


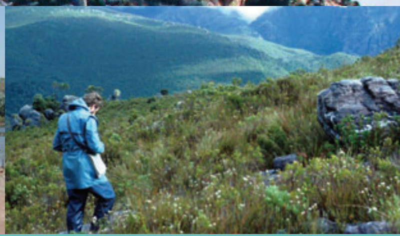


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Mount Isa Crustal Evolution

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Narelle Neumann, Paul Henson and Ben Young (Excursion leader)

A field guide to basin architecture and crustal evolution in the Paleoproterozoic–earliest Mesoproterozoic sequences of Mount Isa, northern Australia: a record of (Nuna) supercontinent breakup

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by

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Contents

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 1685 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 minor deformation and basin inversion at c. 1640 Ma, sedimentation continued across the region until onset of the Isan Orogeny at 1600 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 1640 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 comparable age in western Canada. 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 almost to the point of seafloor spreading (Gibson et al., 2012; Gibson et al., 2008). 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).

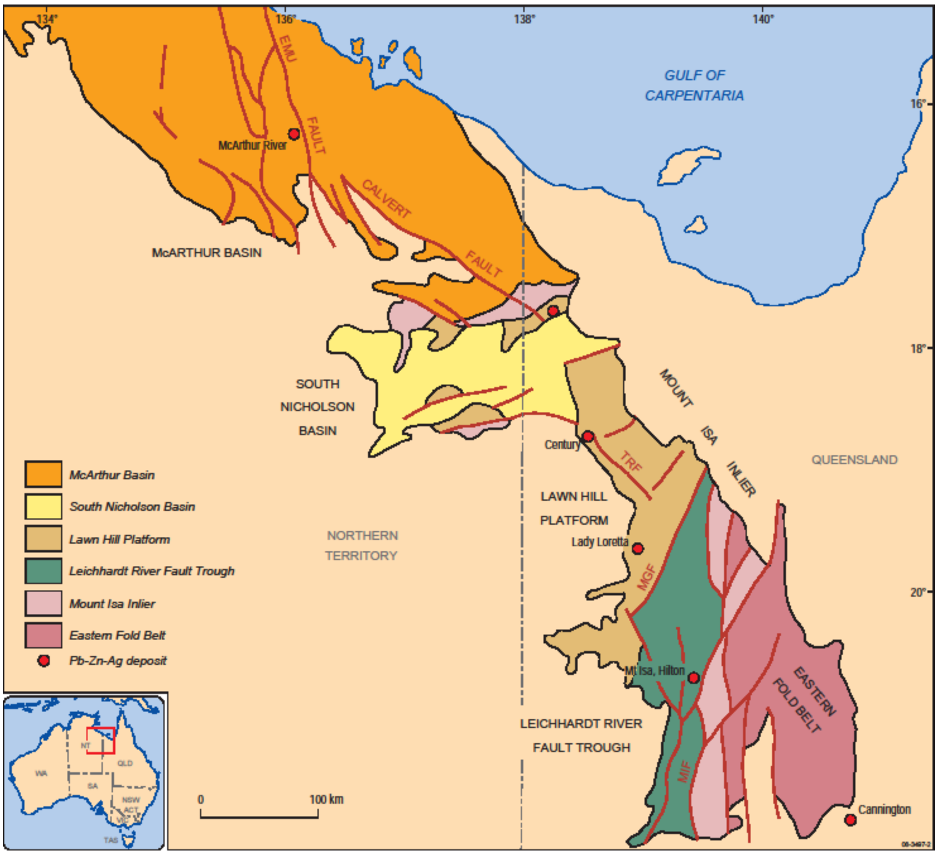

Figure 1. *Principal tectonic elements within the Mount Isa terrain and the Pb-Zn mineral deposits hosted by these different elements. TRF = Termite Range Fault; MGF = Mount Gordon Fault Zone.*

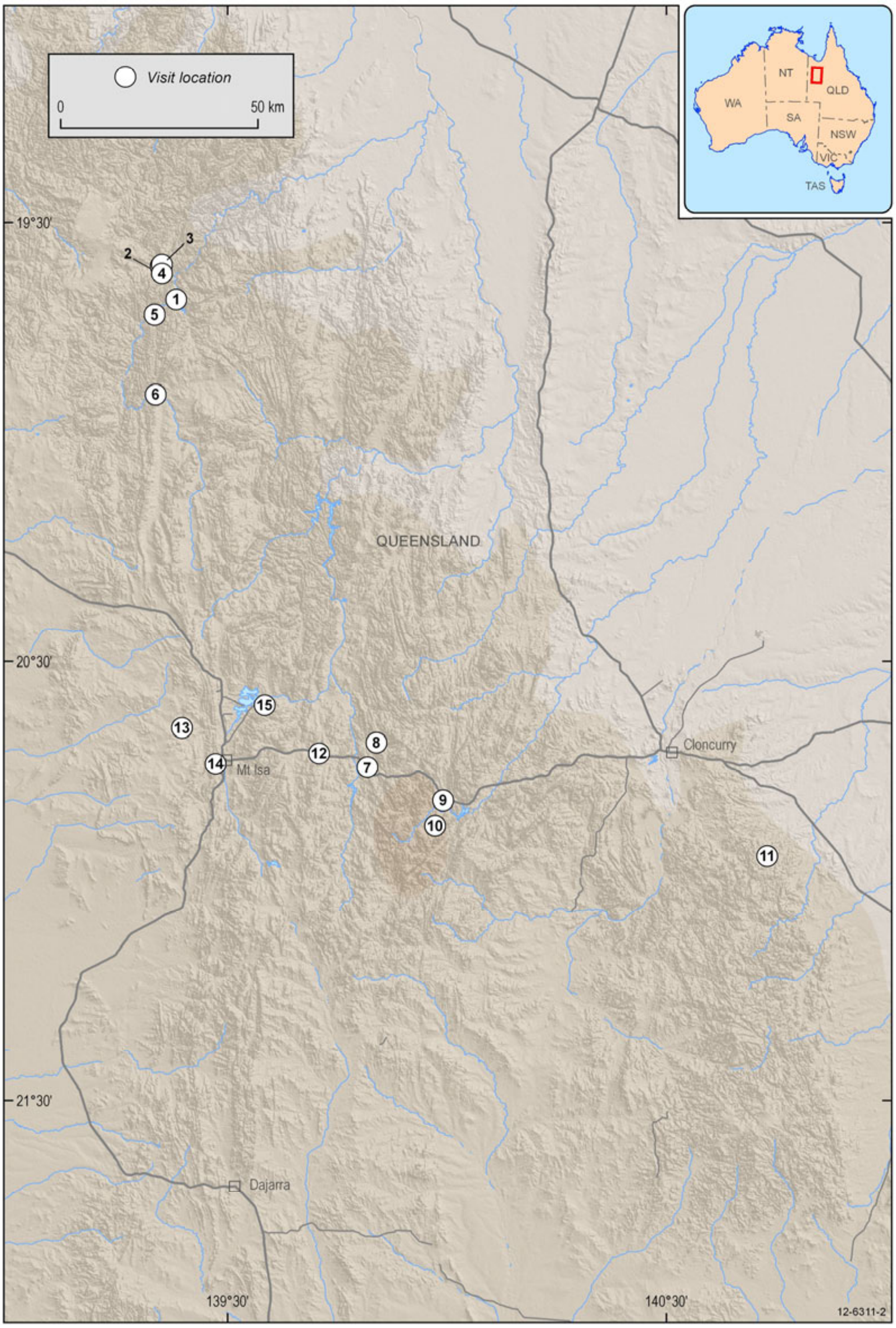

Figure 2. *Digital elevation image showing major roads and tracks, and localities to be visited.*

Excursion Organisation

Excursion Leaders: Dr George Gibson, Geoscience Australia (regional geology and day to day logistics); Mr Ben Young, Xstrata Zinc (Mount Isa mine visit)

Venue: Mount Gordon (Gunpowder) mine and environs: Mount Isa & Cloncurry

Dates: Monday July 30 – Friday August 3, 2012

Arrival in Mount Isa

The excursion commences at Gunpowder Mine at 3:00pm on Monday July 30, thereby enabling participants time to arrive at Mount Isa airport on the mid-day flight from Brisbane. Upon arrival in Mount Isa, participants should congregate outside the airport terminal where the excursion leader and vehicles for the excursion will be waiting. Vehicles will depart from Mount Isa airport for Gunpowder Mine no later than 1:00 pm. The journey to Gunpowder takes about 1.5 hours. Lunch will be picked up in town en route to Gunpowder.

Accommodation & Logistics

Participants remain at Gunpowder mine for two nights (July 30-31) until the morning of day 3 (Wednesday August 1). 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 Gunpowder, and several outcrop visits, the party arrives at Cloncurry and remains there overnight in motel accommodation (Wednesday August 1). The motel will provide an evening meal, breakfast the following morning, and a packed lunch for day 4.

From Cloncurry, the party returns to Mount Isa. The remaining two nights (Thursday August 2 – Friday August 3) are spent in motel accommodation in Mount Isa. All meals will be provided, up to and including breakfast on Saturday, August 4.

The excursion officially ends on the evening of Friday, August 3 (day 5).

Departure from Mount Isa

For those departing on the mid-day flight on Saturday August 4, 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 Xstrata, one of the sponsors of IGC. Plan to set aside two hours for both the film and museum visit; cost per adult is $20.

General Information

As with all Australian mines, visitors staying on site at Gunpowder will be required to undergo a standard OH&S test for alcohol and drugs. This test is routine and nothing to be alarmed about. In order that this test be conducted efficiently and with the least amount of inconvenience to visitors, it is advisable that personal details, including any condition for which medication is being taken, be made available to the on-site medical officer in advance of the visit. A form to this effect should already have been filled out and returned to the field excursion organisers (Quadrant).

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.

On mine visits you will be provided with standard safety equipment – hard hat, steel capped boots, safety vest and goggles. It is also a condition for mine site visits that you be properly attired, including the wearing of a long-sleeved shirt and long trousers.

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).

Some researchers have further argued that this basin was located above a north-dipping subduction zone along the southern margin of the Australian craton (Betts et al., 2011; Betts et al., 2008; Giles et al., 2002). A near-identical tectonic environment has been proposed 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), reinforcing earlier 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). Rather, there is a strong possibility that the older 1800–1600 Ma rift basins of eastern Australia and western Laurentia are genetically related and share a common evolutionary history linked to breakup of a pre-Rodinia supercontinent (Zhao et al., 2002). Other researchers are in favour of links 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).

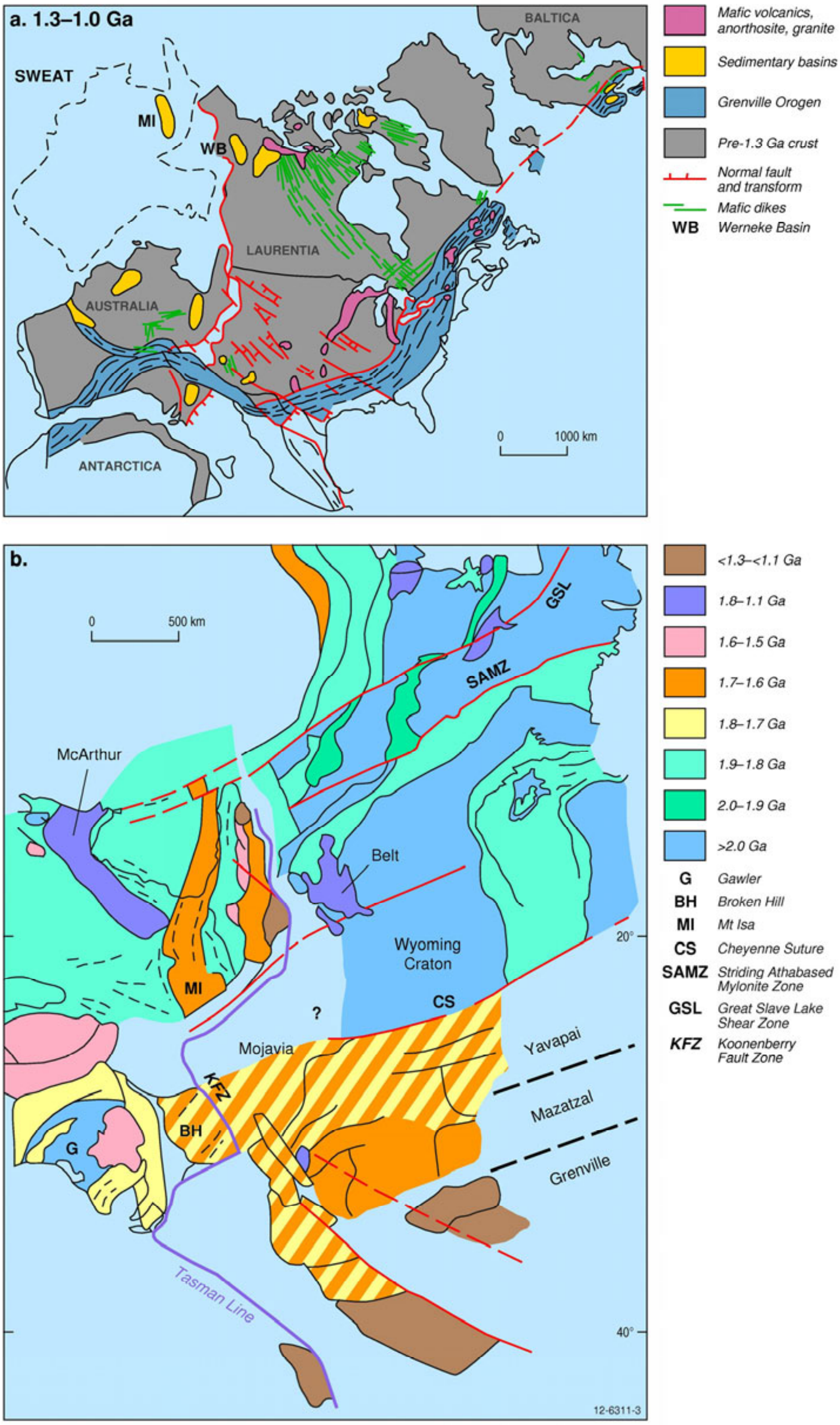

Figure 3. *(a) AUSWUS versus SWEAT reconstruction of Australian and Laurentian rifted margins for Neoproterozoic time. SWEAT restores Australia (dotted outline) and Mount Isa to much the same position opposite NW Canada as existed at the time of the Paleoproterozoic Nuna supercontinent. (b) More detailed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

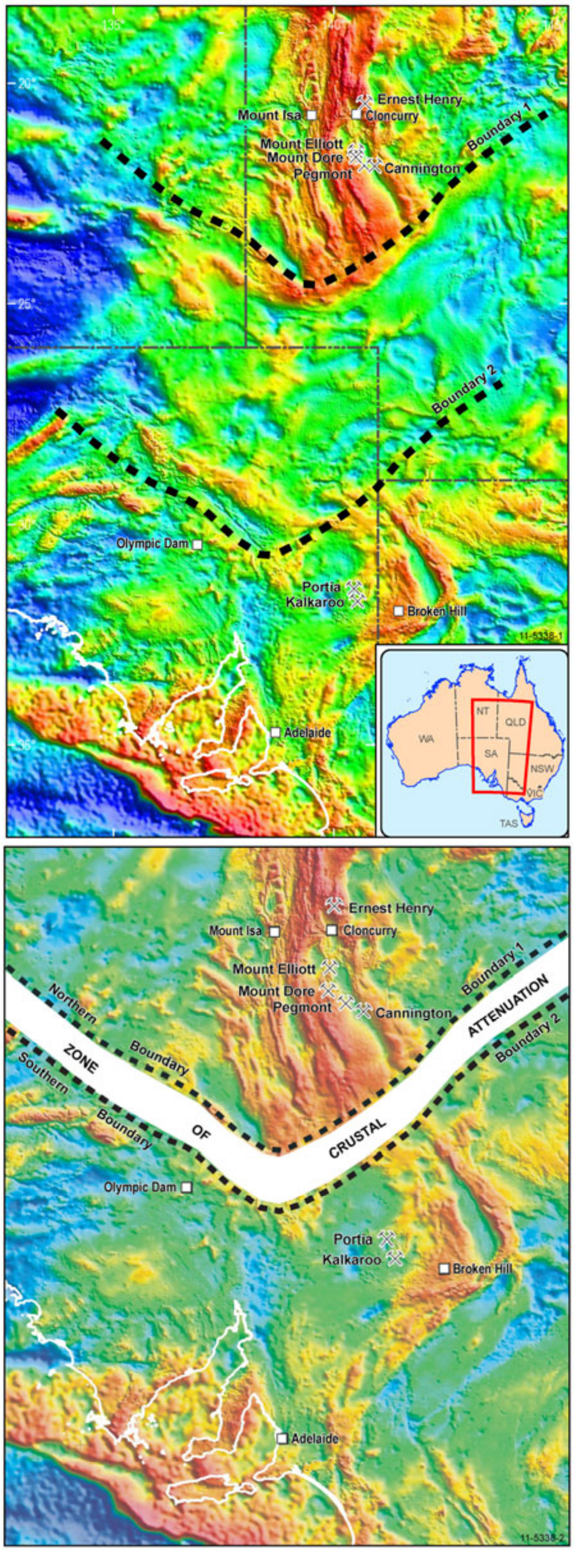

Figure 4. *(a) Uninterpreted gravity anomaly image with Mount Isa and Broken Hill in present-day configuration. (b) Gravity image with Broken Hill basement terrane restored to its pre-Rodinia breakup position opposite the Mount Isa region (after Henson et al., 2011). Note coincidence of Cloncurry-Cannington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

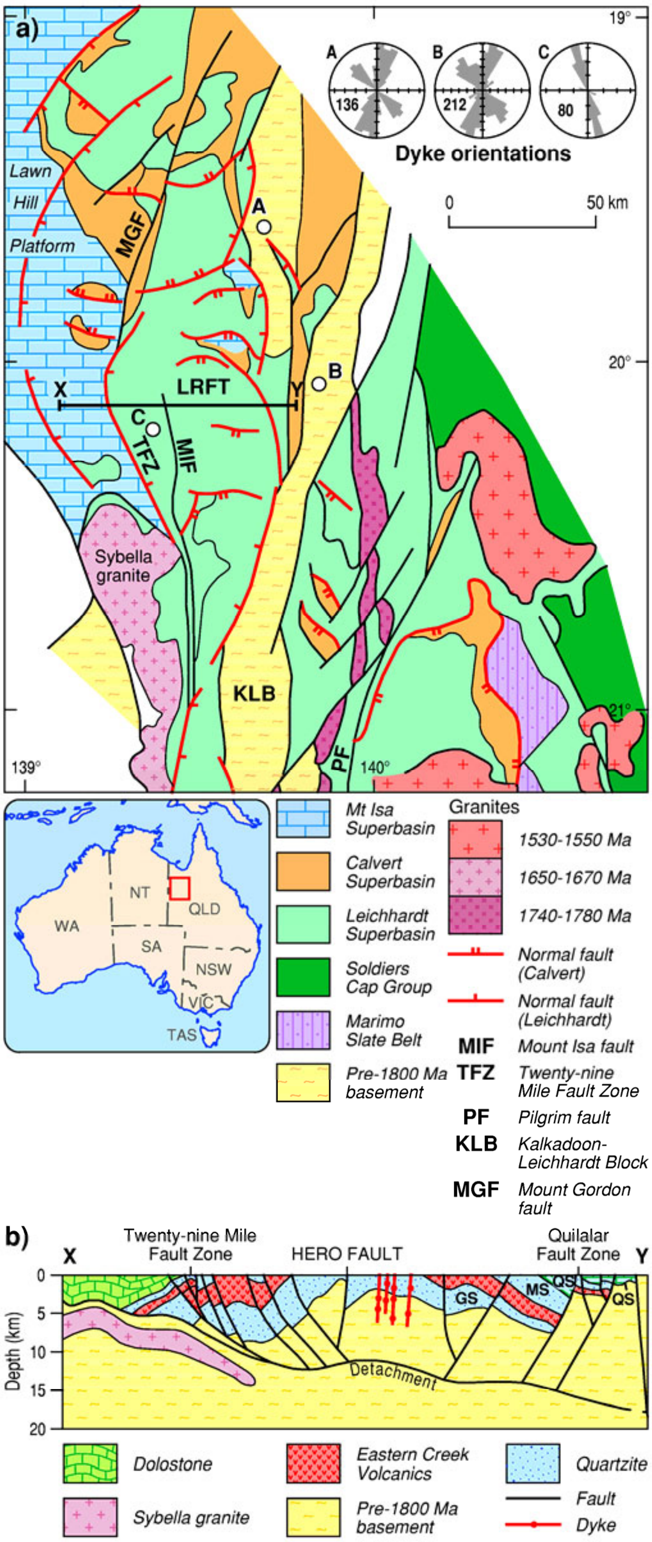

Figure 5: *Simplified geologic map and section for northern part of Leichhardt River Fault Trough (LRFT). Note switch in direction of stratal thickening into Quilalar and Twenty-nine Mile Fault zones at c. 1775 Ma, and parallelism between measured dike orientations (insets A, B and C) and normal fault 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).

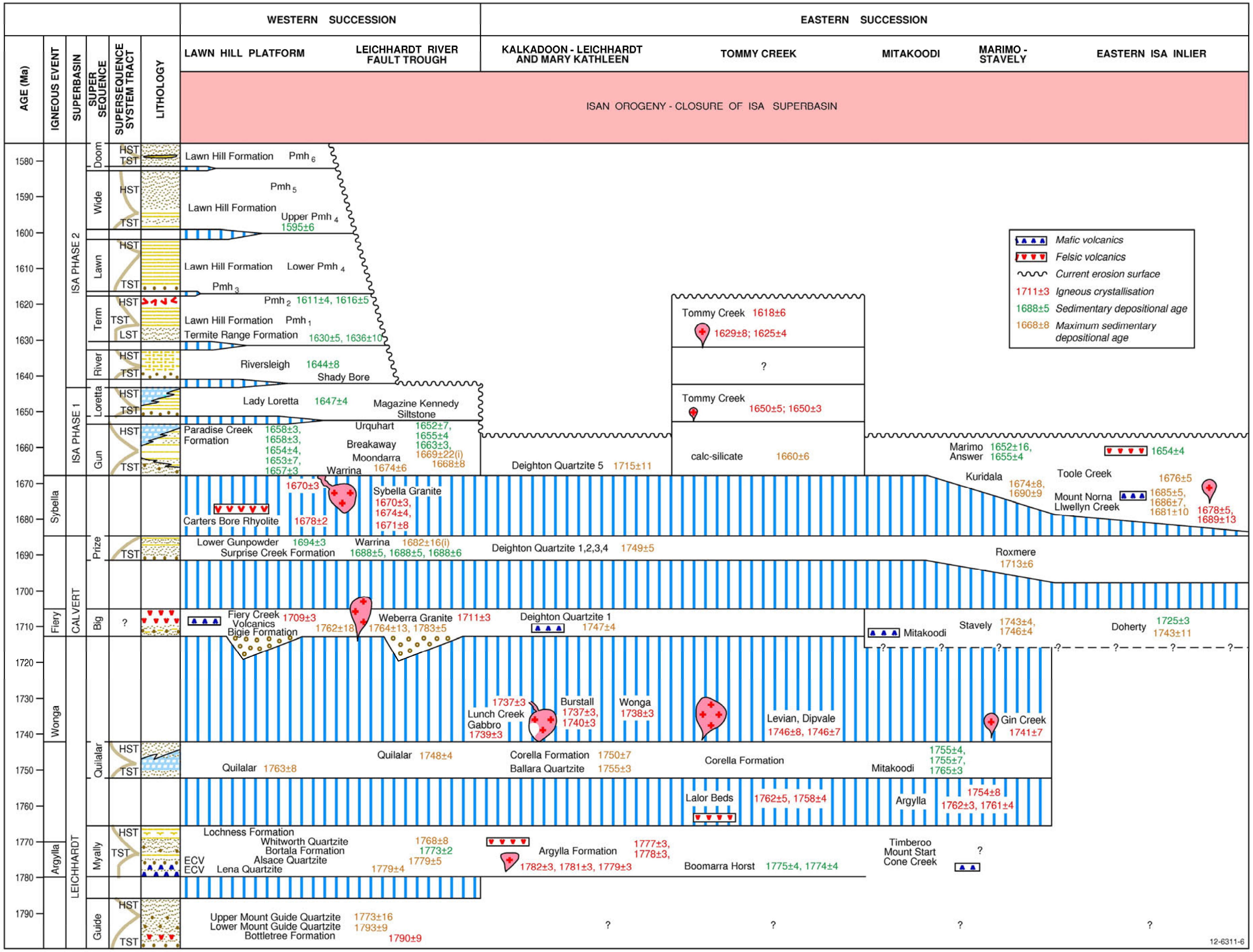

Figure 6: *Chronostratigraphy and interpreted kinematic history for Leichhardt, Calvert and lowermost part of Isa superbasins in Mount Isa region (after Neumann et al., 2006; 2009a; 2009b; Page et al., 2000).*

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., 2000b). 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.

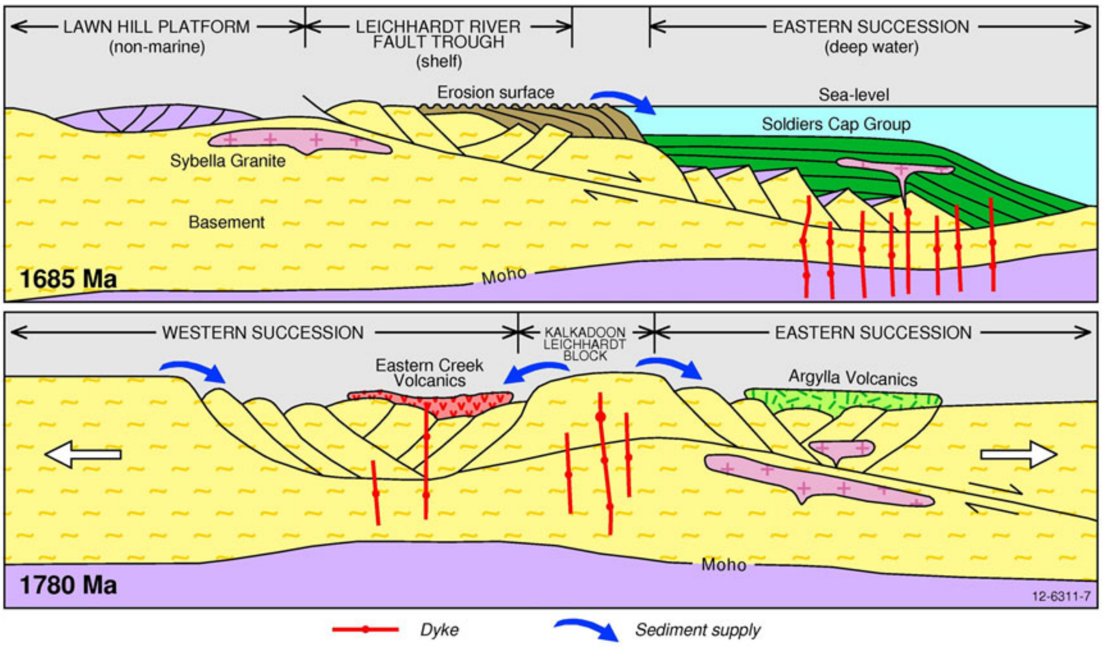

Figure 7: *Generalised W-E crustal sections illustrating links between basin formation, magmatism and syn-extensional detachment faulting in Leichhardt (bottom) and Calvert superbasins (top). Note erosion and reworking of previously deposited platform and near-shore sequences (Prize Supersequence) to 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).*

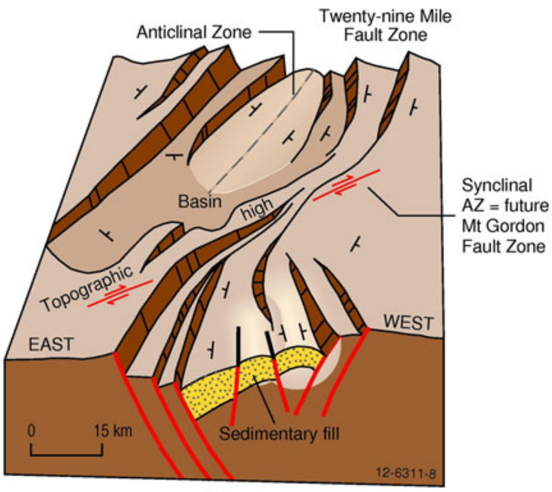

Figure 8: *Schematic representation of basin architecture and fault geometry in the northern part of the Leichhardt River Fault Trough looking south. The future Mount Gordon Fault Zone formed along the accommodation zone (AZ) located between the two sub-basins (after Gibson et al., 2012).*

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.

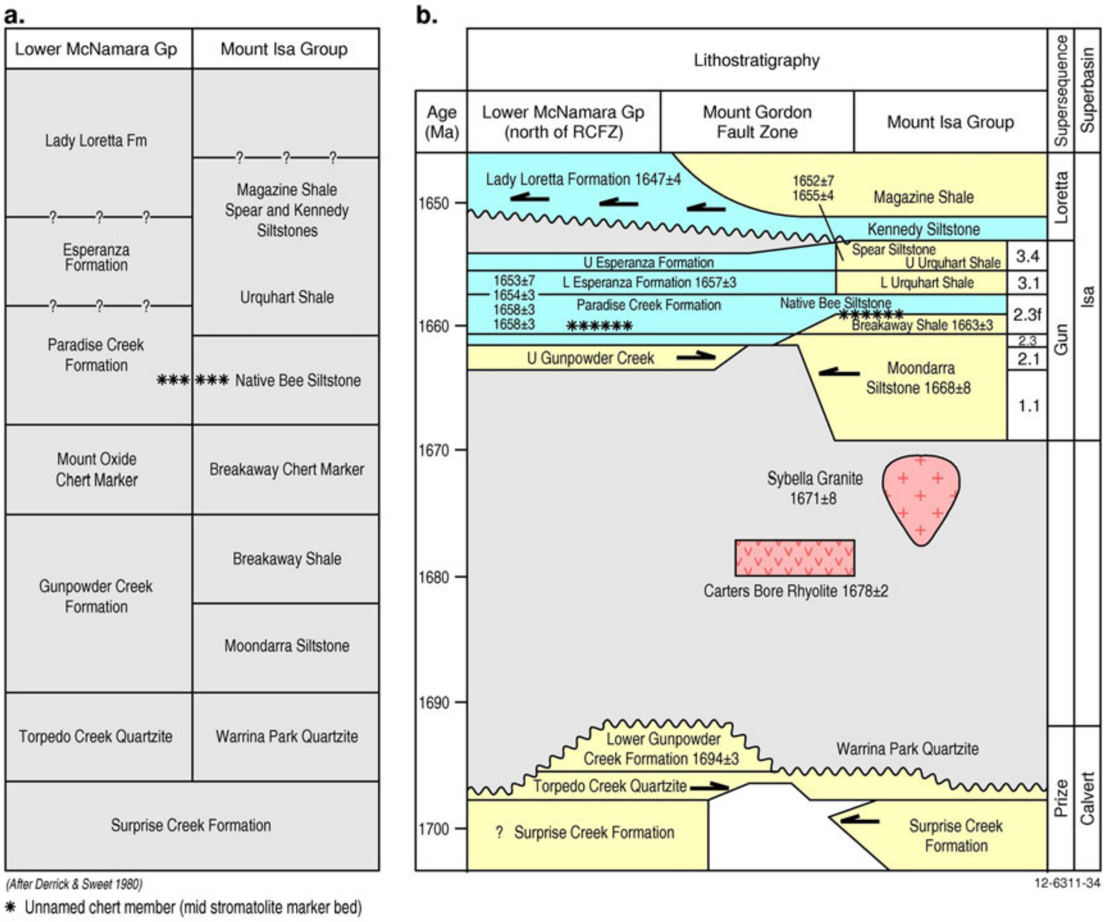

Figure 9: *(a) Correlation of lithostratigraphic units within the McNamara and Mount Isa groups (after Derrick and Sweet, 1980); (b) Alternative correlation of McNamara and Mount Isa groups based on sequence stratigraphy (after Southgate et al., 2000). The major transgressive surface and corresponding 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 potion 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., 2000b).

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.*

Monday July 30
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, Gunpowder Mine.

Tuesday July 31
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, Gunpowder Mine.

Wednesday August 1
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

Thursday August 2
8.30am – 5.00pm. Deep water turbidite facies (Soldiers Cap Group). Kalkadoon-Leichhardt basement rocks; Sybella Granite and Mica Creek extensional fabrics. O'night, Mt Isa

Friday August 3
8.00 - 5:30 Mount Isa mine visit (morning). 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.

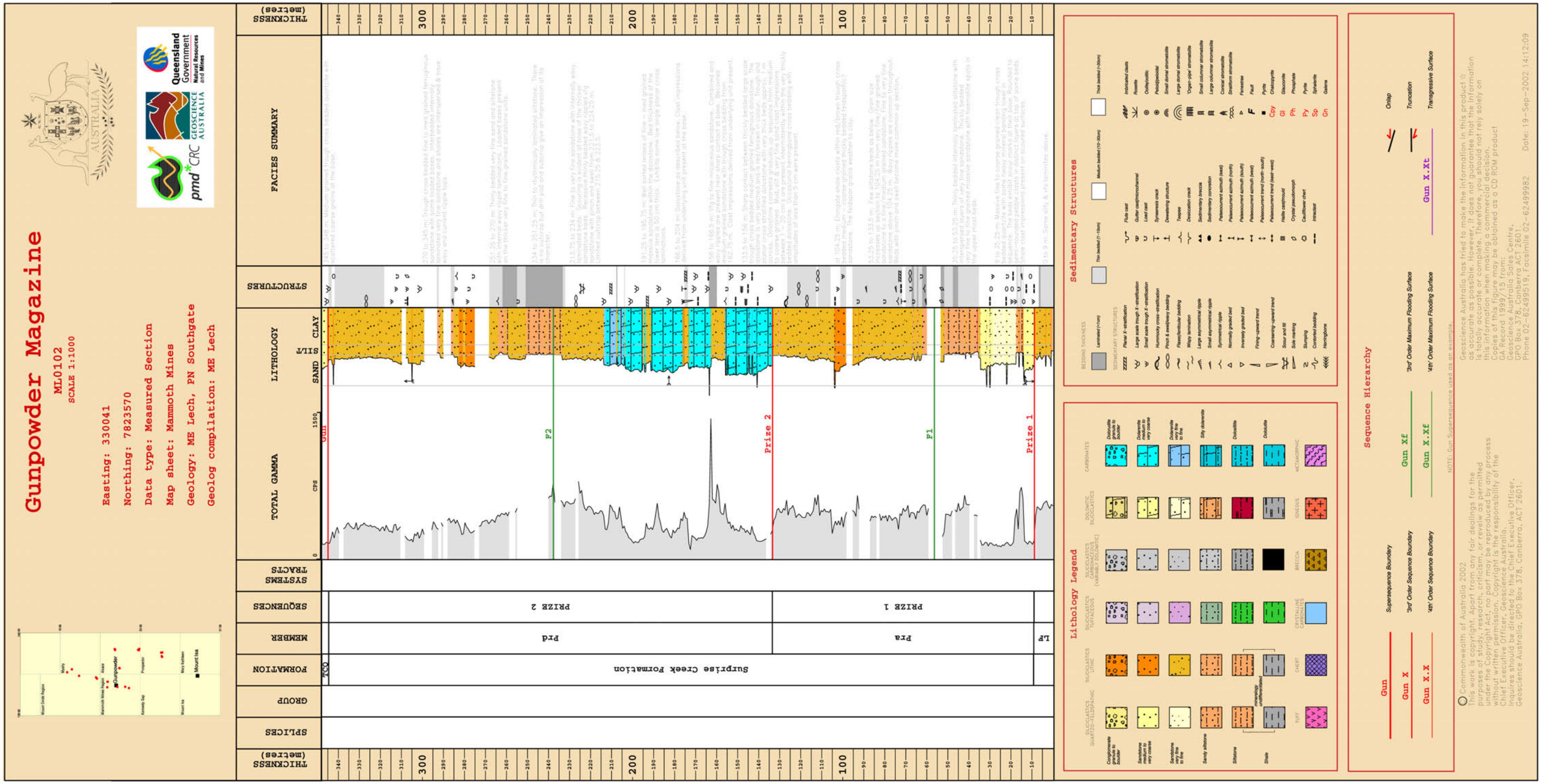

Figure 10: *Measured section/stratigraphic column for Gunpowder Magazine locality (Jackson et al., 2002). Bulk of section is through uppermost Surprise Creek Formation (Calvert Superbasin) and lower part of Isa Superbasin.*

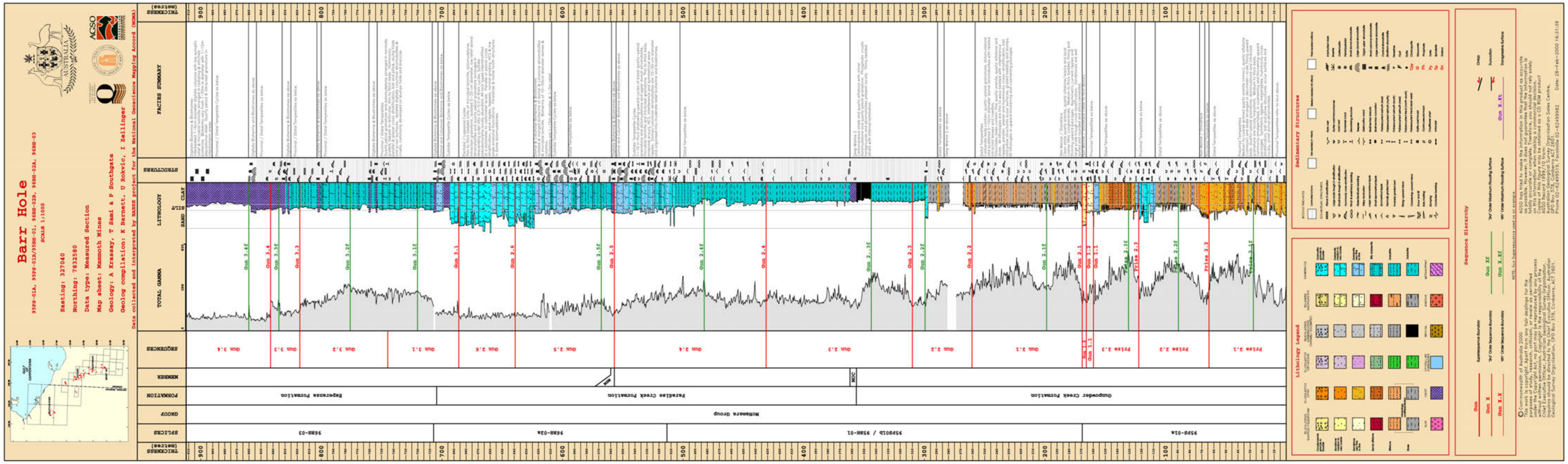

Figure 11: *Stratigraphic column for Barr Hole section in Torpedo Creek (Southgate et al., 1999). Stratigraphy is same as in Gunpowder Magazine section.*

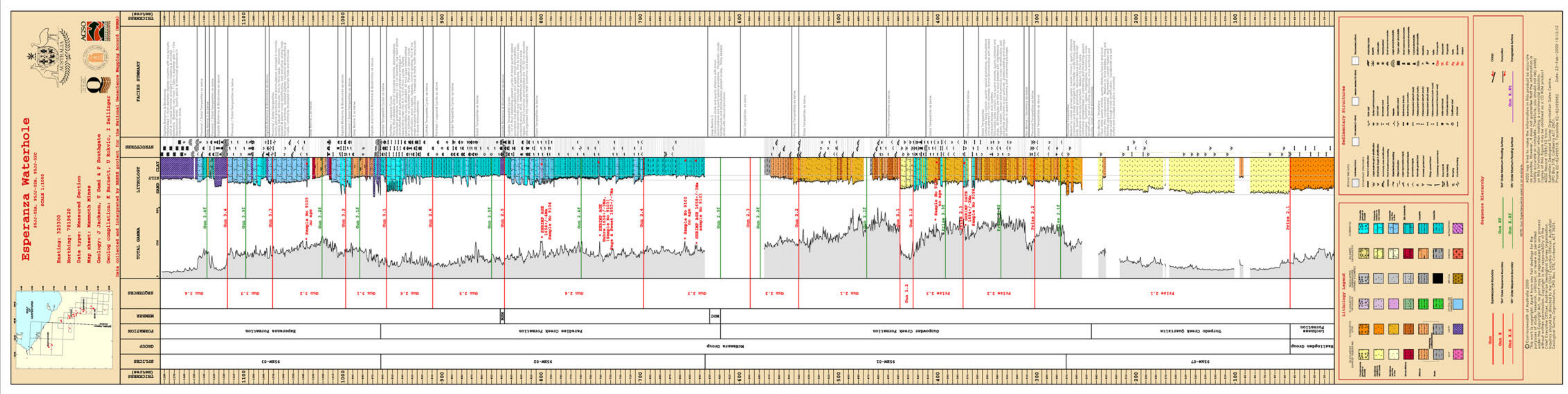

Figure 12: *Measured section for Esperanza Waterhole along strike from both the Barr Hole (Southgate et al., 1999) and Hole-in-Wall sections. The Gun Unconformity is well exposed in this section as is lowermost part of the Isa Superbasin.*

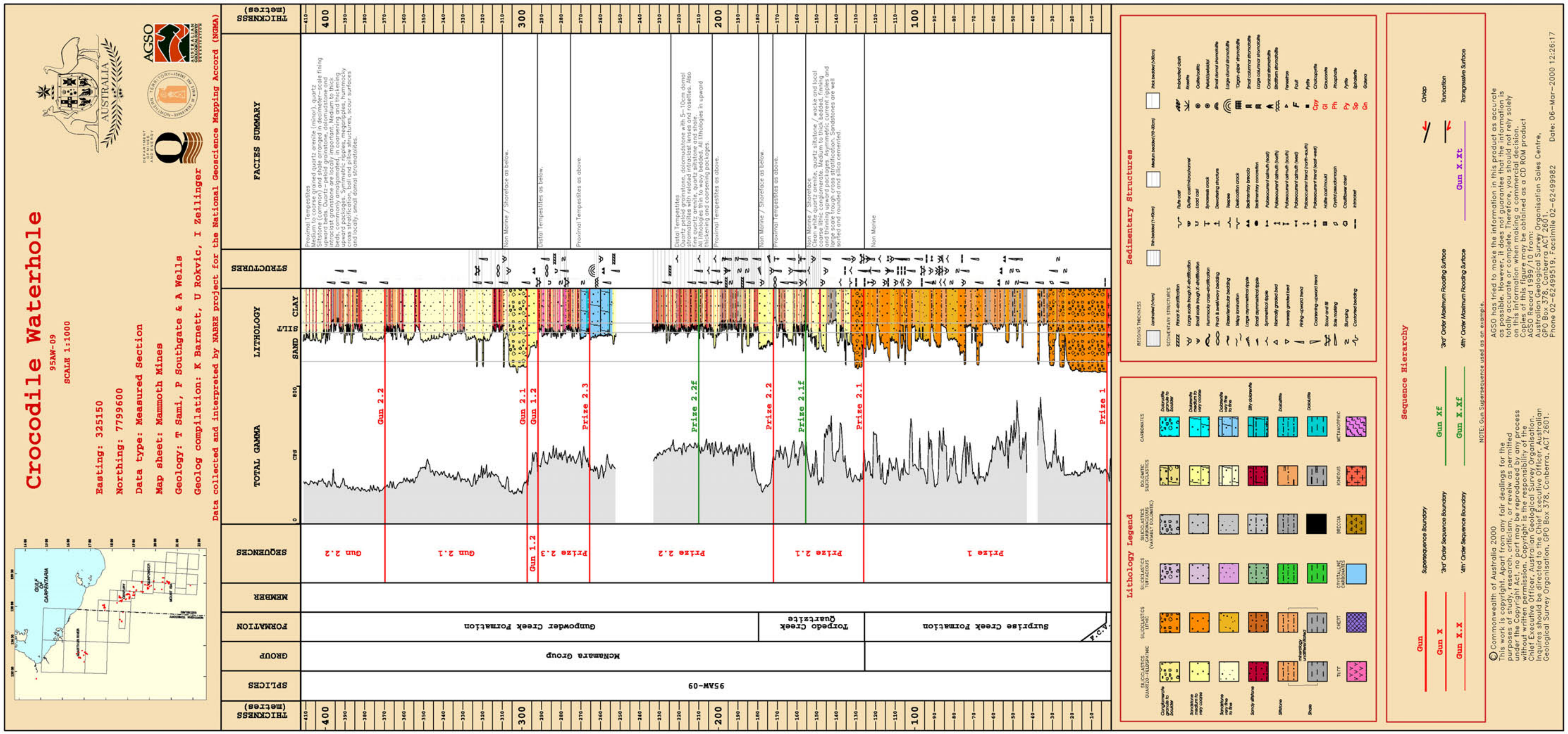

Figure 13: *Crocodile Waterhole and condensed section through Calvert Superbasin into lower units of overlying Isa Superbasin (Southgate et al., 1999). Conglomerates (Bigie Formation) at the base of the Calvert Superbasin are channelized and deeply incised into rocks of the underlying Leichhardt Superbasin.*

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).

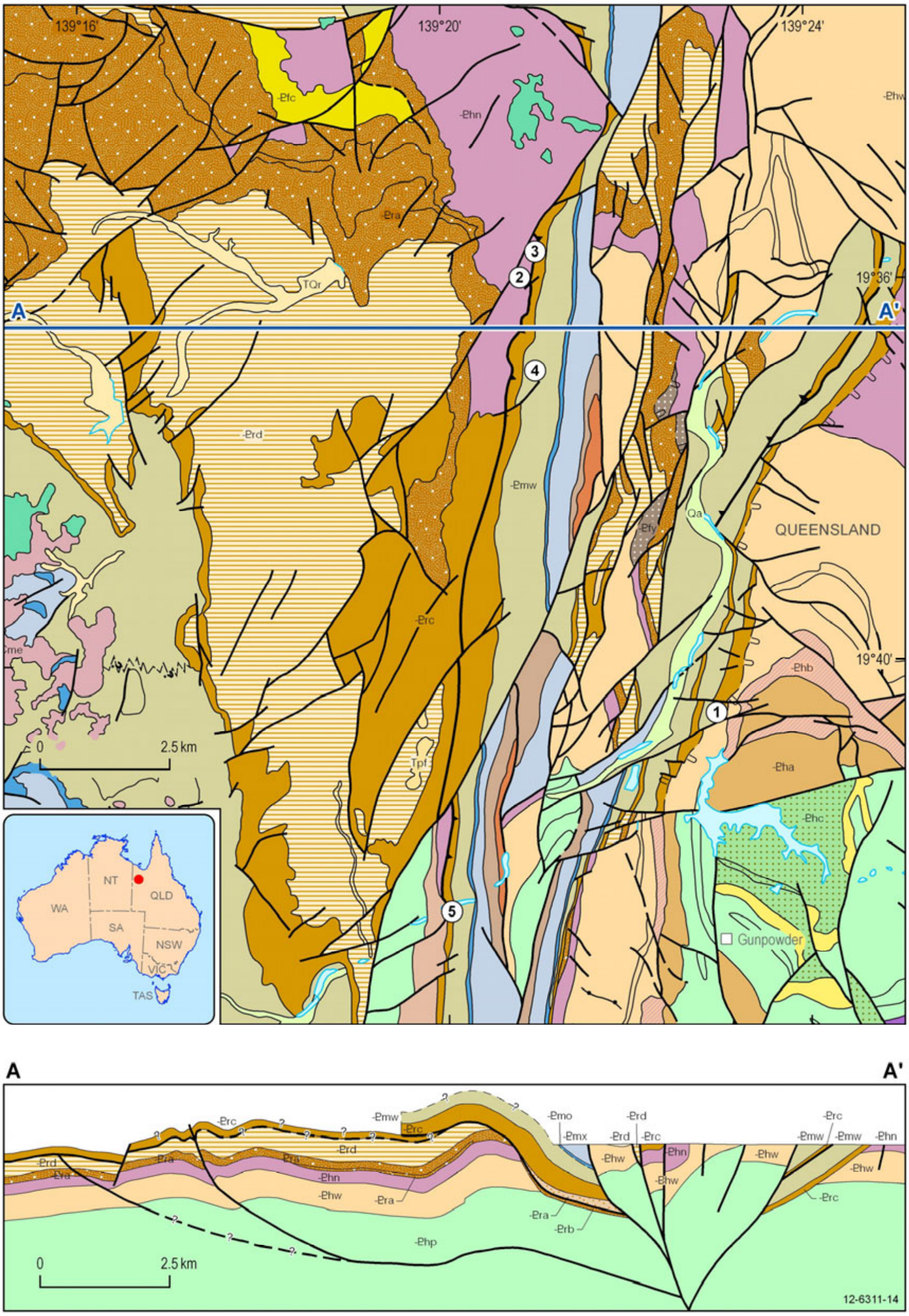

Figure 14: *Geological map and structural cross-section of region around Gunpowder Creek and Mount Gordon Mine.*

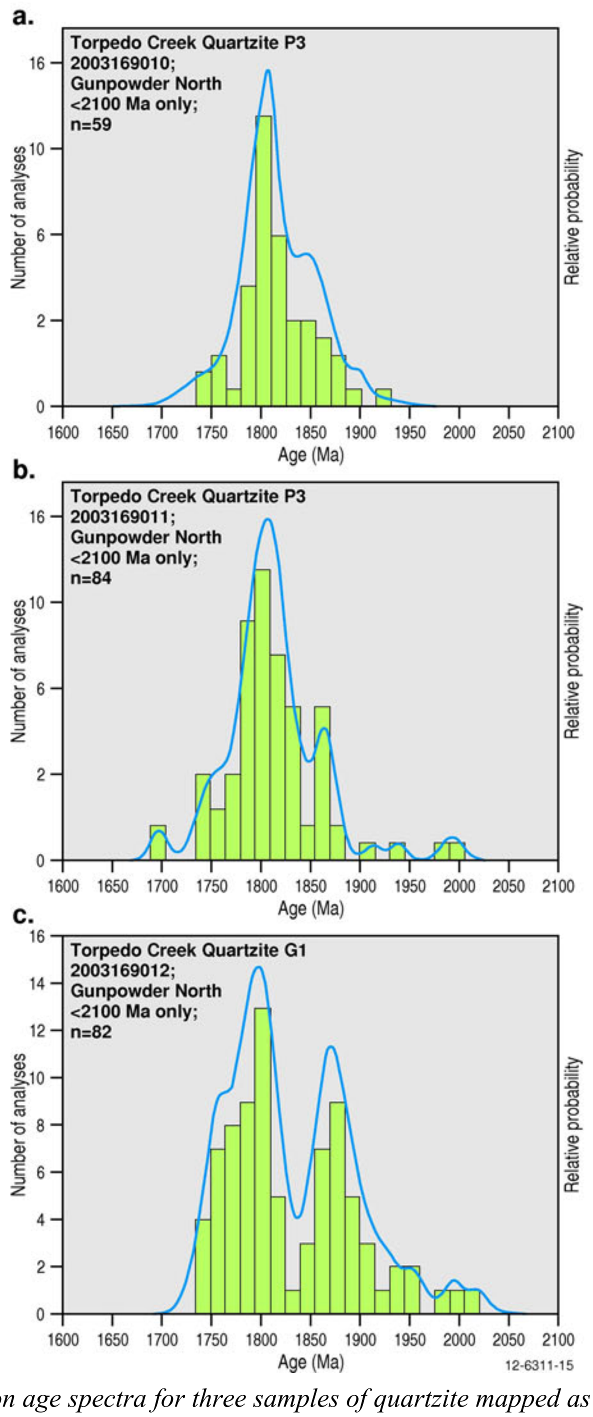

Figure 15: *Detrital zircon age spectra for three samples of quartzite mapped as Torpedo Creek Quartzite at base of Isa Superbasin (Neumann et al., 2009b).*

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.

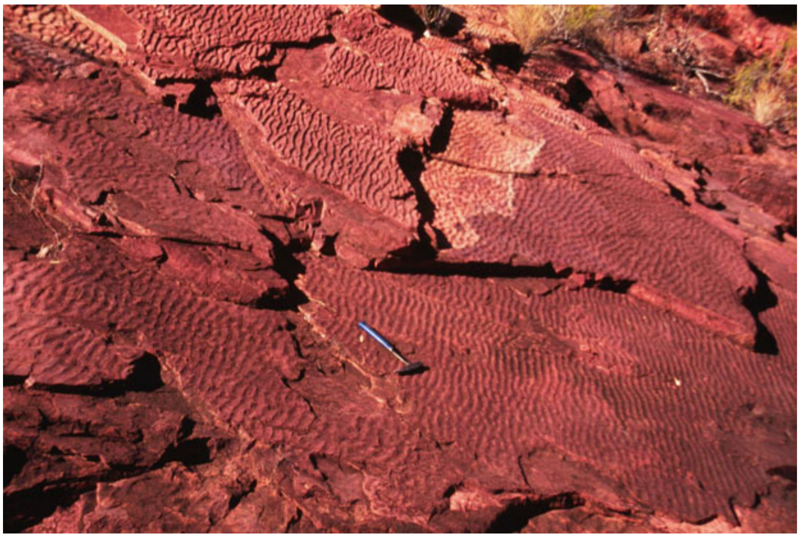

Figure 16: *Redbeds (former mud-flats) in Lochness Formation.*

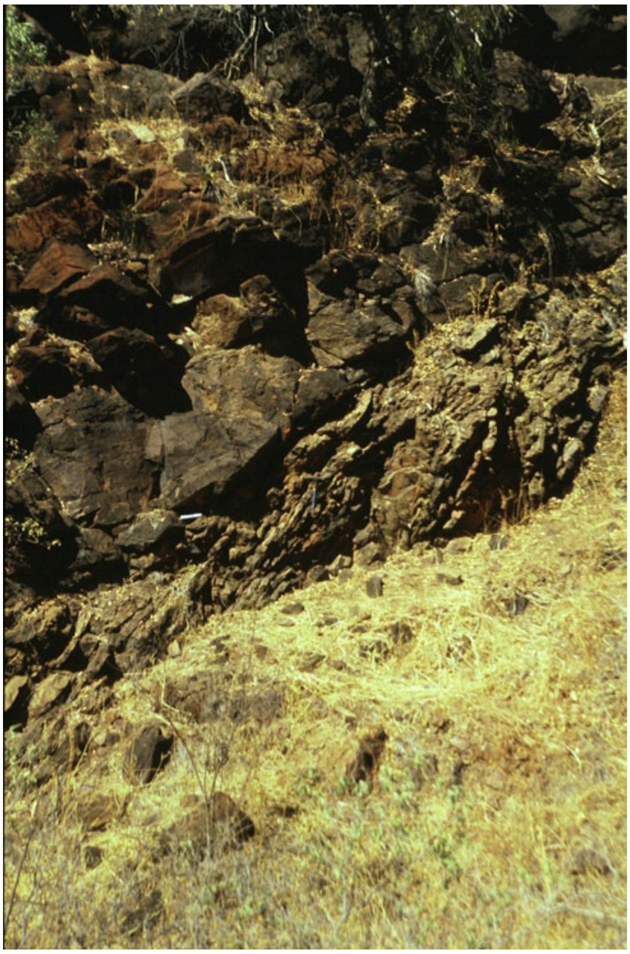

Figure 17: *East-dipping thrust contact between black-weathering gritty dolostone in hangingwall and thin-bedded sandstone and siltstone in footwall. Footwall rocks are deformed into series of variably plunging folds consistent with oblique reverse dip-slip on fault. Hangingwall and footwall rocks have 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., 2000b) 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.

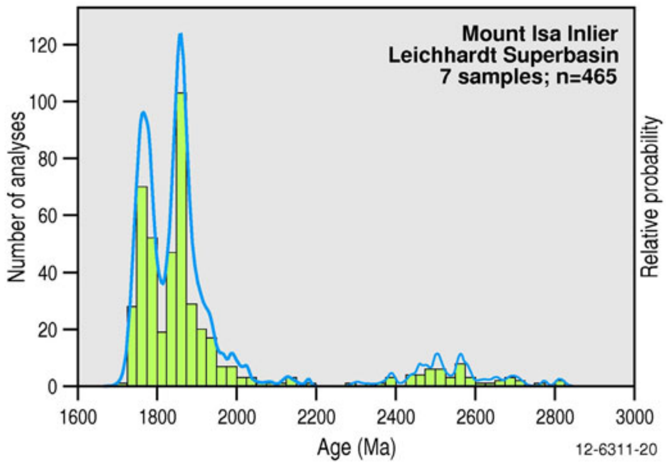

Figure 20: *Detrital zircon age spectra for seven sedimentary rocks in Leichhardt Superbasin. Note prominent peaks at ca. 1780-1760 Ma and 1860-1840 Ma consistent with a source region in both the 1780-1760 Ma Argylla Formation and 1860-1840 Ma granites of the Kalkadoon-Leichhardt block.*

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.

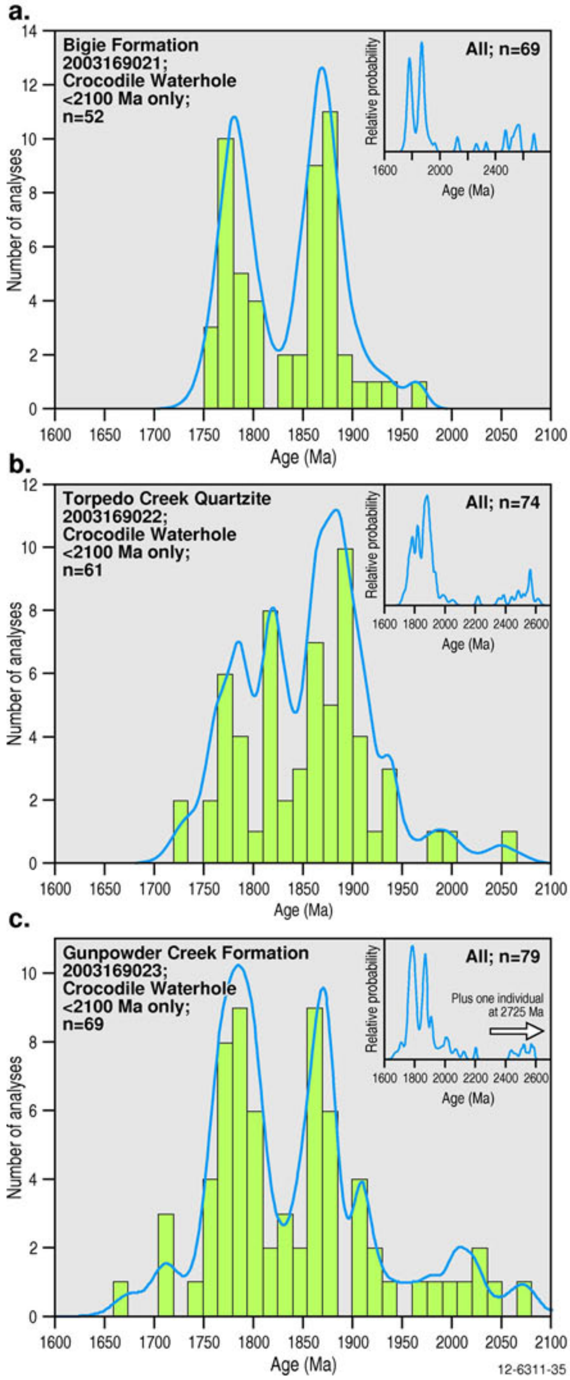

Figure 21: *Dominant peaks in detrital zircon age spectra for successively younger rock units at Crocodile Waterhole. (a) basal conglomerate at base of Calvert Superbasin (Bigie Formation); (b) "Torpedo Creek Quartzite" and (c) upper Gunpowder Creek Formation. Main peaks in each sample are the same peaks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

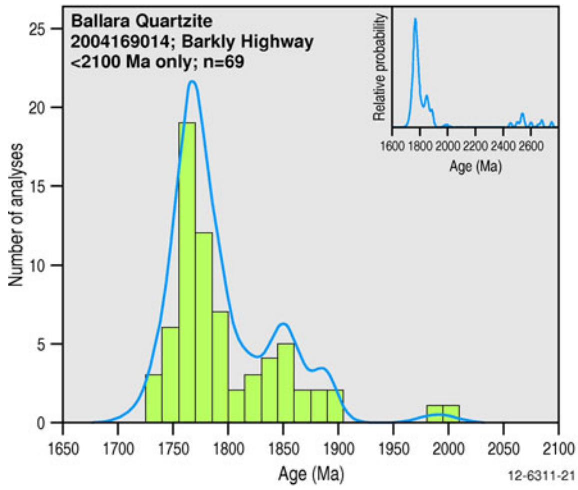

Figure 22: *Detrital zircon age spectrum for Ballara Quartzite, Barkly Highway*

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).

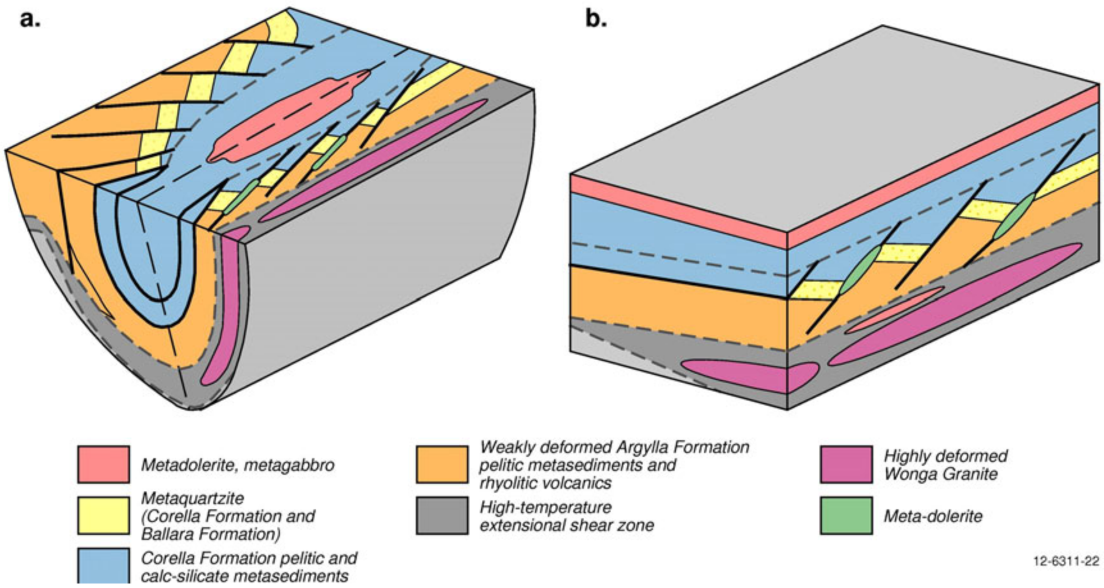

Figure 23: *(a) Schematic representation of folded rock units and stratigraphy in upper and lower plates separated by detachment surface in Rosebud Syncline; (b) Rosebud stratigraphy restored to pre-folding configuration. Note doleritic dykes intruded along normal faults.*

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; (2) 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.

Day 4 – Soldiers Cap Group, Kalkadoon-Leichhardt Block and Sybella Granite

Locality 11: Deep water turbidites (Soldiers Cap Group)

Soldiers Cap Group is the dominant unit making up the eastern part of the Mount Isa region (Figure 26). Some of the best exposures occur in Snake Creek to the southeast of Cloncurry. To reach this locality, follow the Barkly Highway eastward out of Cloncurry as far as the conjuction with the Landsborough Highway (A2 to Winton) and then turn right into the latter. After about 9km, leave the bitumen and turn right onto the gravel road that leads to Mount Norna. Continue south along this road for 15km and then take the left fork to Roxmere Station. Snake Creek is reached 7 km after leaving the fork in the road.

The lowermost part of Soldiers Cap Group comprises quartzofeldspathic turbidites intruded by metadolerite (Llewellyn Creek Formation). It is overlain by a 2800 metre-thick upward fining sequence of quartzite and psammopelitic rocks (Figure 27) intercalated with lesser amounts of amphibolite and metadolerite (Mt Norna Quartzite).

Overlying the Mt Norna Quartzite is a sequence of metabasalt and metadolerite intercalated with lesser amounts of quartzite, pelitic schist and ironstone
mapped as the Toole Creek Volcanics. Metabasaltic rocks in all three units, including the amphibolites and metadolerites, are typically highly evolved, high Fe-tholeiites containing between 11 and 20% $Fe_2 0_3$,; their compositions are consistent with intrusion into an extensional environment or region underlain by thinned and highly attenuated continental crust. The Toole Creek Volcanics are not particularly well exposed and only Mt Norna Quartzite is visited at this locality on Snake Creek.

Turbidites of the Mt Norna Quartzite exposed in Snake Creek are thin- to thick-bedded and commonly conspicuously graded with coarse sandstone at the base, grading upward into thin siltstone or shale (Figure 28). Bleaching is extensively developed in some sandstone-dominated packages, a legacy of fluid migration and albitisation along late fractures. Despite being metamorphosed up to the amphibolite facies, andalusite is not often developed at this locality owing to a lack of suitable

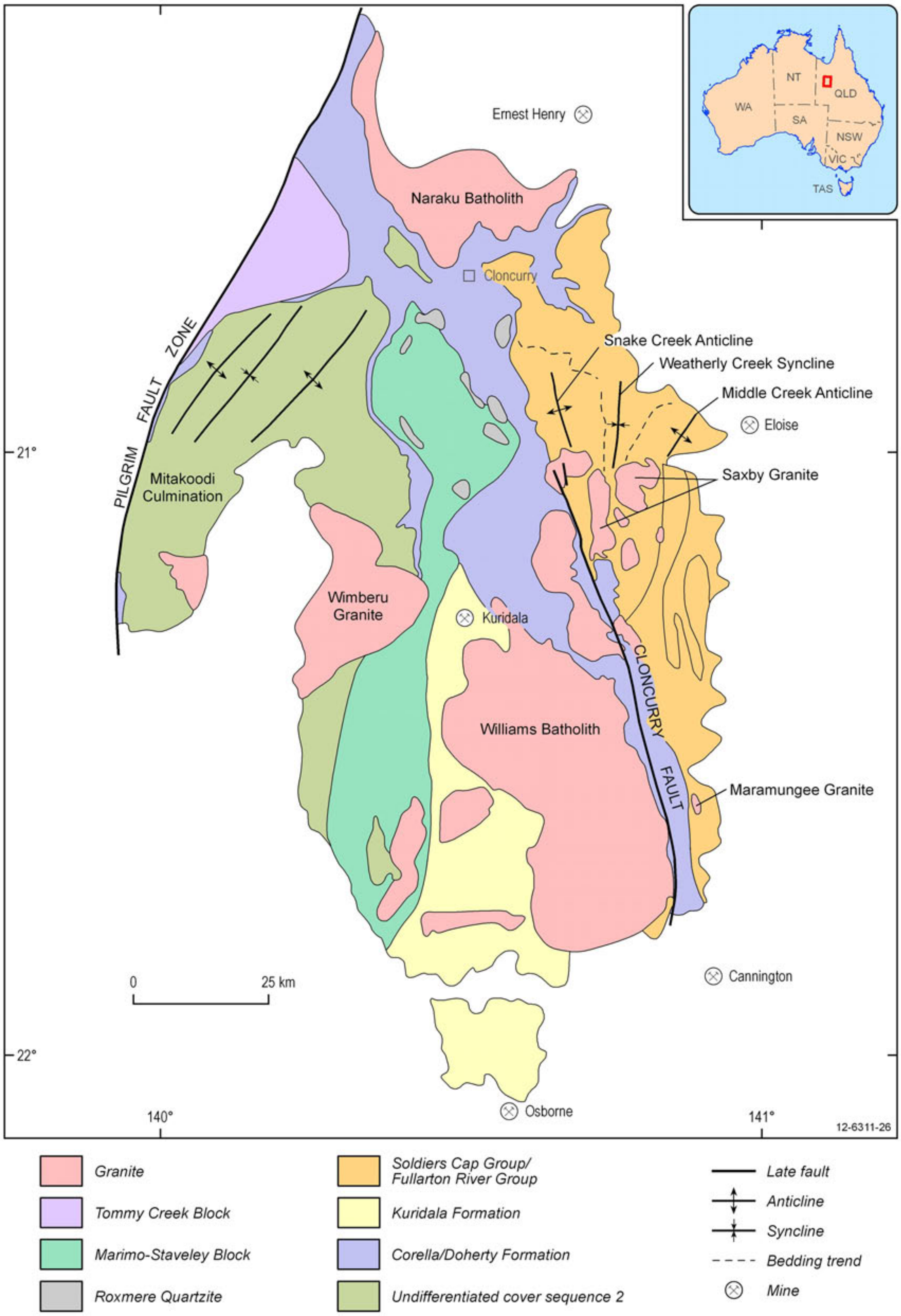

Figure 26: *Simplified geological map of eastern succession showing distribution and location of Soldiers Cap Group (Blenkinsop et al., 2008).*

bulk compositions, unlike the situation at deeper levels within the Llewellyn Creek Formation where this mineral is widely developed in pelitic interbeds.

Deep water turbidites are uniquely developed in the eastern succession and have no stratigraphic equivalent farther west in the Leichhardt River Fault Trough or Lawn Hill Platform. Instead, the western succession was subjected to widespread erosion and reduced sea level as represented by the 20 Myr of missing rock record along the Gun unconformity. Erosion back on the shelf led to deposition of the turbidites in a lowstand position.

Figure 27: *Turbiditic sandstones in Mount Norna Quartzite.*

Deposition of the Llewellyn Creek Formation and Norna Quartzite is constrained by dating of the strongly fractioned Fe-rich mafic rocks that have been intruded into the sequence. A tonalite sample from the Llewellyn Creek Formation yielded a 1686 ± 6 Ma age (Rubenach et al., 2008) whereas a fractionated metadolerite (amphibolite) from higher up in the sequence yielded 1659 ± 4 Ma (Lambeck et al., 2012). Both ages overlap the youngest age population extracted from detrital zircon spectra, suggesting that sedimentation, mafic magmatism and continental rifting were all related to one and the same tectonic event.

A marked change in provenance and/or magmatic activity appears to have occurred around the time Mt Norna Quartzite gave way to Toole Creek Volcanics at around 1655 Ma (Lambeck et al., 2012). This change is best illustrated in Nd isotopic compositions towards the top of Mt Norma Quartzite where there is marked change in $\varepsilon Nd_{(1655\ Ma)}$ values from -8 to -6 in the latter to -2 to -1 in the overlying rocks. This same change in εNd values is seen in other regions across northern Australia and thought to reflect an increase in the amount of juvenile material being transported into the depocentre (Lambeck et al., 2012). However, magmatism of 1655 Ma age is not common in northern Australia and the source of this juvenile component remains unknown. One possibility is that the source rock lies in Australia but has since been buried or eroded; the other possibility is that the source rocks now lie in western North America against which Proterozoic eastern Australia may once have been joined (Figure 3).

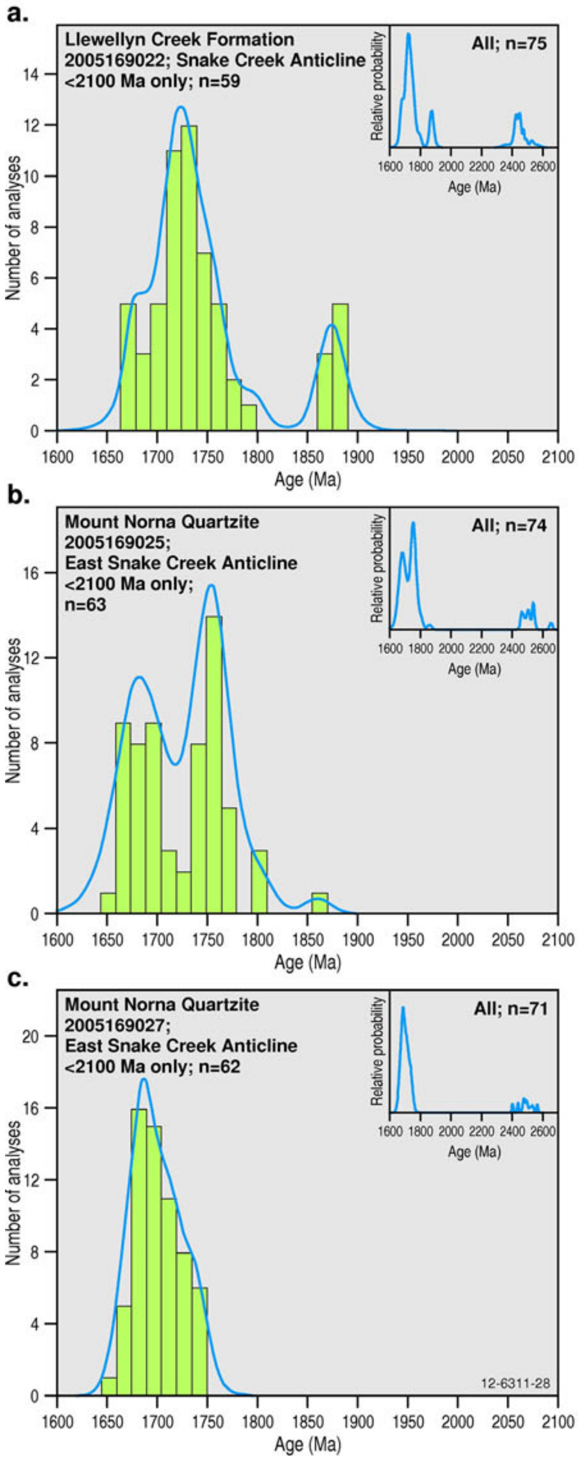

Figure 28: *Detrital zircon age spectra for (a) Llewellyn Creek Formation; (b) & (c) Mount Norna Quartzite in Soldiers Cap Group. The youngest grains in these three samples give a maximum depositional age ca. 1686 Ma which is identical within error to ca. 1685 Ma mafic dykes and sills intruded throughout Soldiers Cap Group.*

Locality 12: 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.

Locality 13: Syn-rift magmatism – the Sybella (Granite) Batholith

Sills of I-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-

Figure 29: *Vertical section through strongly lineated outcrop of Sybella Granite showing former phenocrysts of potassium feldspar 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.*

Leichhardt block or a more highly metamorphosed part of the Leichhardt Superbasin (Gibson et al., 2008).

Granite in these outcrops is conspicuously gneissic and dominated by partially recrystallised augen of pink K feldspar (Figure 29). 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).

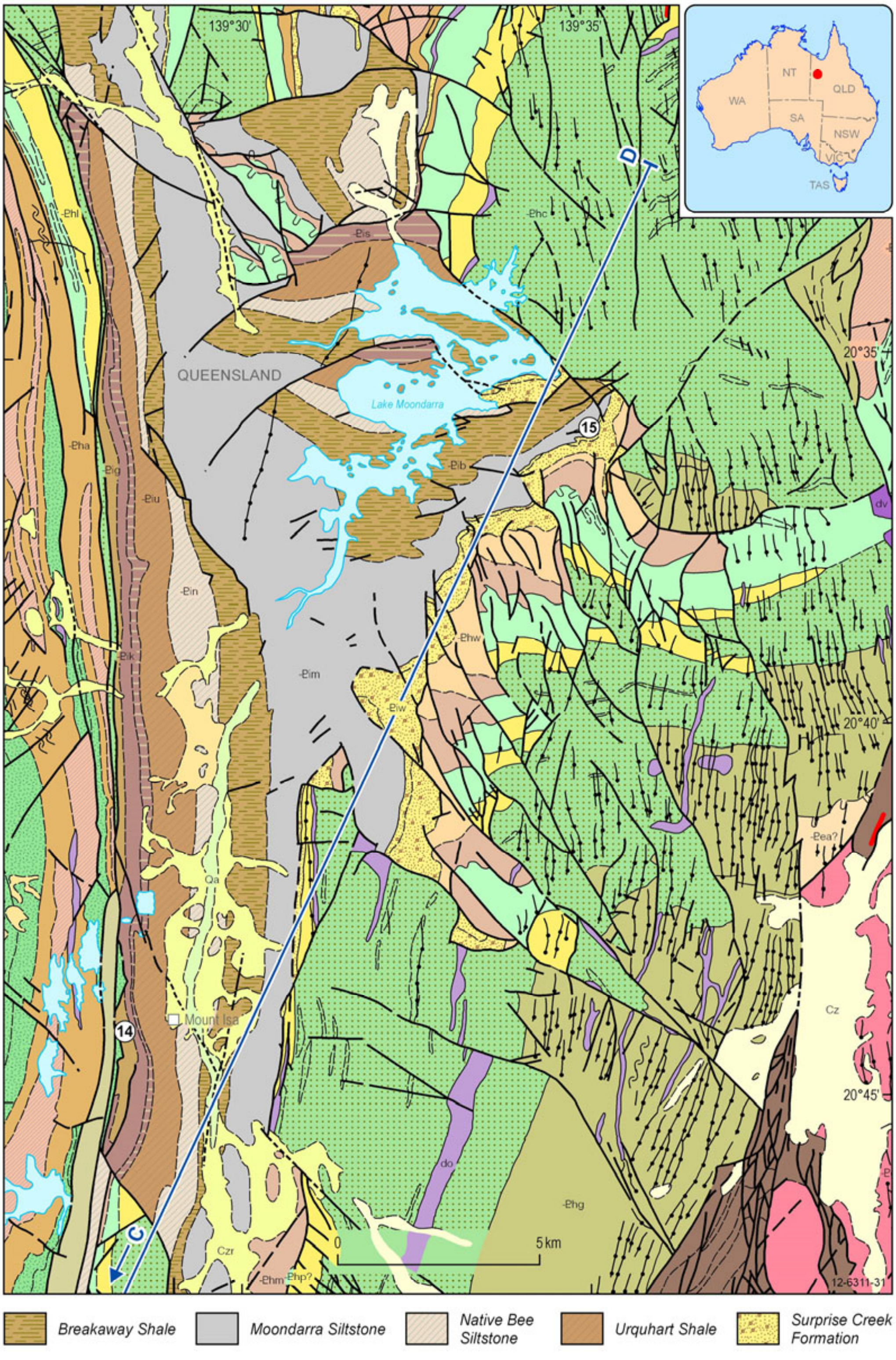

Figure 30: *Geological map of Lake Moondarra area showing reactivated syn-rift structures cutting up section from Leichhardt Superbasin (Brown = Myally Sub-group; green = Eastern Creek Volcanics with interbedded Lena Quartzite = yellow) through overlying Surprise Creek Formation into basal part of Moondarra Siltstone but no higher. Obvious south-verging folds in Breakaway Shale are the result of D1 basin inversion.*

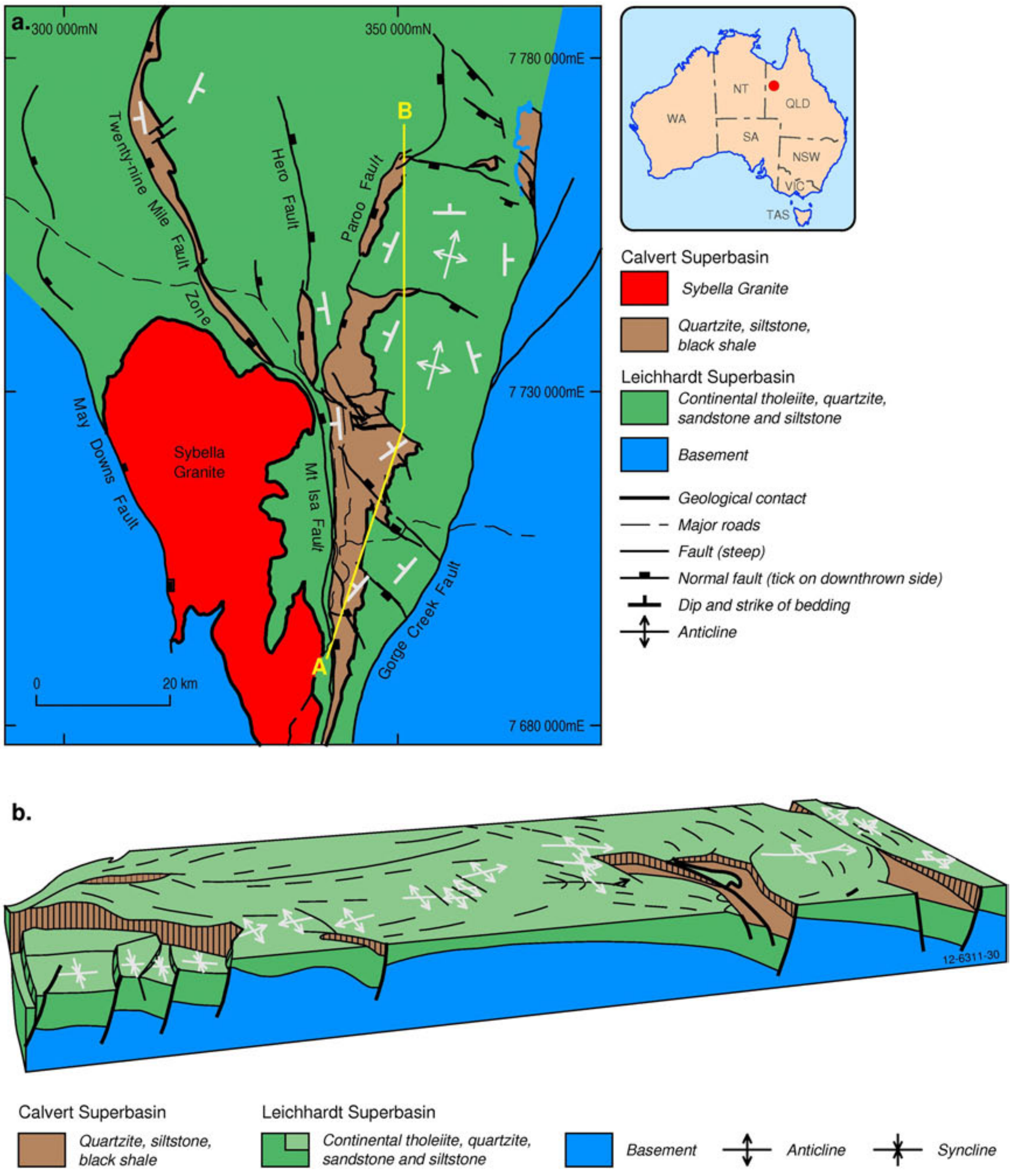

Figure 31: *Simplified district-scale geological map of Mount Isa region and block diagram showing major depocentres into which sediments of the Surprise Creek Formation and Isa Group were deposited. A majority of the associated growth faults are south-dipping.*

Day 5 – Black Star Open Cut Mine; Lake Moondarra section through Surprise Creek Formation and Isa Group

Locality 14: 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 30) 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).

Original fault geometries (Figure 31), though modified by later basin inversion at Lake Moondarra (Figure 32), are locally preserved in an oblique section through the Surprise Creek Formation and lowermost Isa Group (Figure 30). 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 31 & 32) 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 32 & 9b). The Moondarra Siltstone has a maximum depositional age of 1668 ± 8 Ma (Page et al., 2000a).

As with the rocks around Gunpowder Mine, the rocks around Lake Moondarra have undergone a similar history of D1 (Figure 32) and D2 basin inversion. Basin inversion was accompanied by reactivation of normal faults, some of which were first active during deposition of the Moondarra Siltstone (Figure 32) but ceased to be active by the time the immediately overlying Breakaway Shale was deposited (Figure 6). During basin reactivation, these normal faults were reactivated as thrusts, the majority of which are blind and do not penetrate upward into younger parts of the sequence (Figure 32). Instead, the Breakaway Shale and younger units have been deformed into a series of south-verging asymmetric folds (Figure 32) 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., 2000b) from the underlying Breakaway Shale (1663 ± 3 Ma) and uppermost Moondarra Siltstone (1668 ± 8 Ma)(Figure 33). Thereafter, the basin was subjected to only post-rift thermal subsidence.

Interestingly, the youngest detrital zircon population in the Moondarra Siltstone (Figure 33) 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).

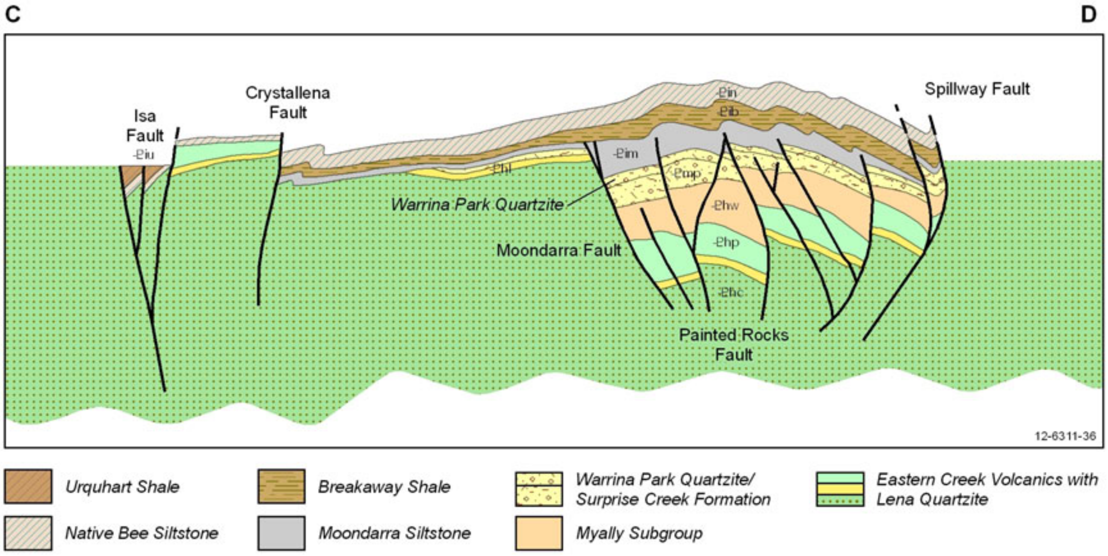

Figure 32: *Structural cross-section through inverted basinal sequences of Leichhardt, Calvert and Isa superbasins in Lake Moondarra area. Note inversion of former normal faults in deeper parts of basin and the absence of such structures in the section above lowermost Moondarra Siltstone. For location of section see Figure 30.*

Locality 15: Mount Isa Mine leases and geology of Black Star Pb-Zn Mine

Following arrival at Xstrata Zinc offices and a short introduction to mine rules regarding safety and other issues, Xstrata staff will provide a guided tour of the open cut mine (Figure 2) and associated camp-scale geology.

Rock units in the Mount Isa and George Fisher mines are steeply dipping and bounded along their western margin by the sub-vertical to steeply-dipping Paroo Fault (Figure 31). 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 (Figure 33). 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 33). Other faults in the region share this geometry and were probably similarly reactivated during basin inversion (Figure 31). It is tempting to speculate that mineralisation was not introduced during deposition of the Urquhart Shale as some researchers have suggested but introduced later during basin inversion (Figure 31). 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).

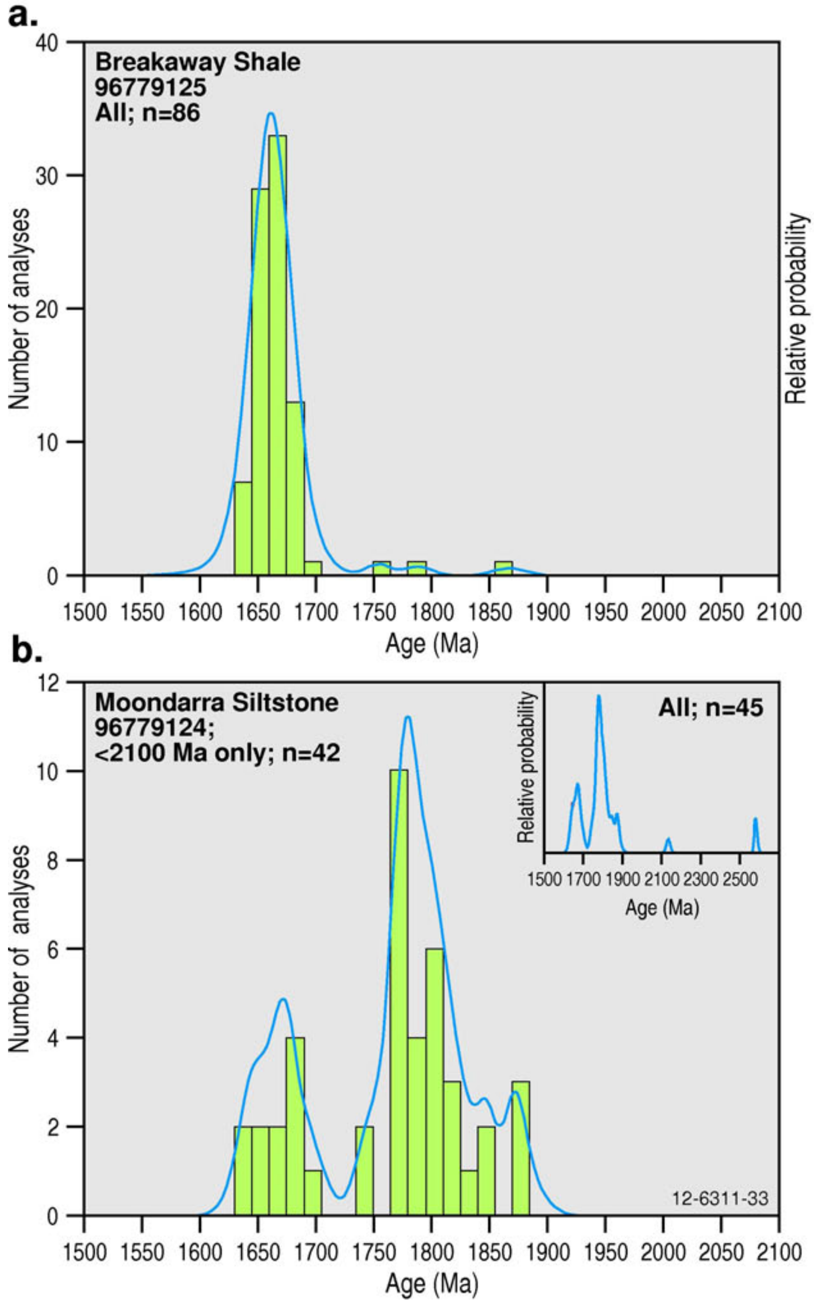

Figure 33: *Detrital zircon age spectra for lowermost Moondarra Siltstone and overlying Breakaway Shale (Page et al., 2000b).*

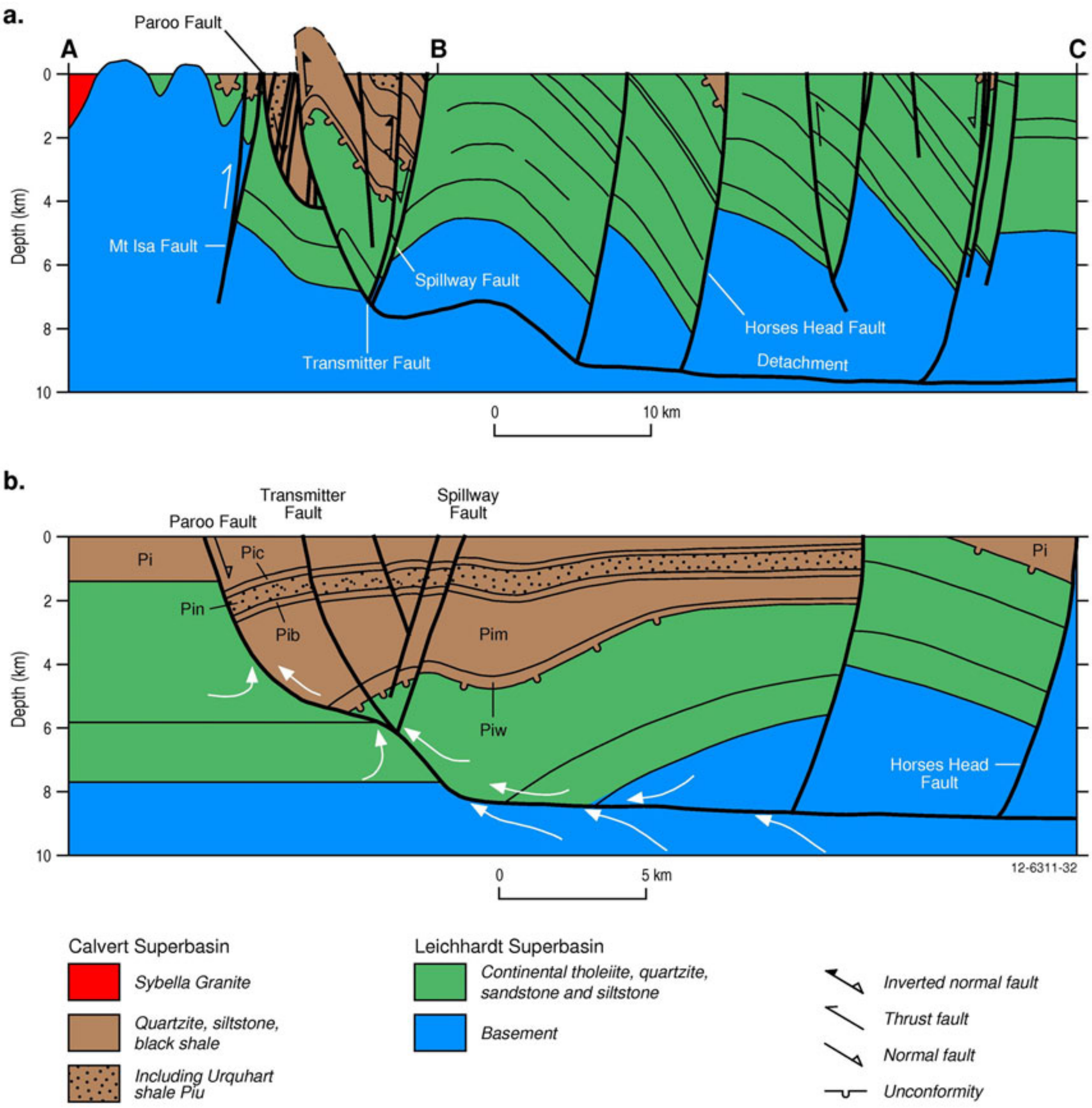

Figure 34: *Cross-section through mineralised sequence at Mount Isa. Note location of Urquhart Shale above ramp or shallow-dipping section in Paroo Fault (Gibson, unpubl.).*

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Nick Oliver introduced us to the excellent exposures of lower plate granites in Green Creek while Tom Blenkinsop provided a guided tour of Soldiers Cap Group in the Snake Creek Anticline. For the many discussions on Mount Isa geology, we thank members of the former Predictive Minerals Discovery CRC, including Nick and Tom, but also Barry Murphy, Klauss Geissner, Russell Korsch, Bob Haydon and John McLellan, along with many of the staff from various exploration companies who attended PMD*CRC meetings and field excursions.

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