‘Corella Formation’ has long been debated and early interpretations included reef debris (Carter et al., 1961). Most subsequent authors, however, agree that they are probably tectonic and related to post-depositional folding, faulting and igneous activity (e.g. Glikson & Derrick, 1970; Blake, 1987; Ryburn et al., 1988). The most comprehensive study has been by Marshall (2003) and Marshall & Oliver (2008), who concluded that the distribution and geometry of brecciation was in part controlled by buckle folding imposed on a heterogeneous rock sequence that was fractured and boudinaged both pre- and syn-folding. They noted that brecciation was far more widespread in the Cloncurry area (rocks we now assign to Staveley Formation) relative to the Mary Kathleen area (Corella Formation *sensu stricto*), where breccias are confined mainly to discrete shears and fault zones. In the Cloncurry area, the stratigraphy may have been at a low angle to the shortening direction, favouring refolding and consequent fracturing. Other contributing factors for brecciation include the proximity to voluminous intrusions, the emplacement of which likely resulted in transient elevated fluid pressure and strain rates, favouring fracturing and brecciation.

The relative paucity of brecciation in units outside the Staveley Formation may reflect a high proportion of incompetent stratigraphy in those units, such as mica schist in the Soldiers Cap Group that was able to accommodate strain by plastic flow. However, this does not explain why the relatively competent, overlying Roxmere Quartzite is not brecciated, even though it was recumbently folded with the Staveley Formation, and in places is completely inverted. However, the Roxmere Quartzite is relatively homogeneous and very thickly bedded, and it is also possible that marble layers within the Staveley Formation, which were not prone to brittle failure, acted as low permeability barriers to fluid flow allowing attainment of elevated fluid pressures in the intervening beds.

The Soldiers Cap Group is locally cut by small pipes and dyke-like bodies of breccia consisting of clasts of Staveley Formation, and these are postulated to have formed from granite-related overpressure and volatile release that resulted in the emplacement of fluidized breccias of Staveley Formation into the overlying rocks (Oliver et al., 2006). However, south-east of Cloncurry, the mapped boundary between the largely brecciated Staveley Formation and Soldiers Cap Group is sinuous in outline and transects the stratigraphy of the latter on a regional scale. The nature of this contact has not been investigated thoroughly, and although it may be a shallowly dipping thrust, it resembles an intrusive boundary, suggesting that the regional breccias were also sufficiently mobile to intrude *en-masse* into the overlying succession, perhaps akin to salt diapirism.

Brecciation was accompanied by widespread, high-temperature (400° – 600°C) metasomatism that resulted in Na–(Ca)-rich assemblages of albite ± actinolite in addition to diopside, scapolite, magnetite and titanite, as well as low-temperature retrograde chlorite alteration. Interpretation of isotopic and mineral chemistry data is consistent with the spectrum of assemblages reflecting fluids of two origins (Marshall & Oliver, 2008; Marshall et al., 2006). Stable isotopic signatures (O, C) of carbonates from the Na–(Ca) assemblages are consistent with the fluids being exsolved from crystallising plutons. Low temperature, low salinity fluids inferred to be of meteoric origin were introduced late in the paragenesis.

Figure 35: *Staveley Formation at Locality 15, showing a large block of relatively coherent, thinly bedded in a matrix-supported breccia.*

Locality 16: Answer Slate — carbonaceous slate with copper mineralisation at Copper Canyon

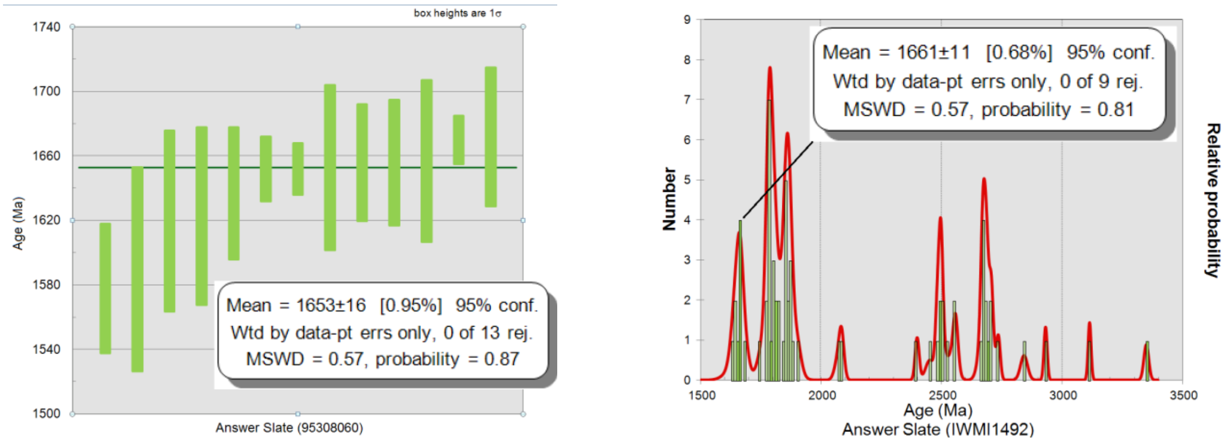
Return to the track and continue south-west, firstly across the open plain with sporadic outcrops mainly of the brecciated facies of the Staveley Formation, and then through more rugged hilly topography that is a mixture of brecciated and more coherent rocks. After about 8.7 km, a junction is reached and the main track turns to the west. Continue on the less distinct track to the south for another 1.3 km stopping near a prominent ridge.

This is the site of a small copper prospect called Copper Canyon (54K 450800 7685750). Strong malachite staining is evident on the slaty cleavage planes in some parts of the outcrop (Figure 37) and on faces exposed by excavations along the eastern side of the ridge. However, drilling under the ridge has not discovered any significant concentrations of primary copper mineralisation.

The slate is part of the Answer Slate and is strongly carbonaceous (Figure 38). It is commonly pitted in weathered outcrop, possibly due to the leaching of small pyrite aggregates or perhaps andalusite or scapolite porphyroblasts.

The Answer Slate is an extensive unit that crops out from south-west of Cloncurry for more than 100 km to the south, and is characteristically carbonaceous. Dating of detrital zircon in siltstone and rare fine-grained tuff gives ages of ~1650–1660 Ma indicating that it is equivalent to the Toole Creek Volcanics and Mount Isa Group, and is significantly younger than the Staveley Formation with which is in contact (Carson et al., 2008; Page, 1998; Geoscience Australia, Online Geochronology Delivery System; Figure 36).

Although the unit has hitherto only been known for small-scale secondary copper mineralisation as at this site, the recognition of an extensive 'black shale' basin of the same age as the Mount Isa Group in the eastern succession has sparked the interest of exploration companies to search for lead–zinc mineralisation in the belt.



(a) (b)

Figure 36*: U-Pb SHRIMP ages for the Answer Slate: (a)weighted mean age from a siliceous siltstone interpreted as a tuff (95208060); and (b) a maximum depositional age for a siltstone (IWMI1492).*

Figure 35: *Copper Canyon prospect (Locality 16) showing malachite stained cleavage planes in carbonaceous slate of the Answer Slate.*

Figure 38*: Carbonaceous siltstone of the Answer Slate at Locality 16, showing pitting, probably due to leaching of pyrite.*

West from here, is a belt up to 10 km wide, known as the Marimo–Staveley Belt, consisting of multiple fault-bounded slices, 1–3 km wide, of Answer Slate alternating with Staveley Formation. In almost all cases, the contacts are defined by ferruginised and/or silicified fault zones. The faults are now steep to vertical, but some of the Staveley Formation appears to lie in the cores of downward-facing antiformal hinges, suggesting that Staveley Formation was thrust over the Answer Slate and then the two units recumbently folded, possibly during D_1. The thrusts and recumbent folds were subsequently tightly re-folded by upright folds during D_2. Movement during the development of the thrusts and recumbent folds was focused along a sole thrust, the Overhang Shear (O'Dea et al., 2006), which separates the Calvert and Isan superbasin rocks of the Marimo–Staveley Domain from older successions of the Leichhardt Superbasin in the Mitakoodi Block that will be examined on Day 5.

Locality 17: Siliceous mylonite between Staveley Formation and Answer Slate

Return 1.3 km to the track junction and take the track to the west for 400 m. This track was on the route of the first deep crustal seismic transect conducted in the Mount Isa area in 1994 by the Australian Geological Survey Organisation (now Geoscience Australia) (Goleby et al., 1996; MacCready et al., 1998; MacCready, 2006).

An outcrop about 100 m south of the track is on the contact between carbonaceous slate (Answer Slate) to the east and Staveley Formation to the west. The outcrop is strongly layered, dipping moderately to the south-east, and is typical of rocks that occur along many of the contacts between the two units. It consists of white bands and lenticles of quartz alternating with brown, more ferruginous and possibly slightly calcareous or dolomitic layers (Figure 39), and may in part be of tectonic origin.

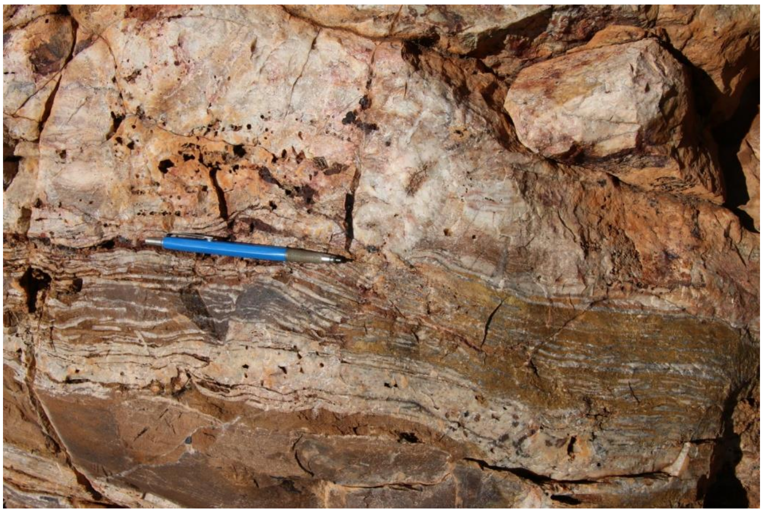


Figure 39: *Silicified mylonite on the contact between Staveley Formation and Answer Slate at Locality 17.*

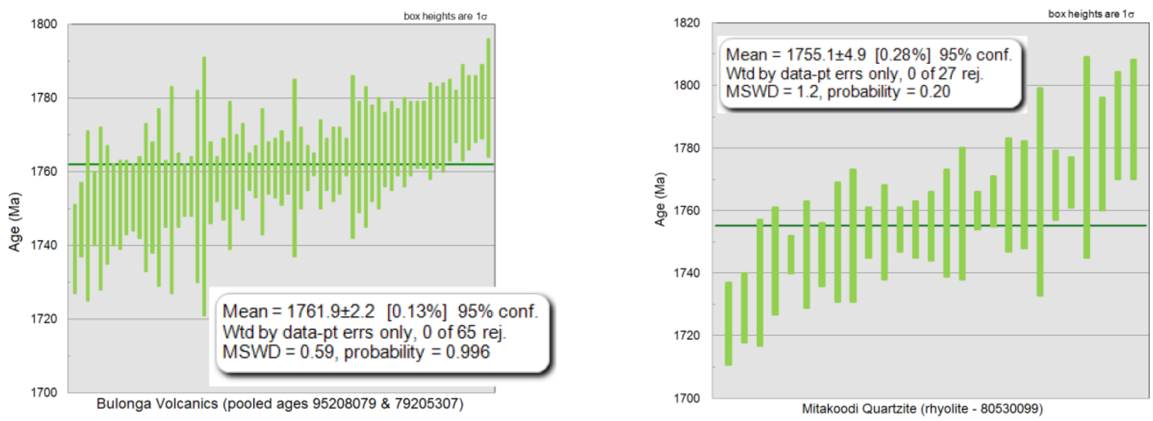
Day 5 — Mitakoodi Block, Kalkadoon-Leichhardt Block

Depart for rocks making up the eastern edge of the Mitakoodi Block (sometimes referred as Mitakoodi Culmination or Mitakoodi Domain), which is a regional anticlinorium that comprises the north-east- trending Duck Creek and Bulonga Anticlines separated by the Wakeful Syncline, and is one of the most prominent large-scale structures in the Mount Isa Province (Figure 41).

The block is bounded on its eastern, northern and western sides by faults or shears. On the east, the Marimo–Staveley Belts lies across the steeply east-dipping Overhang Shear Zone (O'Dea et al., 2006). To the north, the Highway Fault separates the Mitakoodi Block from an enigmatic assemblage of metasedimentary strata and bimodal volcanic rocks in the Milo beds of the Tommy Creek Block. These are dated at ~1615 Ma (Hill et al., 1992; Carson et al., 2011). The western boundary with the calc-silicate rocks of the Corella Formation in the Mary Kathleen Belt is the Pilgrim Fault.

The succession within the Mitakoodi Block although broadly correlated with units in the Leichhardt Superbasin to the west shows significant differences. The anticlinorium is cored by the Bulonga Volcanics, a felsic volcanic suite interpreted to be largely crystal-rich rhyolitic ignimbrite with interbedded quartzose to felspathic sandstone units. SHRIMP U–Pb dating gives ages of ~1760 Ma (Figure 40), somewhat younger than the lithologically similar, but ~1780 Ma-old Argylla Formation to the west (Page 1998; Neumann, Gibson & Southgate, 2009; Geoscience Australia, Online Geochronology Delivery System).

The Bulonga Volcanics are overlain by the Marraba Volcanics, which consist of basaltic lavas and fine-grained clastic successions and are up to 2300 m thick (Derrick, 1980), although they are entirely absent northwest of Cloncurry, where the Bulonga Volcanics appear to be overlain directly by the Mitakoodi Quartzite. Given the age of the overlying Mitakoodi Quartzite (Figure 40), the eruption of the Marraba Volcanics and subsequent deposition of more than 2000 m of sediments happened over a relatively short interval between 1760 and 1755 Ma. The Marraba Volcanics have no correlatives to the west. Together with the Bulonga Volcanics, which are intruded by swarms of mafic dykes, the Marraba Volcanics represent a bimodal, rift-related igneous province confined to the Mitakoodi Block and separate from and younger than the one that characterises the Leichhardt Superbasin to the west.



(a) (b)

***Figure 40**: U-Pb SHRIMP weighted mean ages for: (a) pooled data for two rhyolite samples from the Bulonga Volcanics; and (b) rhyolite from the middle of the Mitakoodi Quartzite. Data from Geoscience Australia, Online Geochronology Delivery System.*

The Marraba Volcanics are overlain by the Mitakoodi Quartzite, a succession of feldspathic to quartzose sandstone with minor siltstone, basalt and rhyolite. The lower part of the succession is up to 2000 m thick and sedimentary structures indicate a shallow subaqueous to shoreline environment (Derrick, 1980). A 40 m-thick porphyritic rhyolite at the top of this lower part has been dated at 1755 ± 4 Ma, similar in age to a tuff in the Ballara Quartzite (Page et al., 1997; Geoscience Australia, Online Geochronology Delivery System; see Figure 40). Potma & Betts (2006) interpreted a locally angular unconformity between the upper and lower parts of the Mitakoodi Quartzite, the contact being marked by matrix-supported polymictic conglomerate (that includes clasts of the underlying rhyolite) suggesting an increase in depositional energy. The upper part is 600–1400 m thick and consists of interbedded metapelite and quartzite and an interval of basalt lavas (the Wakeful Metabasalt Member). Potma & Betts (2006) attributed the local angular unconformity to tilt-block rotation related to extensional faulting during deposition of the Mitakoodi Quartzite.

The overall thickness of the Mitakoodi Quartzite (>3000 m) contrasts with that of the Ballara Quartzite, which although up to 1200 m in the western part of its distribution, thins eastwards so that it is thin (<200 m) to discontinuous where it overlies the Argylla Formation immediately to the west of the Mitakoodi Block in the Mary Kathleen area. This dramatic thickness increase displayed by the Mitakoodi Quartzite and evidence for extensional faulting presented by Potma & Betts (2006) indicates ongoing rifting in the Mitakoodi Block after eruption of the bimodal volcanic succession.

The Mitakoodi Quarzite is overlain both conformably and locally unconformably (Potma & Betts, 2006) by the Overhang Jaspilite, a succession up to 1200 m thick of variably ferruginous and manganiferous siltstone, limestone and marl. It also contains red to grey bands of jasper, that although volumetrically minor, gave the unit its name (Derrick, 1980). In places the limestone contains abundant domal stromatolites. Some of the ferruginous siltstones are strongly laminated and pass into banded-iron-formation, some of which may have a stromatolitic origin (Brown et al., in preparation).

The Overhang Jaspilite may be correlative with the Corella Formation, but is distinctively different to the latter, which lacks the ferruginous and manganiferous rock types as well as the common stromatolites. These dissimilarities further point to the Mitakoodi Block having a different structural setting and depositional environment to the Leichhardt Superbasin west of the Pilgrim Fault. The Overhang Jaspilite is in contact with the Corella Formation at the northern end of the Mitakoodi Block, but the contact may be tectonic.

The regional folds that define the anticlinorium formed during D_2 of the Isan Orogeny, with the overturned Bulonga Anticline in the west forming a regional-scale fold nappe and the Duck Creek Anticline evolving as a ramp anticline above a basal Argylla Detachment (MacCready, 1998; O'Dea et al., 2006).

D_1 folds are mainly preserved in a narrow zone of high strain in pelitic rocks of the upper Mitakoodi Quartzite and siltstone and carbonates of the Overhang Jaspilite. O'Dea et al. (2006) described a wide variation in style and plunge of the D_1 folds, which are generally polyharmonic and non-cylindrical, and include rootless intrafolial, chevron, parallel and similar folds. Layering is locally transposed and shortening in places may be of the order of 90%, but due to the low mica content in the siltstones, cleavage development is not widespread in the Overhang Jaspilite,.

The high-strain zone is bounded by the Overhang Shear and the intensity of deformation increases towards it, suggesting that movement on the shear was synchronous with the D_1 fabric development in its footwall. The high-strain zone and associated folds and fabrics as well as the Overhang Shear Zone extend along the entire eastern limb of the Duck Creek Anticline and are folded around its hinge, and overprinted by D_2 fabrics.

The Overhang Shear in places is marked by a 10–15 m-wide quartz mylonite that dips steeply towards the east. It has a strongly developed, planar foliation. However, detailed microstructural analysis indicates that ductile fabrics have been statically annealed and generally display granoblastic mineral textures, so that mineral elongation directions and asymmetric shear fabrics are scarce (O'Dea et al., 2006). Nevertheless, Huang (1994) documented left-lateral displacement (indicated by relict quartz porphyroclasts and S–C fabrics) and recorded rare mineral lineations plunging moderately to the north-north-west. Given that the Overhang Shear Zone and its associated folds and fabrics are folded around the Duck Creek Anticline to become the Highway Fault, unfolding it suggests that the shear zone developed as a north- to northwest-directed overthrust. D_1 displacement resulted in emplacement of the Marimo-Staveley Belt over the Overhang Jaspilite and produced an asymmetric fold train in its footwall and regional scale recumbent folds and thrusts in the hanging wall (O'Dea et al., 2006).

At other locations the shear zone has been overprinted, or was re-utilised during a more brittle tectonic regime, and is defined by siliceous breccias that have been included in the Chumvale Breccia unit. The Chumvale Breccia is confined to the Overhang Jaspilite and mostly occurs near the upper faulted contact of the latter, but its origin is not fully understood. It consists of irregular fragments and blocks of quartz and quartzite in a friable siliceous, ferruginous to manganiferous, and locally calcareous matrix. It is generally massive, but is diffusely layered in places. In places it appears to form flat-lying plateaux rather than linear belts and the siliceous breccia passes down slope into calcareous breccias similar to those in the Staveley Formation, suggesting that some of the silicification could partly be due to Cenozoic laterite profile development (Derrick, 1980).

Locality 18: Mitakoodi Quarztite (Mt Isa–Townsville railway line)

Drive westwards from Cloncurry along the Barkly Highway towards Mount Isa for 11 km and then take the turnoff to Duchess and Dajarra on the left, and follow the road south for 20 km to the crossing of Slaty Creek. The crossing is flanked by two prominent bluffs of ferruginised, siliceous breccia mapped as part of the enigmatic Chumvale Breccia. Here it probably marks the contact between the Overhang Jaspilite and Stavely Formation, although neither of these units are well exposed here.

About 400 m past the causeway, a service track for the Townsville–Mount Isa railway turns off to the right. Follow this track for 1.7 km and stop in a valley between two prominent ridges. The ridges consist of very thick bedded, medium-grained quartzo-feldspathic sandstone. The beds are usually massive, but locally have low-angle trough cross-bedding, particularly towards the tops of beds.

The valley is the expression of an unamed unit of metabasalt about 200 m thick, and one of two intervals within the Mitakoodi Quartzite. A more persistent unit in the upper part of the Mitakoodi Quartzite is named as the Wakeful Metabasalt Member. At this locality the basalt is scoriaceous at the top, where it is abruptly overlain by very fine-grained, dark grey quartzite. In places it is also peperitic and forms a breccia with 'pillows' of scoriaceous basalt in a matrix of very fine-grained sandstone or siltstone (Figure 43).

Locality 19: Overhang Shear – siliceous mylonite

Return to the main road and continue south for 5.8 km. The road along this section follows a valley formed by the recessively weathered Wakeful Basalt Member, but it is poorly exposed.

A dirt track turns off to the left and is the main access road for Top Camp, a small alluvial gold field. The first 800 m traverses across the upper part of the Mitakoodi Quartzite and then into a ridge of dark coloured, ferruginous to manganiferous siltstones of the Overhang Jaspilite. At a large creek crossing about 1.5 km from the main road is another prominent outcrop of siliceous breccia that marks the Overhang Shear.

From here, the road turns to the south-east in Staveley Formation in the hanging wall of the shear, although because the road follows an alluvial tract, outcrop is restricted to a few small rubbly rises. Prominent black ridges to the west in the Overhang Jaspilite locally define hinge zones to isoclinal F_1 folds. The dark staining on these ridges is manganese alteration that post-dates the folding and locally has been further concentrated by supergene processes. A small manganese mine that occurs on a ridge just west of the road about 6 km from the turnoff, is the

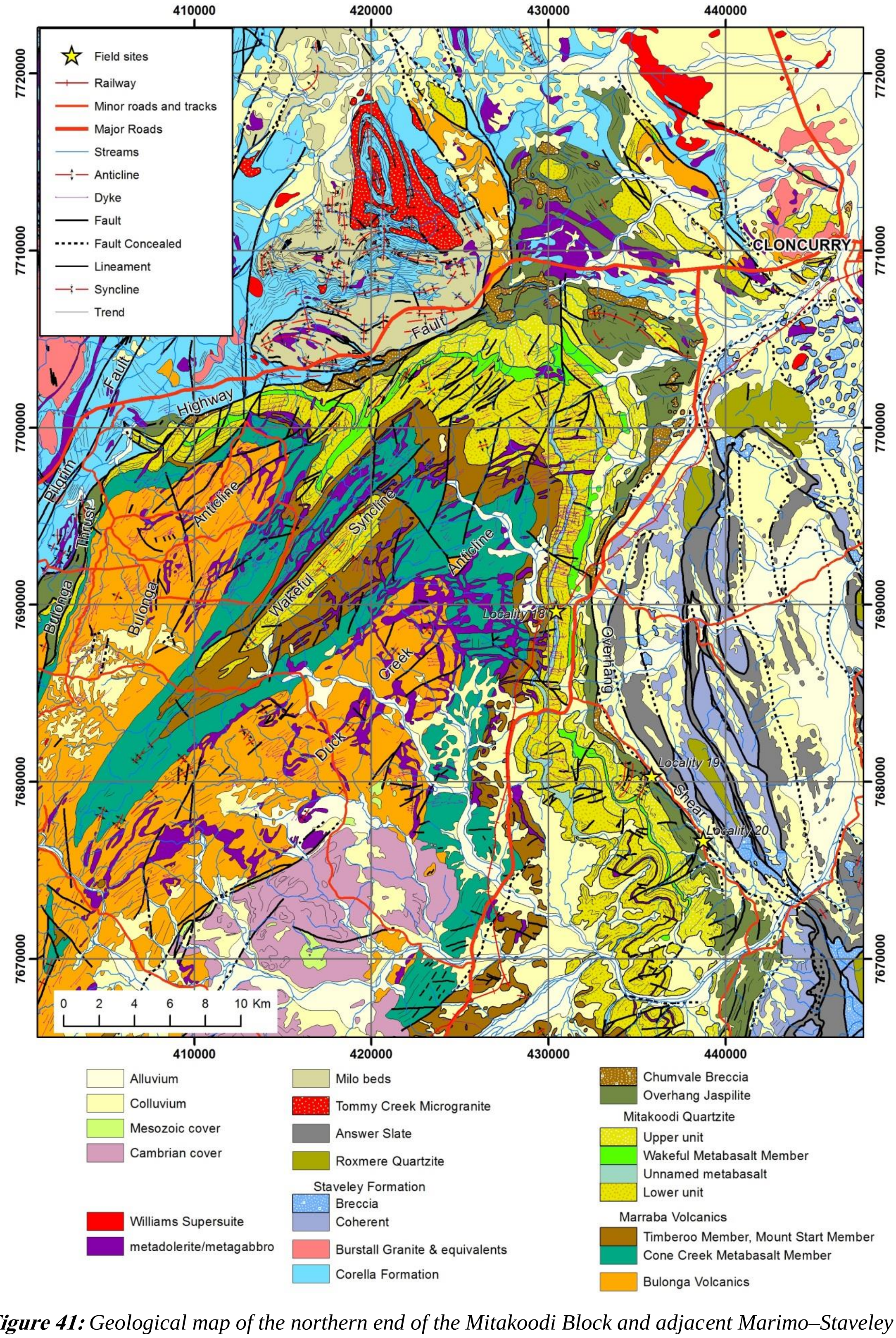


Figure 41: *Geological map of the northern end of the Mitakoodi Block and adjacent Marimo–Staveley belt*

Figure 42*: Mitakoodi Quarzite near Locality 18, showing ridges of quartzo-feldspathic sandstone and an intervening valley floored by metabasalt*

Figure 43: *Peperitic metabasalt consisting of 'pillows' in a matrix of fine-grained sedimentary rock.*

Overhang mine, from which the unit is named. The range of hills to the east is a fault-bounded slice of Answer Slate.

Park the vehicles 6.8 km from the turnoff, and walk 250 m south-west to a prominent ridge. This stop highlights a typical outcrop of the Overhang Shear Zone where it forms a ridge of quartz-rich material ~20 m wide that separates the Overhang Jaspilite to the west from the Staveley Formation to the east. As elsewhere, the shear zone at this locality is characterised by alternating bands of quartz that represent a remnant shear fabric associated with the ductile evolution of the shear zone. Most of the quartz is fine-grained and granoblastic, although there is a weak mineral elongation locally and larger, 1–2cm porphyroclasts of quartz are entrained in the foliation and some define a sinistral shear sense.

Figure 44: *Overhang Shear at Locality 19 represented by a siliceous mylonitic rock, dipping steeply to the east.*

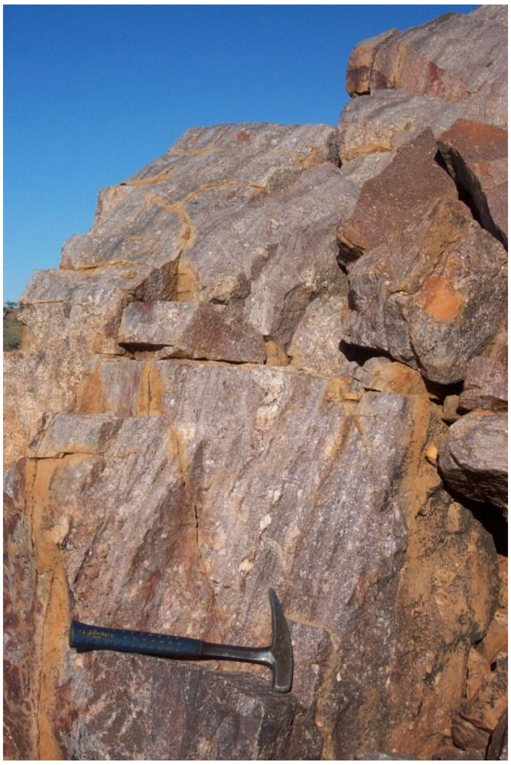


Figure 45: Siliceous mylonite in the *Overhang Shear at Locality 19 showing a strong laminar fabric and porphyroclasts of quartz.*

Locality 20: Overhang Jaspilite — spectacularly folded jaspilitic siltstone

Continue another 5 km south-east along the road. The road mainly parallels the Overhang Shear, but near here it crosses back into the Overhang Jaspilite. The rocks are limestone and siltstone but here consist of siltstone with thin bands of red–grey banded chert or jaspilite that originally gave the unit its name. This point is in the footwall relatively close to the shear, and the resulting high strain produced trains of isoclinal folds (Figure 46).

Figure 46: Isoclinally folded jaspilite layers in siltstone of the Overhang Jaspilite at Locality 20.

Locality 21: Basement gneisses of Kalkadoon-Leichhardt Block

The rocks exposed at this locality (Figure 2) form part of the Kalkadoon-Leichhardt basement block which separates the Mount Isa region into western and eastern successions. This basement block is about 30-50 km wide and comprises mainly felsic intrusions and related comagmatic volcanics, along with subordinate amounts of gabbroic to dioritic intrusions and variably migmatised metasedimentary rocks into which these various magmatic rocks have been emplaced.

Most of this magmatism is generally thought to have occurred between 1860 Ma and 1840 Ma during the closing stages of the Barramundi Orogeny (Bierlein et al., 2011; Neumann et al., 2009a) and is similar in age and isotopic composition to variably deformed and metamorphosed intrusive rocks cropping out west of the Leichhardt River Fault Trough (Bierlein et al., 2011). Claims that parts of the Kalkadoon-Leichhardt Block may be underlain by Archean crust (McDonald et al., 1997) have yet to be confirmed although mafic and felsic magmatic rocks from both this block and the area west of the Leichhardt River Fault Trough share common late Archean-Paleoproterozoic crustal residence times (T_{DM} ca 2600-2300 Ma). Geochemically, however, the felsic magmatic rocks farther west would appear to have undergone a greater degree of crustal assimilation, consistent with the proposition that crustal thickness increases westward and that these intrusive bodies sampled a basement of predominantly late Archean to Paleoproterozoic age.

In contrast, rocks of the Soldiers Cap Group and eastern succession in general, are intruded by 1550-1530 Ma granites giving Nd model ages and crustal residence times between 2300 and 2100 Ma (Bierlein et al., 2011). This has led to suggestions that the eastern succession is floored by a basement terrane that is not only different in age to that farther west but allochthonous with respect to the rest of Mount Isa (Bierlein et al., 2011). If this is interpretation is indeed correct, then it follows that some form of suture or former subduction zone must lie between the now juxtaposed but compositionally and isotopically very different basement terranes. It also follows that this originally separate eastern basement terrane must have been accreted no later than 1780-1760 Ma because by that time the Argylla Formation was being emplaced across both the western and eastern successions. A corollary of this interpretation is that the ca. 1850 Ma felsic magmatism in the Kalkadoon-Leichhardt Block is subduction-related and represents some form of magmatic arc (Bierlein et al., 2011).

An alternative explanation for the different isotopic compositions and Nd model ages between the western and eastern successions is that granites intruded into Soldiers Cap Group and adjacent units were sourced from a continental crust that had undergone much greater amounts of attenuation and basaltic underplating.

Day 6 – Sybella Batholith and Lake Moondarra section through Surprise Creek Formation and Isa Group

Locality 22: Syn-rift magmatism – the Sybella (Granite) Batholith

Sills of Rapakivi-textured A-type granite crop out in a series of low hills along the road into May Downs Station (Figure 2). They form some of the most northerly exposures of Sybella Granite and at this locality were intruded syn-kinematically into already deformed amphibolite and calc-silicate rock. The country rocks into which these sills were intruded are thought to represent basement of equivalent age to the Kalkadoon- Leichhardt block or a more highly metamorphosed part of the Leichhardt Superbasin (Gibson et al., 2008). Rapakivi-style textures are commonplace and widely developed in this particular part of the Sybella Batholith as evidenced by abundant partially recrystallised augen of pink K feldspar (Figure 29) around which thin rims of albite have developed.

A lineation defined by asymmetric tails on K feldspar porphyroclasts defines the sense and direction of syn-rift extension (Gibson et al., 2008). On rotation of the granite sill to its pre-tilt (folding) orientation, a top-to-the-ENE is indicated. No less importantly, this same direction is also evident in xenoliths elongated in the direction of magmatic flow, indicating that intrusion occurred contemporaneously with crustal extension. Sybella Granite at this locality has been dated at 1674 ± 4 Ma (Neumann et al., 2006) and thus overlaps the age of sedimentation in the youngest part of the Calvert Superbasin, further supporting suggestions that intrusion occurred contemporaneously with crustal thinning and rifting (Figure 7).

Locality 23: Lake Moondarra transect through inverted basin sequence (Calvert-Isa Superbasins)

The Mount Isa mine leases are located in the upper part of the Isa Group, and more particularly within black shales of the intensely mineralised Urquhart Shale. This same formation hosts the George Fisher Pb-Zn mine, some 20 km farther north. Lake Moondarra (Figure 48) provides only limited exposure through the Urquhart Shale and the area is better suited to an investigation of the lithological units that underlie the Urquhart Shale and the mineralisation hosted by this formation. Indeed, it has been suggested that the rocks underlying this formation may be the ultimate source of both the fluids and the metals that gave rise to mineralisation (Southgate et al., 2006).

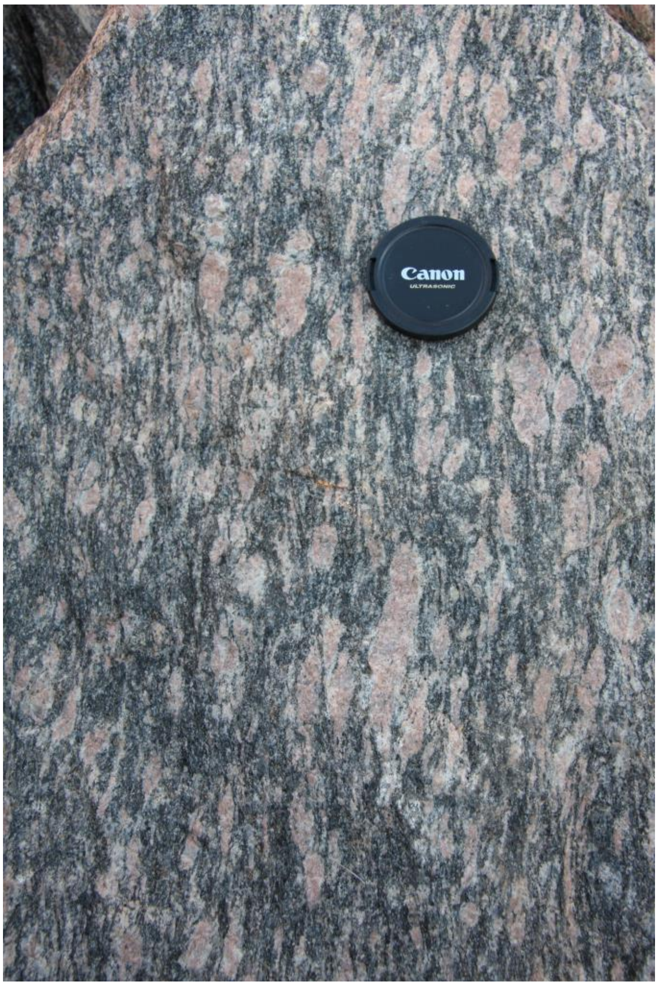


Figure 47: *Vertical section through strongly lineated outcrop of Sybella Granite with Rapakivi-style textures in which former phenocrysts of potassium feldspar have been reduced to porphyroclasts with partially recrystallised asymmetric tails. Tails yield top-to-ENE sense of shear (bottom left to top right) on rotation of fabric into original sub-horizontal orientation.*

Original fault geometries (Figure 49), though modified by later basin inversion at Lake Moondarra (Figure 48), are locally preserved in an oblique section through the Surprise Creek Formation and lowermost Isa Group (Figure 50). Together, these two units form part of an upward fining sedimentary sequence that bears a striking similarity to rocks of the McNamara Group exposed around Gunpowder Mine. These similarities are particularly marked in the case of the Warrina Quartzite and overlying Moondarra Siltstone (Isa Group; Figures 48 & 50) which are widely regarded as temporal equivalents of the Torpedo Creek Quartzite (identified here as Prc) and Gunpowder Creek Formation respectively (Figure 9a). Correlation between these widely separated units would imply that the Gun Unconformity at Lake Moondarra lies within the Moondarra Siltstone and above the unit mapped as Warrina Park Quartzite (Figure 50 & 9b). The Moondarra Siltstone has a maximum depositional age of 1668 ± 8 Ma (Page et al., 2000b).

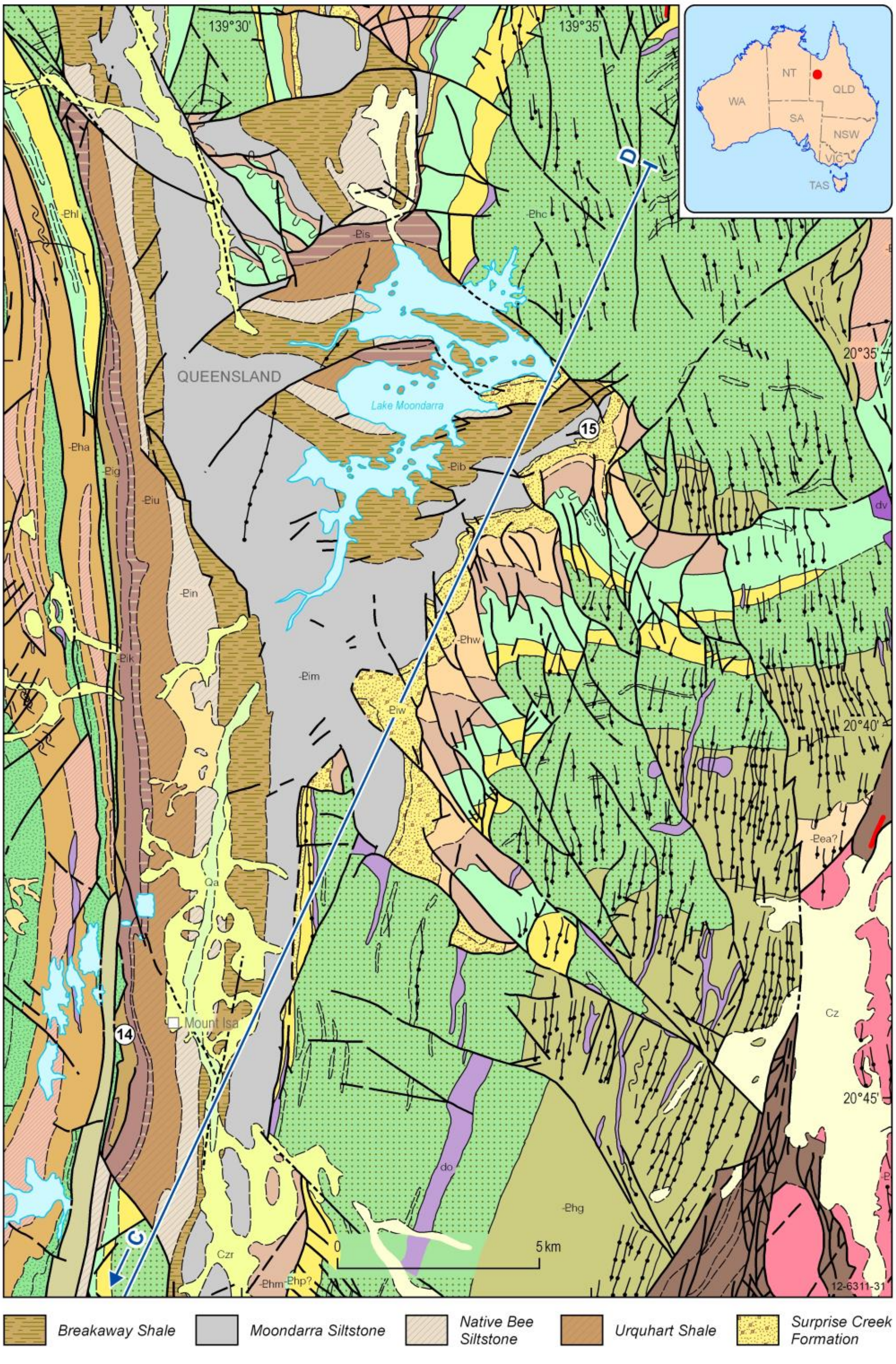


Figure 48: *Geological map of Lake Moondarra area showing reactivated syn-rift structures cutting up section from Leichhardt Superbasin (Brown = Myally Sub-group; green = Eastern Creek Volcanics with interbedded Lena Quartzite = yellow) through overlying Surprise Creek Formation into basal part of Moondarra Siltstone but no higher. Obvious south-verging folds in Breakaway Shale are the result of D1 basin inversion.*

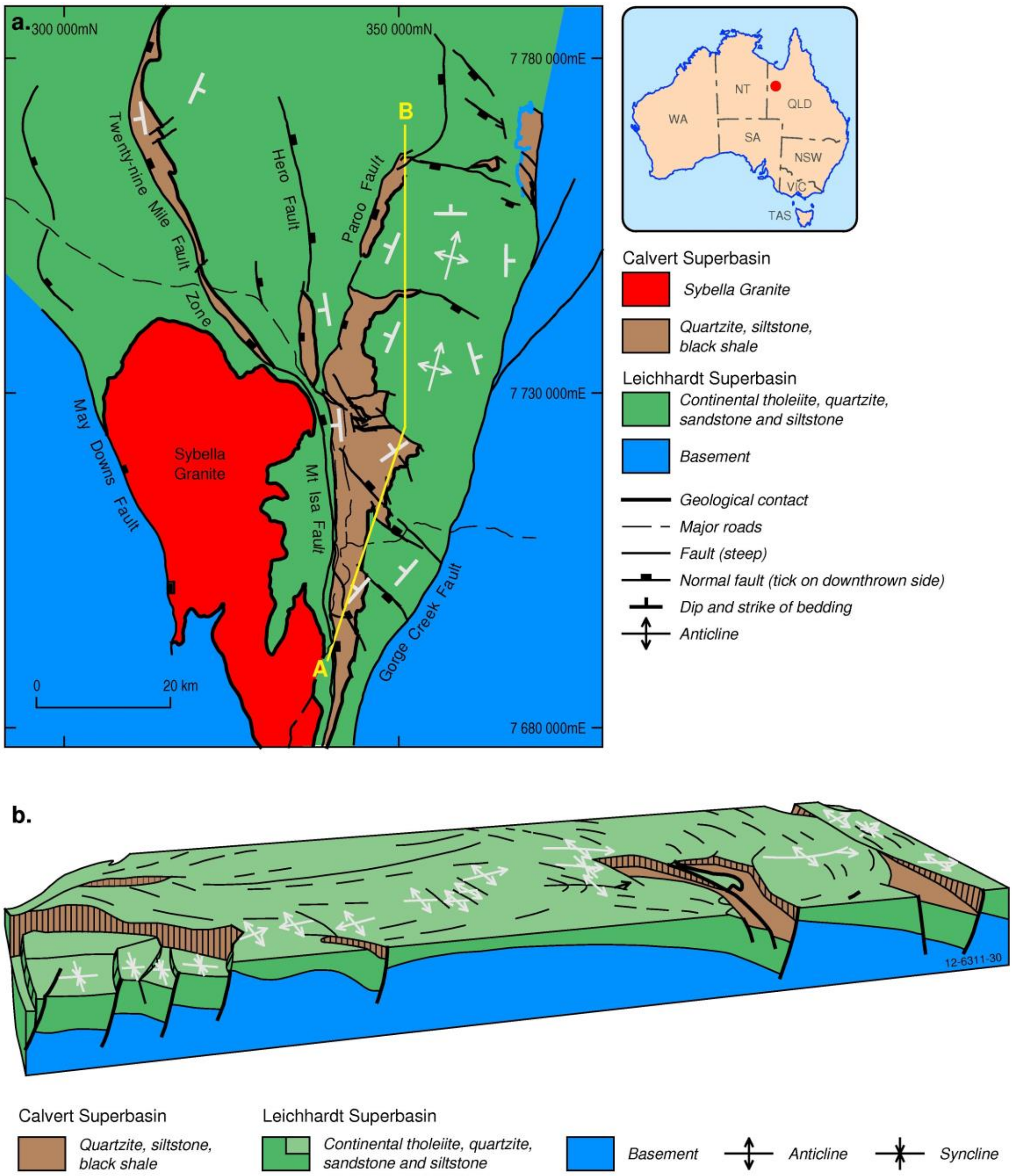


Figure 49: *Simplified district-scale geological map of Mount Isa region and block diagram showing major depocentres into which sediments of the Surprise Creek Formation and Isa Group were deposited. A majority of the associated growth faults are south-dipping.*

As with the rocks around Gunpowder Mine, the rocks around Lake Moondarra have undergone a similar history of D1 (Figure 50) and D2 basin inversion. Basin inversion was accompanied by reactivation of normal faults, some of which were first active during deposition of lowermost Moondarra Siltstone (Figure 48) but ceased to be active by the time the immediately overlying upper Moondarra Siltstone and Breakaway Shale were deposited (Figure 6). The Gun Unconformity, first seen at Esperanza waterhole, marks the boundary between the syn- and post-rift sequences (Prize and Gun supersequences). During basin reactivation, normal faults were reactivated as thrusts, the majority of which are blind and do not penetrate upward into younger parts of the sequence (Figure 50). Instead, the Breakaway Shale and younger units have been deformed into a series of south-verging asymmetric folds (Figure 50) that can be traced down-section into the reactivated normal faults (thrusts). These relations are important in so far as they suggest that the Breakaway Shale and younger units, including the ca. 1653 Ma Urquhart Shale, were not deposited during rifting but represent part of a post-rift sequence. If this is indeed the case, then rifting in the Mount Isa region had ceased before ca. 1653 Ma and probably much earlier as evidenced by the youngest detrital zircon ages obtained (Page et al., 2000a) from the underlying Breakaway Shale (1663 ± 3 Ma) and uppermost Moondarra Siltstone (1668 ± 8 Ma)(Figure 51). Thereafter, the basin was subjected to only post-rift thermal subsidence.

Interestingly, the youngest detrital zircon population in the Moondarra Siltstone (Figure 51) has an age that overlaps the age of Sybella magmatism (Figure 6), raising the possibility that this siltstone was either deposited contemporaneously with volcanism associated with granite intrusion or was derived through erosion of this (by now uplifted) granite.

An episode of basin inversion around ca. 1640 Ma interrupted this phase of thermal subsidence, and after this date the Isa region was again subjected to widespread intra-continental rifting. This event led to further crustal thinning and may even have evolved to the point of seafloor spreading farther east (Figure 7).

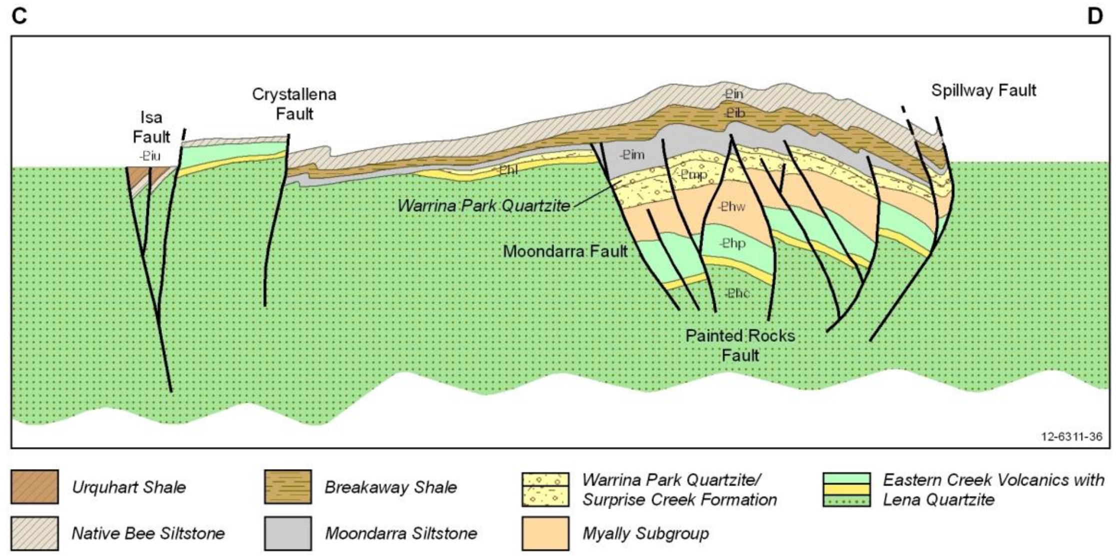


Figure 50: *Structural cross-section through inverted basinal sequences of Leichhardt, Calvert and Isa superbasins in Lake Moondarra area. Note inversion of former normal faults in deeper parts of basin and the absence of such structures in the section above lowermost Moondarra Siltstone. For location of section see Figure 48.*

Rock units in the Mount Isa and George Fisher mines to the west are steeply dipping and bounded along their western margin by the sub-vertical to steeply-dipping Paroo Fault (Figure 49a). The orebody at Mount Isa is located above a ramp or less steeply dipping section of the Paroo Fault below which greenstones of the Eastern Creek Volcanics are developed (Fig. 52). This structure acted as a thrust fault during basin inversion but more likely originated as a normal (growth) fault as evidenced by the fact that the younger strata are in its hangingwall and juxtaposed against older units in the footwall (Figure 52). Other faults in the region share this geometry and were probably similarly reactivated during basin inversion (Figure 49). It is tempting to speculate (Gibson, Hutton & Holzchuch, 2017) that mineralisation was not introduced during deposition of the Urquhart Shale as some researchers have suggested but introduced later during basin inversion (Figure 52). Indeed, given the geometry of this fault, it is more than likely that reactivation and thrusting would have led to dilatancy above the ramp section in the fault thereby greatly facilitating the ingress of mineralising fluids. A syn-tectonic origin for mineralisation has long been advocated by Perkins (1997).

Based on SHRIMP U-Pb zircon ages derived from inferred tuff rocks within the Urquhart Shale, deposition of this unit is estimated to have occurred ca. 1654-1652 Ma (Page and Sweet, 1998). This is identical within error to a SHRIMP 207Pb/206Pb age of 1654 ± 5 Ma obtained from another tuff bed in Paradise Creek Formation farther north (Page and Sweet, 1998).

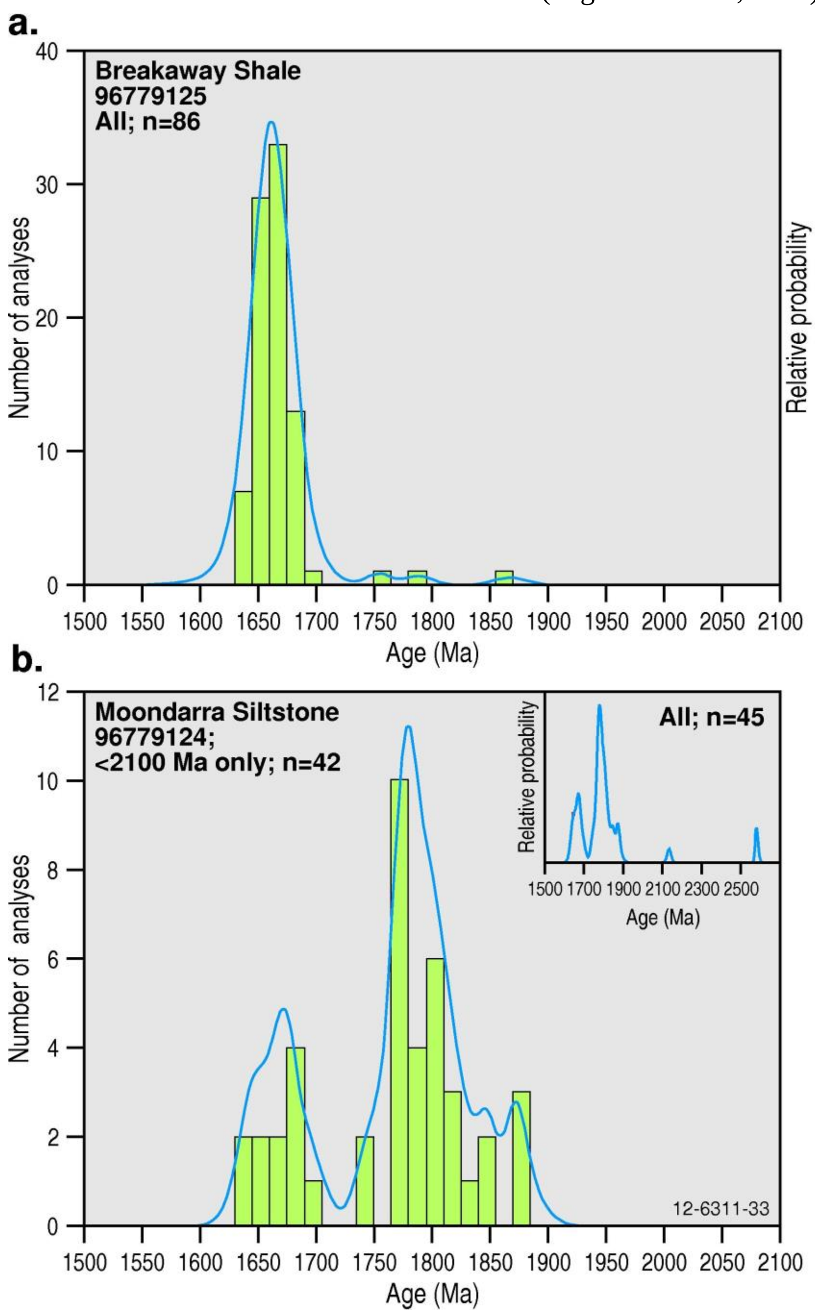


Figure 51: *Detrital zircon age spectra for lowermost Moondarra Siltstone and overlying Breakaway Shale (Page et al., 2000a).*

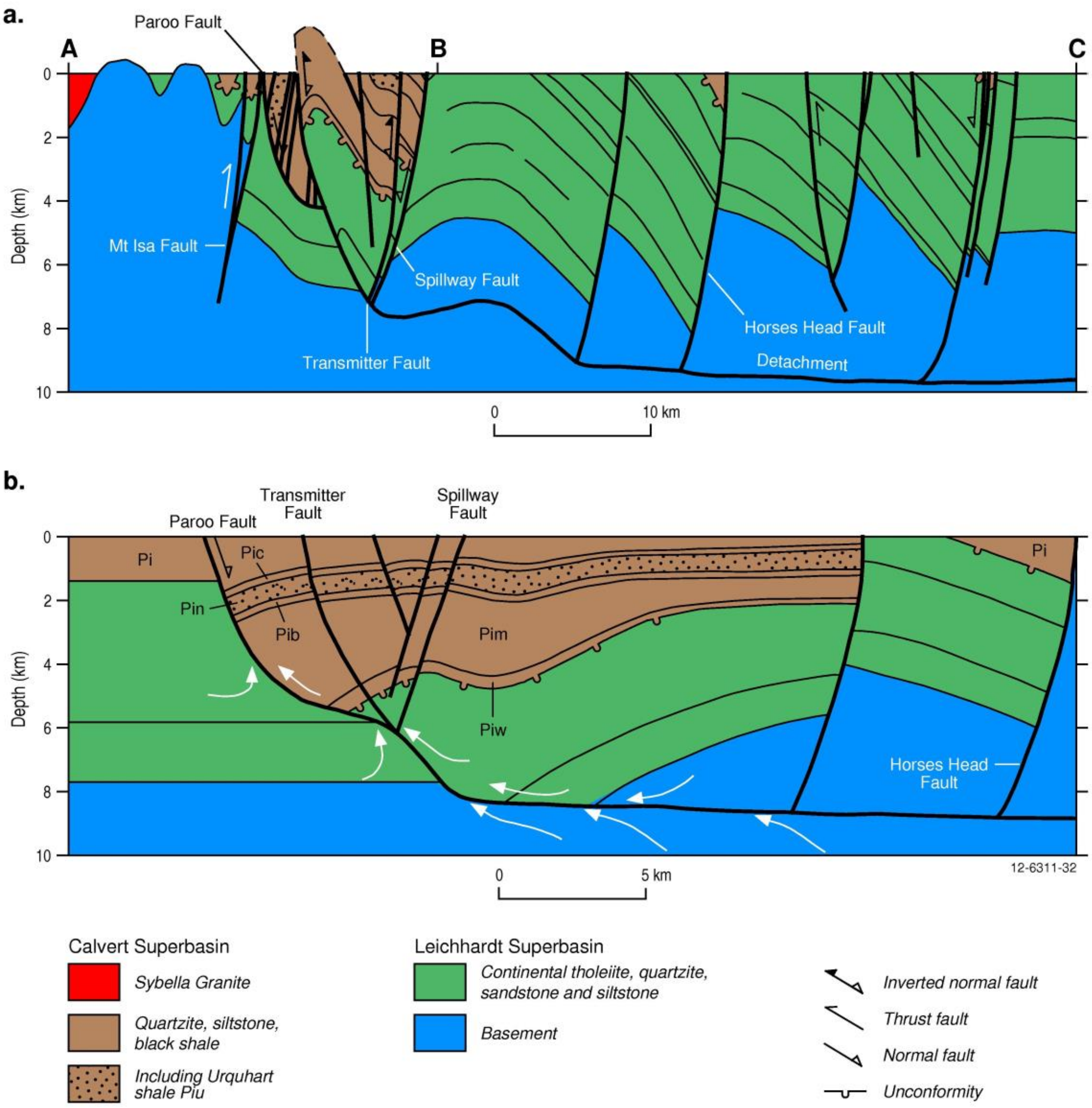


Figure 52: *Cross-section through mineralised sequence at Mount Isa. Note location of Urquhart Shale above ramp or shallow-dipping section in Paroo Fault (Gibson, unpubl.).*

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