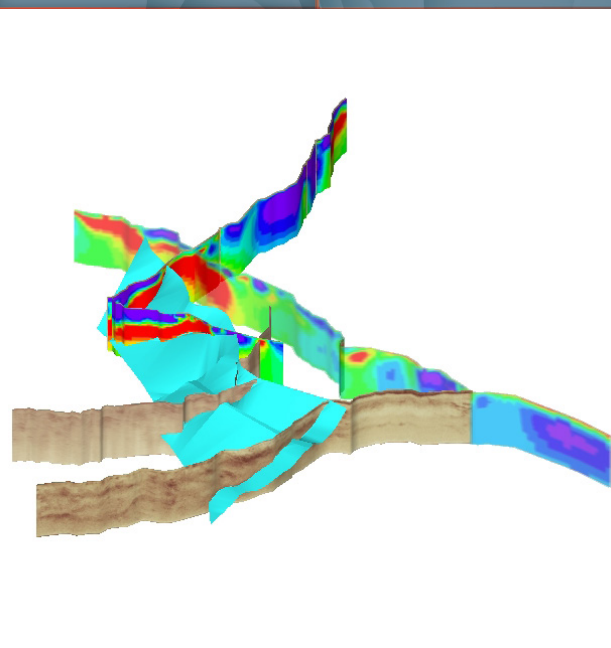
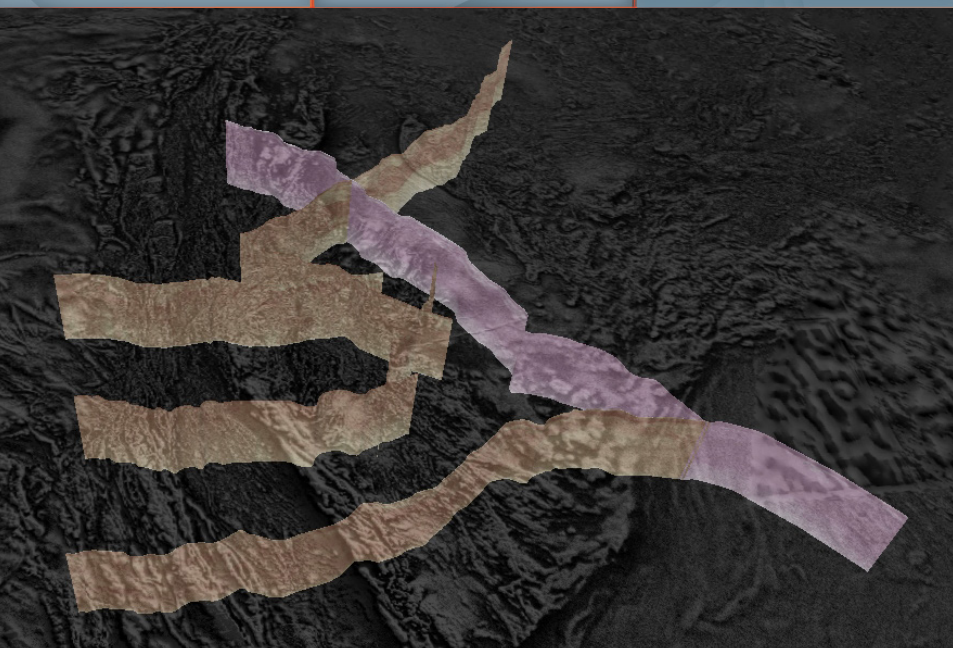


Queensland Geological Record 2021/04

**Notes on the geological interpretation of deep seismic transect 14GA-CF1,
including inferences from other associated regional datasets**

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Cover photographs: Left: 3D view of greyscale magnetic image of northwest Queensland (looking north) draped over the network of deep seismic profiles mentioned in the text; the primary subject of this study is the northwest-trending 14GA-CF1 seismic profile shown in purplish hues. Right: 3D view of deep seismic sections mentioned in the text (looking north) with selected co-incident magnetotelluric profiles displayed; proposed eastern Mount Isa collision zone, the Gidyea Suture (in aqua), is inferred from seismic and magnetotelluric contrasts on all sections except for 14GA-CF1 where its position remains enigmatic.

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Summary

The 14GA-CF1 seismic transect adds new detail to previous understandings of the subsurface linkages between the Mount Isa and Georgetown Provinces, including new detail of the longitudinal extent of the Mesoproterozoic? Millungera Basin. The transect also provides the first full crustal image of the continent-scale Diamantina Lineament which abruptly terminates the Mount Isa Province at its southern extremity. The latter is revealed as a crustal-scale south-dipping fault penetrating the MOHO at the crust/mantle boundary, forming the northern margin of a northeast-trending rift-like basin controlling deposition of the earliest Thomson Orogen successions.

The northern segment of the seismic profile images the eastern margin of the Mount Isa Inlier as a southeast-dipping extensional fault system (displaying some later Isan Orogeny inversion) facilitating development of the (now subsurface) Julia Creek Basin during the latest Paleoproterozoic. The basin extends to a depth of ~6.5 s two-way travel time (TWT) (~20 km) and is inferred to comprise mainly moderately to poorly reflective meta-sediments, mafic lavas and sills of the Soldiers Cap Group, underlain by a basal relatively non-reflective sequence of uncertain affinity.

By comparison with the intersecting 07GA-IG1 seismic profile, the Julia Creek Basin section is here recognised as being contiguous with the Kowanyama Seismic Province of Korsch *et al.* (2012), while the underlying more reflective lower crustal section is recognised as a continuation of the Numil Seismic Province defined by Korsch *et al.* (2012) from the 07GA-IG1 profile. The now deeply-buried Numil crustal layer forming basement to the Julia Creek Basin displays a segmented, block-faulted character in the 14GA-CF1 profile, probably reflecting its fragmentation during basin development prior to its eventual foundering and burial by the Julia Creek Basin succession. An upper more reflective section of the Numil Province crust has also been delineated in the 14GA-CF1 profile, and has also been recognised in the orthogonal 07GA-IG1 deep seismic profile.

A zone running the length of the eastern margin of the Mount Isa Inlier has been identified where discrete Numil-Isa seismic and conductivity contrasts occur. However, no feature similar in character to the Gidyea Suture Zone defining the eastern margin of the Mount Isa Inlier on the 07GA-IG1 seismic profile has been identified from the 14GA-CF1 profile crossing the margin further to the northeast. Moreover, the Numil-Isa basement contrast is not evident at depth across this segment of the Mount Isa margin, where the Isa basement displays more Numil-style characteristics. These features point to a more complex history for the eastern Mount Isa margin than previously proposed, and highlight the need for further careful integration of existing and new geophysical, geological and isotopic datasets to resolve the origin, timing and significance of crustal-scale structures underpinning the region.

1. Introduction

This report contains geological interpretations, inferences and implications derived from an assessment of the Southeast Mount Isa deep seismic reflection transect (14GA-CF1), a survey commissioned by the Geological Survey of Queensland (GSQ) and undertaken in collaboration with Geoscience Australia in 2014.

The transect extended northwestward over a distance of 670 km along public roads linking the townships of Longreach, Winton and Julia Creek before terminating at the road junction of Four Ways. The 14GA-CF1 transect was followed by three more transects across northwest Queensland linking Boulia, Birdsville and Winton, all completed by the end of 2015 (see Figure 1). The seismic programs were aimed at developing future energy and mineral exploration opportunities in covered greenfields terrains flanking the eastern and southern Mount Isa Inlier.

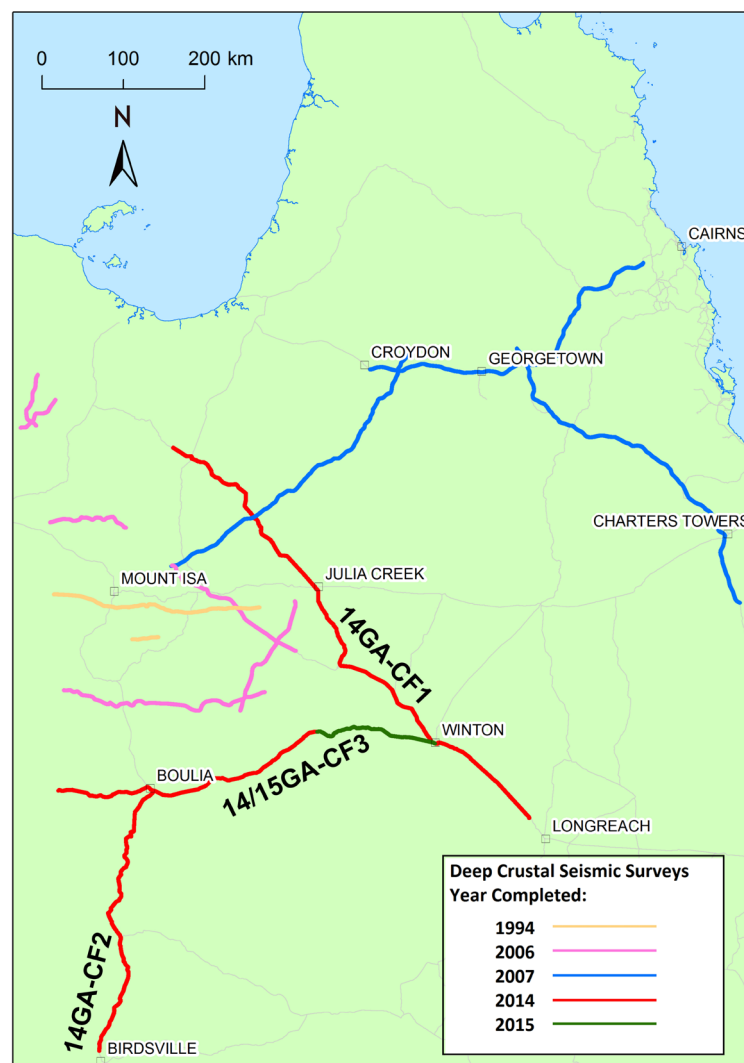


Figure 1. Location of 2014-15 deep seismic transects (labelled) and older 1994-2007 deep seismic transects.

This most recent suite of new lines, together with seismic surveys collected over the past 25 years, now form a continuous network of reflection seismic data covering Queensland's most prospective mineral provinces.

2. Geological summary

The 14GA-CF1 transect crosses the currently defined southern margin of the Precambrian **North Australian Craton** (NAC) which is well defined in regional magnetic and gravity data where it lies beneath relatively thin cover basins comprising strata of the Carboniferous-Triassic **Galilee Basin** and overlying Mesozoic **Carpentaria-Eromanga Basin**. The geophysically-defined southern NAC margin is marked by the **Diamantina Lineament** (locally expressed at the surface as the **Cork Fault**), a complex zone which is well imaged in the seismic data, along with the crustal section further to the south assigned to the **Thomson Orogen** (see Figure 2). Due to the whole-of-crust focus of the deep seismic survey, fine detail of the Palaeozoic-Mesozoic cover basins is not well resolved. As a result, this report focusses on the large-scale structural architecture of the NAC and Thomson Orogen sections of the crust.

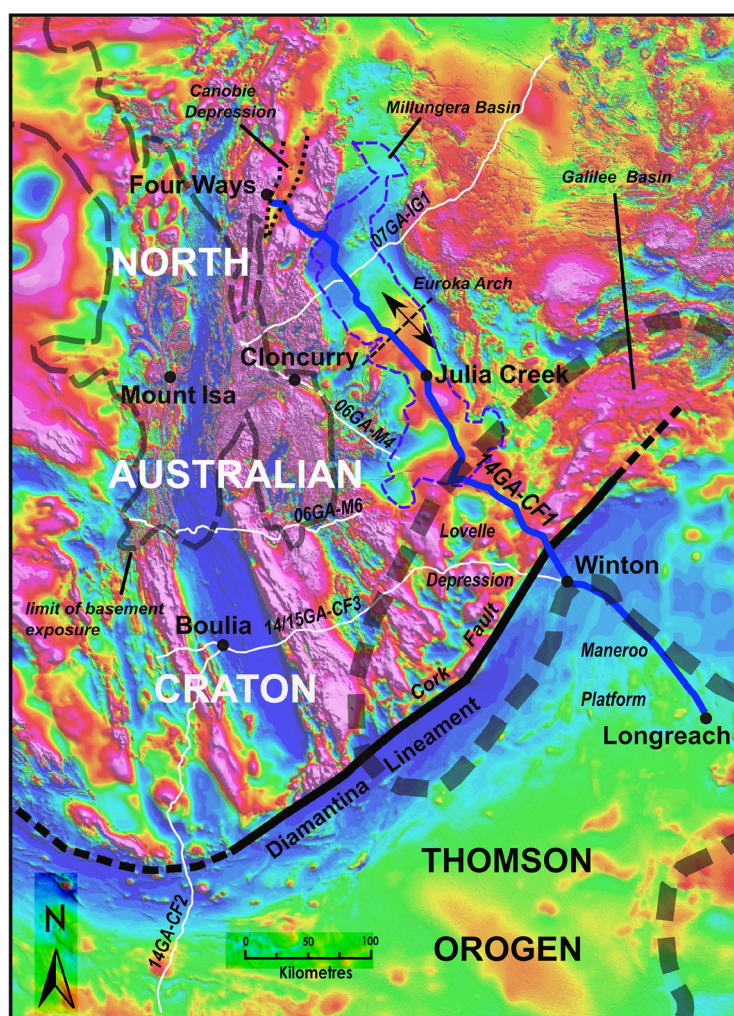


Figure 2. TMI-1VD magnetic image of northwest Queensland showing location of seismic transects, cover basins and major geological elements discussed in the text.

The crustal section within the bounds of the NAC to the north of the Diamantina Suture comprises multiple layers (from top to bottom):

- (1) an upper thin layer of Palaeozoic and Mesozoic cover basins (Eromanga and Carpentaria Basins underlain by Early Permian to Triassic Galilee Basin sediments in the south and Middle Triassic sub-basins in the north (*e.g.*, the Canobie Depression).

(2) underlying strata of the Mesoproterozoic? **Millungera Basin** (first identified in the 2007 GA-GSQ Isa-Georgetown deep seismic program).

(3) weakly to moderately reflective deformed strata of the **Kowanyama Seismic Province** (Korsch *et al.*, 2012), forming a deep basin up to 20 km thick (informally referred to here as the **Julia Creek Basin**), dominated by meta-sediments exposed at the surface to the west as the Soldiers Cap Group (part of the Mount Isa Inlier's Eastern Succession).

(4) a strongly to moderately reflective lower crustal layer up to 25 km thick underlying the Julia Creek Basin (equivalent to the **Numil Seismic Province** of Korsch *et al.*, 2012) bounded by a well-defined reflective MOHO surface at its base.

The crustal section south of the Diamantina Lineament comprises basement of progressively thinned and modified Proterozoic continental crust, with an overlying rift feature adjacent to the suture flanked by the wide deep **Thomson Orogen** sedimentary system to the south. These are overlain by thin cover of the Galilee and Eromanga Basins continuous with equivalent cover rocks to the north.

3. Regional geological background and tectonic development

Rocks of the Mount Isa Province exposed across Northwest Queensland form a richly-mineralized segment of the Paleoproterozoic North Australian Craton (NAC) which extends eastwards under cover to include the Georgetown Province.

The northwest-trending 14GA-CF1 deep seismic transect images the eastern subsurface extension of the Mount Isa Inlier before continuing southward across the inlier's abrupt termination along the continent-scale Diamantina Lineament into the adjacent deep basin sequences of the Phanerozoic Thomson Orogen.

3.1 Mount Isa Province

The Mount Isa Inlier preserves a complex history of episodic magmatism, basin formation and inversion spanning more than 350 million years between ~1870 and 1500 Ma. The earliest recognized orogenic cycle (the **Barramundi Orogeny**) involved deformation and metamorphism at ~1870 Ma, culminating in the emplacement of linearly-extensive calc-alkaline granitoid batholiths and associated felsic volcanics until ~1840 Ma. Barramundi-aged rocks form the crystalline basement of the Mount Isa terrane and can be found throughout much of northern Australia. These basement rocks are exposed at the surface as the **Kalkadoon-Leichhardt Block** – a meridional magmatic belt forming the central core of the inlier, flanked by a series of complex superimposed and stacked younger basins to the east and west, collectively referred to as the **Eastern** and **Western Successions**. The latter comprises a less deformed, more coherent succession than the former, allowing the identification of a number of supersequences (refer to Figure 4) based on sequence stratigraphic principles (Southgate *et al.*, 2000). The 14GA-CF1 deep seismic transect primarily images subsurface equivalents of the more complexly deformed and metamorphosed Eastern Succession.

The oldest of Mount Isa's episodic rifting events is preserved at the base of both the Eastern and Western Successions as the **Leichhardt Superbasin** - characterised by ENE-WSW oriented extension accompanied by widespread bi-modal volcanism and associated sedimentation lasting from ~1790 Ma until ~1730 Ma. The Leichhardt River Fault Trough immediately west of the Kalkadoon-Leichhardt Block was the main centre of mafic volcanism with accumulation of 5-8 km of the fluvio-lacustrine **Eastern Creek Volcanics** over a short period of time between 1790 and 1780 Ma, while rhyolites and ignimbrites of the **Argylla Formation** were deposited synchronously east of the Kalkadoon-Leichhardt Block. Extension propagated further eastward with time, where the felsic ~1760 Ma **Bulonga Volcanics** and overlying basalt-dominated **Marraba Volcanics** were erupted east of the regional Pilgrim-Quamby Fault system.

Extension culminated in development of ~1740 Ma core complexes. These are exposed east of the Kalkadoon-Leichhardt Block as a linear belt of deformed granites (the **Wonga Belt**), and further east in the Selwyn region as the **Gin Creek Granite** and surrounding **Double Crossing Metamorphics**. Minor felsic volcanism also occurred at this time in the easternmost exposed portion of the Mount Isa Inlier (**Mount Fort Constantine Volcanics**). Extension was followed by cooling and burial by shallow marine sag-phase carbonates and sands (Jackson *et al.*, 2000). These are currently exposed in the Eastern Succession as the distinctive **Ballara/Mitakoodi Quartzites** and overlying **Corella Formation** calc-silicate rocks. Sedimentation in the western Mount Isa Inlier was terminated by a discrete inversion event at ~1740 Ma, correlated with far-field plate collisions to the east (the **Leichhardt Event** of Blaikie *et al.*, 2017).

Significant extension was soon re-initiated but with a switch in orientation into a NE-SW direction. In the Western Succession, this event was accompanied by deposition of the relatively well-preserved fluvial to shallow marine, sedimentary and volcanic sequences of the **Calvert Superbasin** and succeeding **Isa Superbasin** (~1730-1640 Ma and ~1640-1580 Ma respectively; Gibson *et al.*, 2015). The uppermost (Gun Supersequence) section of the Calvert Superbasin contains the fine-grained post-rift sediments of the **Mount Isa Group**, hosting the Tier 1 Mount Isa copper-lead-zinc orebody. This more recent interpretation (Figure 4) replaces earlier stratigraphic schemes (Southgate *et al.*, 2000, 2013; Withnall & Hutton, 2013) which place the Mount Isa Group at the base of the overlying Isa Superbasin, post-dating the ~1670 Ma emplacement of the syn-kinematic extensional **Sybella Batholith** into the underlying Leichhardt Superbasin west of Mount Isa.

Further east, the onset of syn-Calvert sedimentation is recorded as mixed shallow-water carbonates and siliciclastics of the **Staveley Formation** (~1740-1725 MDAs) and discrete structurally emplaced blocks and sand blankets of the overlying Mount Albert Group (**Knapdale**, **Deighton** and **Roxmere Quartzites** with ~1749-1713 MDAs). A hiatus in Eastern Succession sedimentation soon followed, eventually followed by renewed extension, drowning the earlier shelf sequence by deeper water turbidites of the **Kuridala** and **Soldiers Cap Groups**, beginning at ~1685 Ma (Neumann *et al.*, 2009a). The latter forms the easternmost belt of Proterozoic rocks exposed in the Mount Isa region, and makes up the bulk of the upper crustal section imaged by the 14GA-CF1 transect, lying beneath younger cover rocks. The Soldiers Cap Group has been divided into three mapped formations – the basal pelitic **Llewellyn Creek Formation**, the overlying more psammitic **Mount Norna Quartzite**, and the uppermost **Toole Creek Volcanics** - a sequence of fine variably metamorphosed carbonaceous siltstones and shales interleaved with mafic sills and lavas. The Soldiers Cap Group is contiguous with the Kuridala Group in the southern part of the inlier, with both units comprising turbidite packages which may represent broad stratigraphic correlatives. Both groups show a marked southward increase in high temperature/low-medium pressure metamorphic grade, commonly ranging up to amphibolite and locally granulite facies.

The Toole Creek Volcanics are thought to correlate with other similar fine-grained carbonaceous Eastern Succession packages nearby, including the **Hampden Slate member** of the Kuridala Group and the **Marimo Slate** and **Answer Slate**. Detrital zircon dating suggests a common ~1650 Ma depositional age for this suite of fine-grained rocks (Neumann *et al.*, 2009a and b), indicating a temporal and depositional correlation with the Mount Isa Group sequence to the west. Eastern Succession sedimentation is thought to have finally ceased following deposition of this fine-grained package, with the exception of a localised sequence of calc-silicate, schist, and meta-rhyolite in the Tommy Creek area with ages as young as ~1620 Ma (Carson *et al.*, 2011).

Calvert Basin development throughout most of the Mount Isa Inlier was brought to a halt by the widespread **Riversleigh Inversion Event** at ~1640 Ma which involved north-south to northeast-southwest directed shortening. The succeeding **Isa Superbasin** fluvial to shallow marine sedimentary sequence was restricted to the westernmost segment of the Mount Isa Inlier (Lawn Hill Platform), and represented a basic change in basin style with little or no accompanying magmatism and depocentres linked to ongoing tectonism rather than regional extension. Isa Superbasin sedimentation continued until ~1595 Ma, overlapping the onset of multiple phases of deformation and metamorphism occurring over a protracted interval from ~1610 Ma to ~1500 Ma, grouped together as the **Isan Orogeny**. Gibson *et al.* (2020) favour the Riversleigh Inversion Event as the earliest component of the Isan Orogeny, marking a major change in plate motion synchronous with a hairpin bend in the apparent polar wander path for northern Australia.

The **Isan Orogeny** has equivalents to the west in the Northern Territory (the **Chewings Orogeny**), in eastern Queensland (the **Jana Orogeny** of the Georgetown Province), and in New South Wales (the **Olarian Orogeny** of the Curnamona Province). The orogeny is characterised by an early thin-skinned, north-northwest verging, thrusting event (informally categorized as the D1 deformation event) followed by a series of thick-skinned north-south oriented folding and later brittle faulting events (grouped together as D2 deformation events; MacCready *et al.*, 1998; Giles *et al.*, 2006b).

Major north-trending late D2 brittle faults compartmentalise Eastern Succession geology. In particular, the older ~1780 Ma Leichhardt Superbasin volcanic sequences are separated from the younger ~1760 Ma volcanic packages further east by the crustal-scale listric east-dipping **Pilgrim Fault**, bifurcating to the northeast as the **Quamby Fault**, and perhaps extending to the north as the **Coolullah Fault**. Further east, the north-trending **Cloncurry Fault** represents a long-lived, basin-bounding, deep crustal structure that shows evidence of multiple episodes of ductile and brittle reactivation (Austin & Blenkinsop, 2008, 2010). This fault in part marks the inverted boundary between shelfal carbonates of the Staveley Formation and deeper water turbidites of the Soldiers Cap Group.

Further late D2 east-west shortening was facilitated by northeast trending wrench faults with a general dextral sense of movement (*e.g.*, **Fountain Range**, **Overlander**, **Wonga**, **Mount Remarkable** and **Quamby Faults**). These may represent re-activated older pre-Barramundi structures which have fundamentally compartmentalised north-south basin development.

In the waning stages of the Isan Orogeny and immediately after (~1540-1490 Ma), the Eastern Succession saw widespread igneous intrusion dominated by A-type batholiths of the **Williams-Naraku Granite**, some of which show

evidence of deformation during the brittle faulting episode. Betts *et al.* (2009) consider this magmatic period to result from plume-related crustal melting produced by a broad, northward-migrating hotspot.

Subsequent to the Isan Orogeny, the now dominantly subsurface terrestrial sediments of the intracratonic **Millungera Basin** were deposited in the Mesoproterozoic? over a wide area of Soldiers Cap Group rocks east of their current exposure at the edge of the Mount Isa Inlier (see Figure 2). The Millungera Basin was first discovered from the deep seismic reflection survey conducted by Geoscience Australia and the Geological Survey of Queensland in 2006 and 2007 (Hutton *et al.*, 2009). The basin is interpreted to be approximately 3 km thick, with three sequence stratigraphic cycles inferred (Korsch *et al.*, 2011).

In Northwest Queensland, early breakup of the supercontinent **Rodinia** (see following discussion) is expressed as north-trending Neoproterozoic tillite-bearing rift basins unconformably overlain by more widespread Cambrian-Ordovician sediments of the **Georgina Basin**. Further west, extension at this time resulted in the formation of the **Centralian Superbasin**. Reorientation of Rodinian extension directions in the latest Neoproterozoic saw the Mount Isa terrane dismembered along its southern margin accompanied by development of the Thomson Orogen (see discussion below).

The Georgina and Millungera Basin cover sequences record later Palaeozoic shortening events that presumably also reactivated faults within the Proterozoic basement. The early-middle Devonian phase of the **Alice Springs Orogeny** resulted in mild folding and fault inversion within the Georgina Basin (*e.g.*, Toko Syncline and Pilgrim Fault/Burke River Inlier; see Greene, 2010). A later shortening event is evident in the Proterozoic basement and overlying Millungera Basin east of the exposed Mount Isa Inlier, where westward-verging thrusts and folds are visible in the 07GA-IG1 seismic profile. This event also involves westward transport of a ~380 Ma subsurface pluton, which provides the only age constraint for this episode. This shortening event may be related to Tabberabberan closure of the Palaeozoic Hodgkinson Basin near the current east coast of Queensland.

3.1.1 Plate tectonic context

The Mount Isa Inlier records sedimentary, magmatic and tectonic histories that are comparable with other terranes of similar age to the east in the **Georgetown Province** and to the south in the **Curnamona Province** (see Figure 3) prompting speculation of a contiguous connection between them for at least the later phases of their history (Henson *et al.*, 2011; Pourteau *et al.*, 2018; see Figure 4), where they formed Australian components of the supercontinent **Nuna** (Betts *et al.*, 2016).

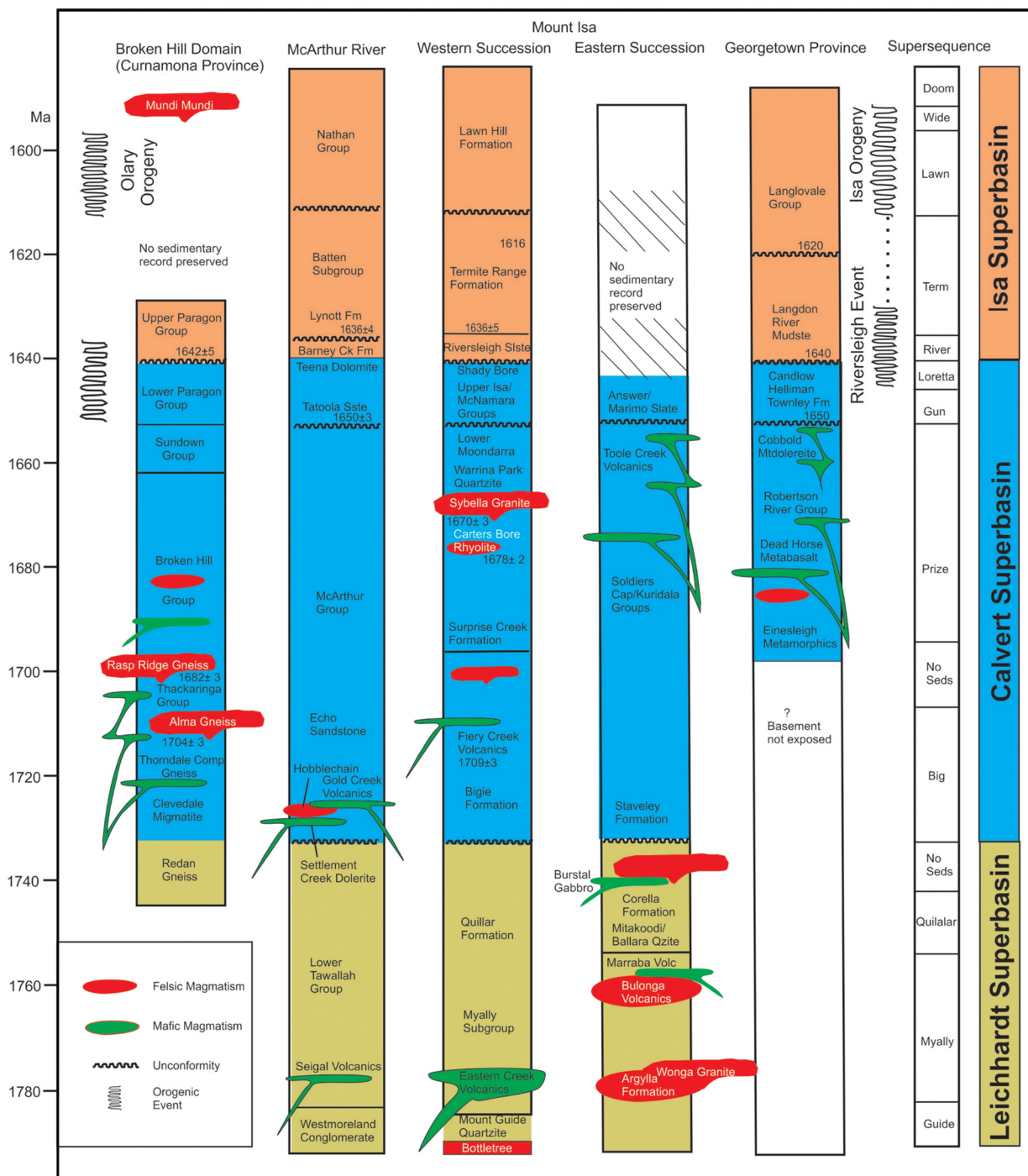


Figure 3. Time-space plot demonstrating common depositional and tectonic histories shared by the major Paleoproterozoic provinces of eastern Australia (after Gibson et al., 2020); plot shows supersequence subdivisions for the Eastern and Western Mount Isa Successions and correlation of Mount Isa Superbasin phases across Georgetown and Curnamona Provinces.

Note: that boundary between Calvert and Isa Superbasins is placed at 1640 Ma based on seismic, structural, and paleomagnetic evidence (Gibson et al., 2017; Idnurm, 2000) rather than at 1670 Ma as previously argued by Southgate et al. (2000).

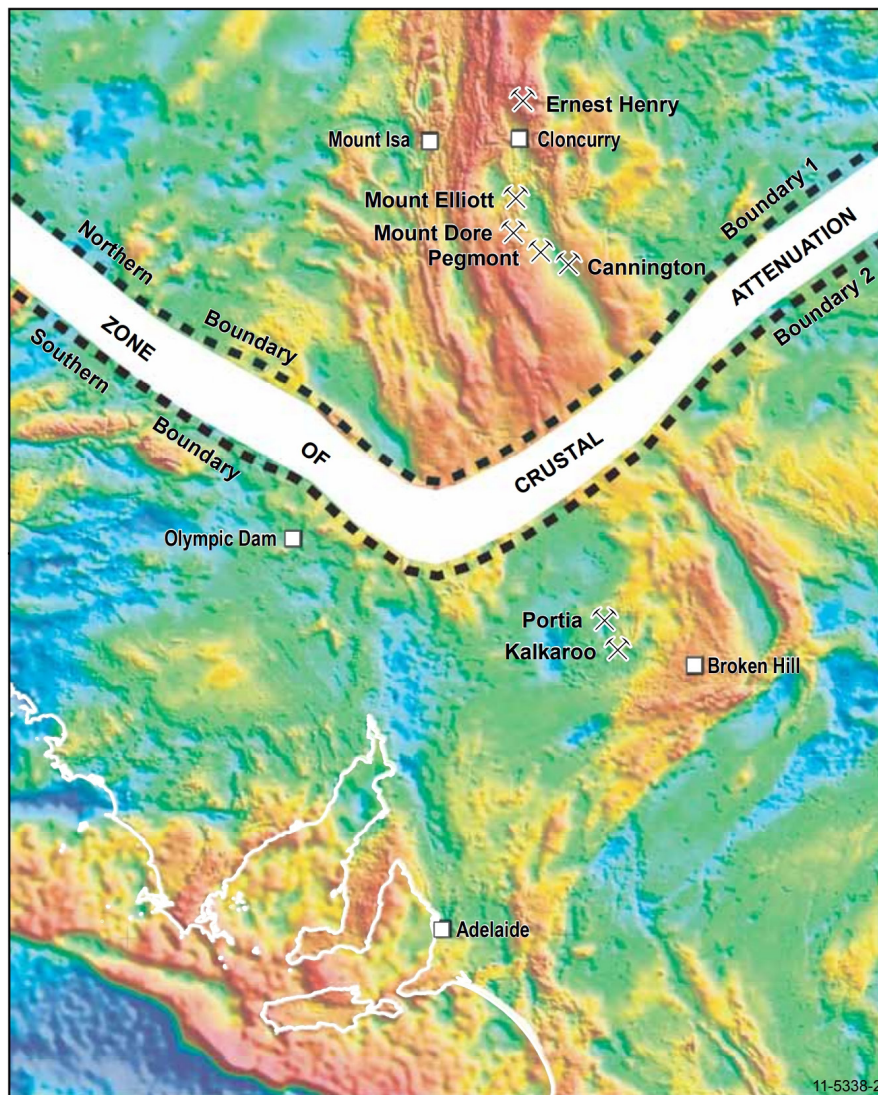


Figure 4. Regional gravity image modified to show proposed Neoproterozoic configuration of the Mount Isa Province (in the north) and unrotated co-joined Curnamona Province and Gawler Craton (in the south); area of attenuated crust shown in white (after Henson *et al.*, 2011).

The progressive development of superbasin sequences across the Mount Isa region has been linked to various tectonic scenarios generally involving either plate interactions with the Laurentian continent to the east (Betts *et al.*, 2016; Gibson *et al.*, 2008, 2017, 2018, 2020; Pourceau *et al.*, 2018; Nordsvan *et al.*, 2018), or with the conjoined Australian and Antarctic continents to the southwest (Giles *et al.*, 2002; Betts *et al.*, 2003, 2006; Karlstrom *et al.*, 2001; Scott *et al.*, 2000).

Gibson *et al.* (2008, 2017, 2018, 2020) relate superbasin development to backarc extension behind a magmatic arc east of the Georgetown Province that rifted off the Australian margin along with its underlying continental basement at ~1655 Ma before being re-united with the passive margin no later than 1640 Ma (see Figure 5).

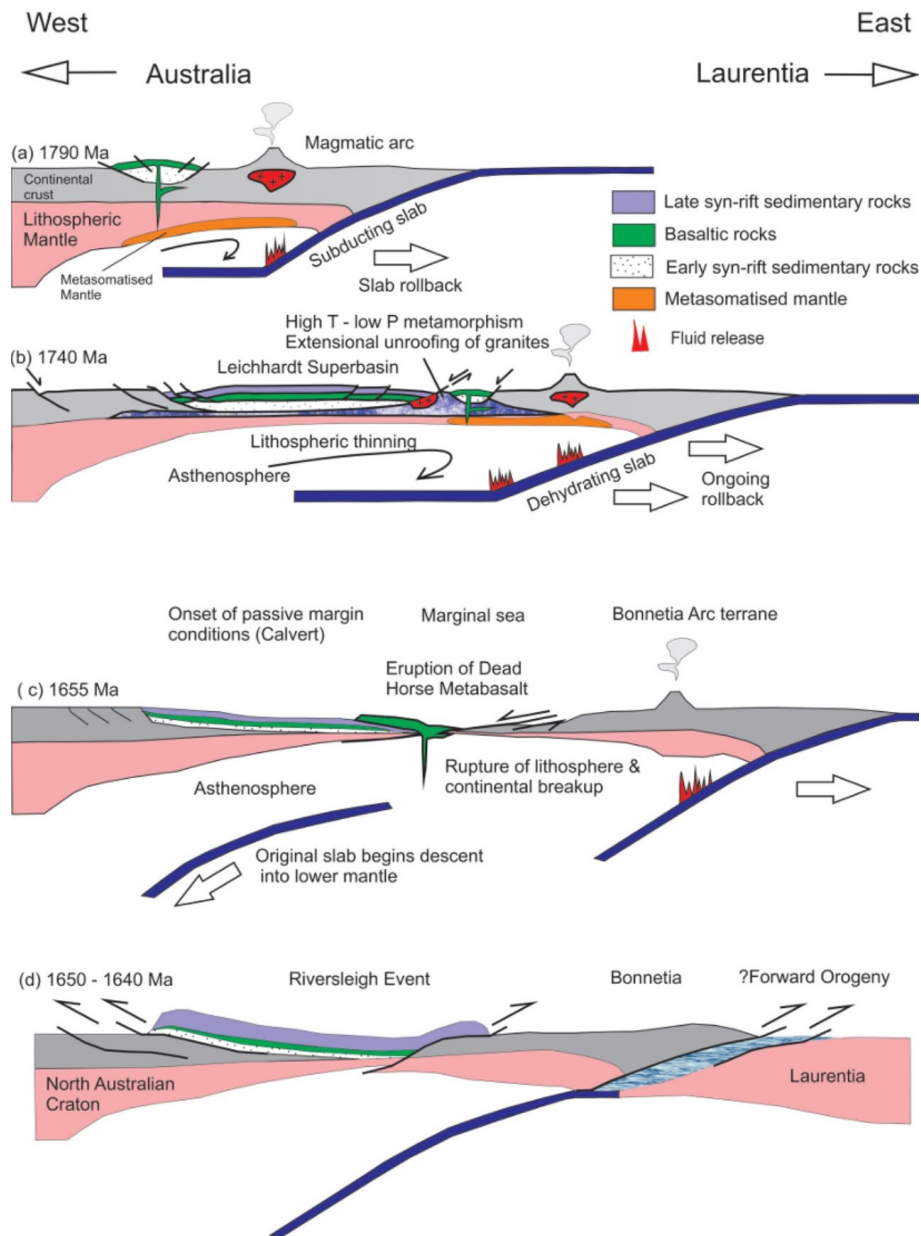


Figure 5. Proposed model for 1800-1650 Ma Mount Isa/Georgetown basin evolution from Gibson *et al.* (2018):

(a) Onset of extensional faulting and rift-related magmatism at 1790 Ma in a backarc extensional setting. Subduction commenced ≥ 1840 Ma following separation of Laurentia from Australia;

(b) Subduction rollback and lithospheric thinning are well advanced by the end of Leichhardt Superbasin time (1740 Ma); flat-slab subduction leads to reduced amounts of basaltic magmatism but rifting continues accompanied by extensional unroofing of earlier-formed 1780 Ma granites and mid-crustal rocks;

(c) Following rupture of the lithosphere at 1655 Ma, basaltic magmatism is driven by decompressional melting of the asthenosphere. Passive margin conditions established in the Mount Isa and Georgetown regions while subduction and arc magmatism continue to east;

(d) Arc-continent collision commencing at ~ 1650 -1640 Ma with arc and its underlying continental substrate (Bonnetia) obducted onto the Laurentian margin; backarc basin begins to collapse and invert during the Riversleigh Inversion Event.

Pourteau *et al.* (2018) and Nordsvan *et al.* (2018) also relate superbasin development to backarc extension in the overriding plate of a westward-dipping subduction zone east of the Georgetown Province. Nordsvan *et al.* (2018) considered the Mount Isa Province to have been separated by an interior ocean from Laurentian systems further to the east where the early Georgetown Province sequences (**lower Etheridge Group**) were deposited. In their model,

the younger Georgetown Province rocks (**upper Etheridge Group**) were deposited after separation from Laurentia by backarc extension associated with an eastward-dipping subduction zone along the western edge of Laurentia, before final amalgamation with the NAC (see Figure 6). Pourceau *et al.* (2018) interpreted the final Nuna suture as a region of bivergent thrusting focused on a west-dipping master fault identified from the 07GA-IG1 deep seismic profile (see Figures 7 and 15).

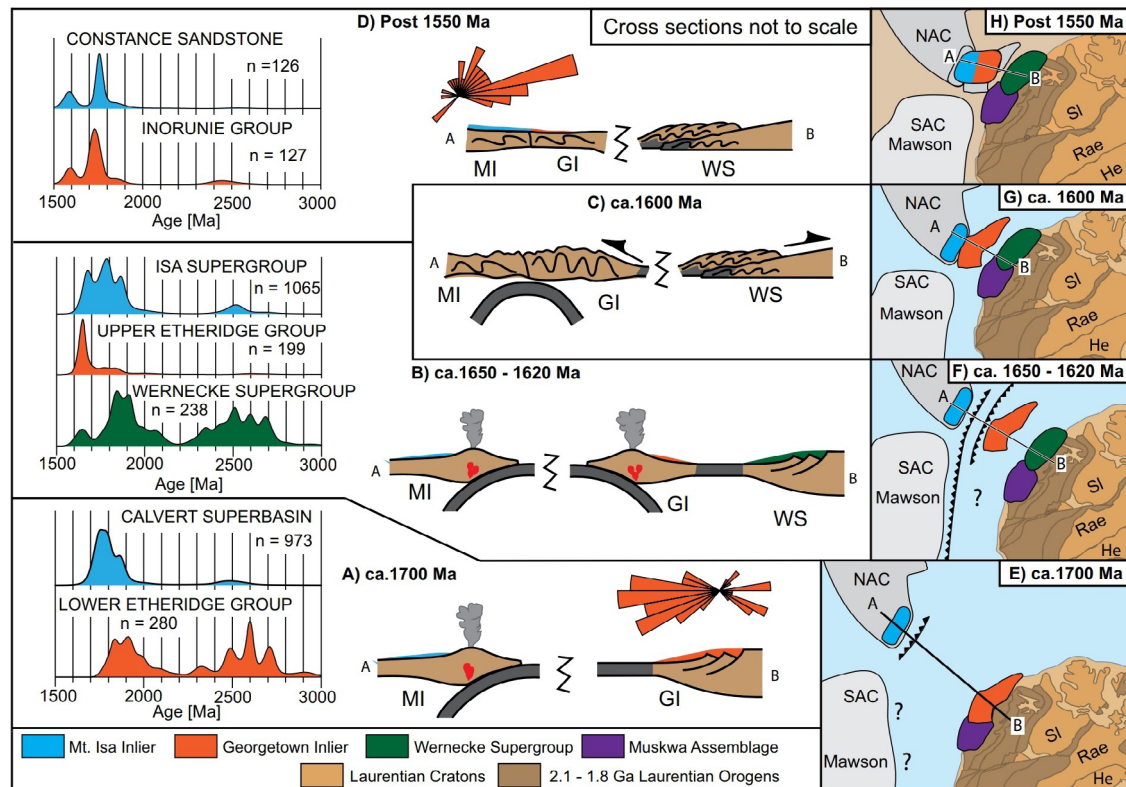


Figure 6. Tectonic model and paleogeographic reconstructions proposed by Nordsvan *et al.* (2018); Comparative age equivalent detrital zircon age spectra from the Georgetown Inlier, the Mount Isa Inlier (MI) and the Laurentian Wernecke Supergroup.

A and E: ~1700 Ma. Sediments in the Georgetown Inlier were initially deposited in a passive margin while sediments in the Mount Isa Inlier were deposited in a backarc basin to a west-dipping subduction zone (Betts *et al.*, 2016). He—Hearne craton, Sl—Slave craton;

B and F: ~1650–1620 Ma. Development of an east-dipping subduction zone off the western margin of Laurentia prompted backarc rifting between the Georgetown Inlier and Laurentia causing complete separation by ~1650 Ma. WS—Wernecke Supergroup;

C and G: Continued subduction leads to accretion of the Georgetown Inlier to the North Australia craton (Isan-Jana Orogeny) and the Racklan Orogeny in west Laurentia;

D and H: Post–1550 Ma. Detrital zircon age spectra from the Inorunie Group strongly resembles the Constance Sandstone of the Mount Isa Inlier, suggesting a correlation and further indicating a connection after 1550 Ma.

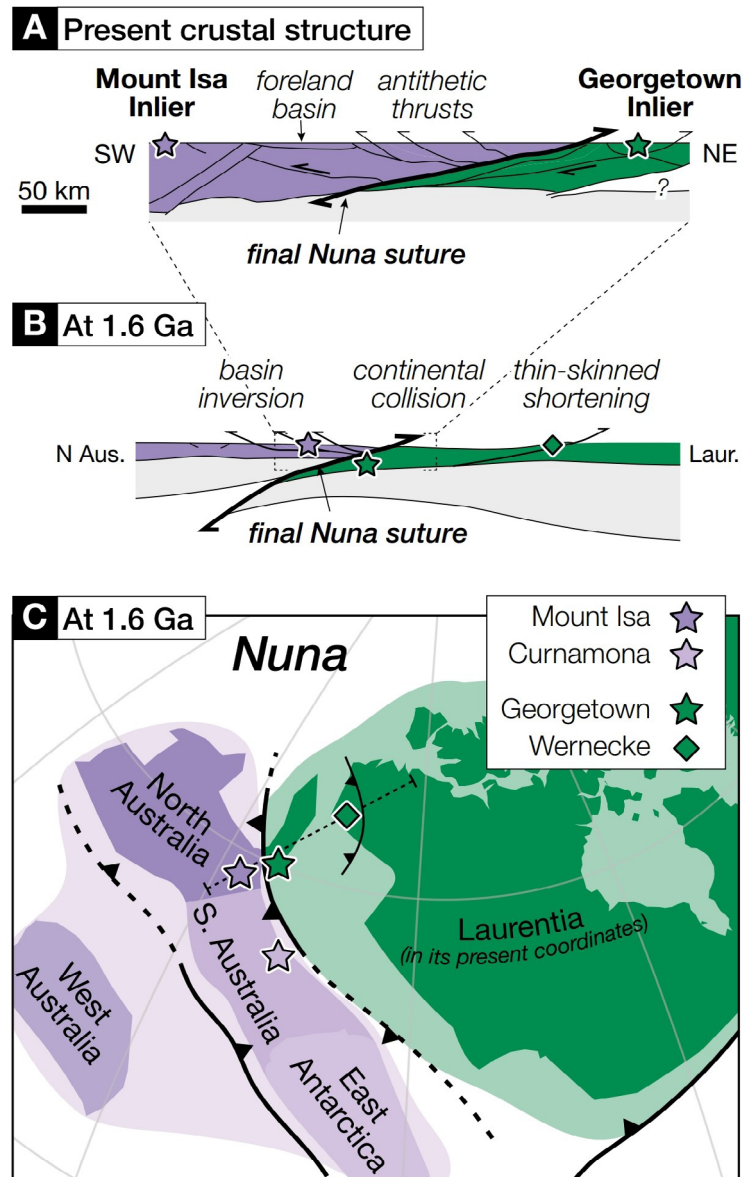


Figure 7. Model for Late Proterozoic amalgamation of Mount Isa and Georgetown terranes proposed by Pourteau *et al.* (2018):

(A) Isa-Georgetown crustal section (adapted from Korsch *et al.*, 2012) with features interpreted to relate to the final Nuna-Laurentia suture;

(B) schematic lithospheric cross section illustrating collision of Laurentian promontory (Georgetown) with the eastern NAC at ~1600 Ma producing far-field bivergent thrusting in both crustal blocks;

(C) possible final merged configuration of Australia-Antarctica-Laurentia components of Nuna at 1600 Ma.

Alternative correlations of backarc extension with northward-dipping subduction of the South Australian Craton (SAC) beneath the NAC (Giles, 2002; Betts *et al.*, 2003) have been further modified by Betts *et al.* (2009) who related orogenic activity to plume interactions with the SAC/NAC subduction system.

In these proposed tectonic scenarios, the phases of the **Isan Orogeny** represent the inboard expression of plate collisions along either the southern or eastern boundary of the NAC (or both; Betts *et al.*, 2002; Betts & Giles, 2006, Abu Sharib, 2016), interpreted as the final stages of amalgamation of the supercontinent **Nuna** (Betts *et al.*, 2016; Pourteau *et al.*, 2018).

Following the Isan Orogeny, post-orogenic global plate re-organisation around 1300-1000 Ma is thought to have resulted in the formation of the supercontinent **Rodinia**, including amalgamation of the North Australian Craton with the West and South Australian Cratons.

Breakup of the Rodinian supercontinent began in the late Neoproterozoic (~850 Ma) and proceeded in a series of complex and protracted phases which some authors relate to a period of superplume magmatism (Li *et al.*, 2008; Ernst *et al.*, 2008). A widespread passive margin basin developed at this time over several thousand kilometres from North Queensland down to southeastern Australia and into the Transantarctic Mountains.

3.2 Thomson Orogen

Rodinian breakup accelerated in the latest Neoproterozoic with dramatic splitting of the crust at the southern margin of the Mount Isa Inlier along a family of northeast-trending structures including the **Diamantina Lineament** to form an extended passive margin floored by highly extended continental and/or oceanic crust. Microcontinental fragments were likely separated from the Mount Isa Province, and transported several hundred kilometres to the south as the **Curnamona Province**.

The deep basin that developed at the southern termination of the Mount Isa Province saw deposition of thick meta-sedimentary and felsic volcanic sequences, locally intruded by a variety of granitoids, which together have been assigned to the **Thomson Orogen**. The Thomson Orogen sequence juxtaposed against the southern Mount Isa Inlier is poorly understood due to the lack of exposure and widespread distribution of younger post-orogenic cover basins up to 2 km in thickness.

From drillhole examination, Carr *et al.* (2014) and Purdy *et al.* (2016) have described at least three deep marine to locally fluvial sedimentary packages within the orogen. These subsurface sequences, as well as equivalent Thomson Orogen surface exposures mapped in eastern Queensland, have been divided into two distinct provenance packages based on detrital zircon geochronology (Fergusson *et al.*, 2007; Purdy *et al.*, 2016; see later discussion).

3.3 Younger cover basins

3.3.1 Galilee Basin

The southern NAC margin and adjoining Thomson Orogen margin are overlain by the basal sediments of the latest Carboniferous-Middle Triassic **Galilee Basin**, which are in turn overlain by the more extensive Jurassic-Cretaceous sedimentary package of the **Eromanga Basin**. The Galilee Basin is a large, intracratonic coal-bearing basin, whose northernmost segment (the **Lovelle Depression**) lies along the southern section of the 14GA-CF1 transect, lapping to the south onto a Thomson Orogen basement high (the **Maneroo Platform**).

The Lovelle Depression sequence is up to 1200 m thick and includes a thick sequence of locally tuffaceous, mainly Early Permian terrestrial sediments of the **Jochmus Formation** at the base, overlain by the Late Permian coal-bearing sediments of the **Betts Creek beds**, the Triassic fluvial **Warang Sandstone** and the uppermost finer sediments of the **Moolyamber Formation**. The Cork Fault and subparallel Wetherby structure have acted as normal north-dipping growth faults during sedimentation, with the thickest sections developed immediately to the north of these faults. Middle Triassic equivalents of the Galilee Basin may occur at the northern end of the seismic transect at the base of the **Canobie Depression** (Williams & Gunther, 1989; Korsch *et al.*, 2011). Galilee Basin sedimentation has been ascribed to subsidence induced by a combination of foreland loading and mantle convection (de Caritat & Braun, 1992).

As the seismic survey was designed to focus on large crustal features, no attempt has been made in this report to delineate the various Galilee Basin units.

3.3.2 Carpentaria and Eromanga Basins

The youngest cover sequences resolved in the seismic transect are the fluvial to marine sediments of the Jurassic-Cretaceous **Carpentaria Basin** (in the north) and contiguous **Eromanga Basin** (in the south). These basins are interconnected over a basement high referred to as the **Euroka Arch**, whose axis is orthogonal to the seismic transect (see Figure 2 and 8). These intracontinental basins cover a very large area of inland Queensland, New South Wales and South Australia, and result from intraplate rifting or intracratonic sag.

Along the length of the seismic transect the basal strata comprise the coarse fluvial clastics of the Early Cretaceous **Gilbert River Formation** (and equivalent Hutton Sandstone/Cadna-owie Formation/Hooray Sandstone sequence in the Eromanga Basin), which give way to overlying marine glauconitic sands and silts of the **Wallumbilla Formation**. The apex of this marine transgression is marked by deposition of limestones and carbonaceous shales of the **Toolebuc Formation** and succeeding **Allaru Mudstone**.

Deposition is locally controlled by synchronous faulting with thicker sequences evident in places within shallow grabens and troughs (*e.g.*, the **Canobie Depression** at the northern end of the seismic section).

As the seismic survey was designed to focus on large crustal features, no attempt has been made in this report to delineate the various constituent units of the Carpentaria and Eromanga Basins.

4. Seismic profile - crustal components

4.1 Upper crust

4.1.1 Carpentaria and Eromanga Basins

The Jurassic-Cretaceous sediments of the Eromanga and Carpentaria Basins form the surficial cover layers of the 14GA-CF1 transect, and reach up to 2 km thick in the region of the Cork Fault (see Figure 8). This fault and associated northeast-trending faults (*e.g.*, the Wetherby structure) show evidence of syn- and post-depositional mainly normal movement. The Eromanga Basin sequence thins significantly to the north over the Euroka Arch, before transitioning into the equivalent Carpentaria Basin sequence which gradually begins to thicken again to around 1300 m forming a broad half graben bounded by a basement horst at around CDP 65000 (see Figure 8). The sequence is developed once again north of the horst, where the rift-like **Canobie Depression** is imaged at the end of the transect reaching 833 m total depth (Williams and Gunther, 1989). The Toolebuc Formation forms a visibly continuous horizon across the Euroka Arch for almost the whole length of the transect (see Figure 8).

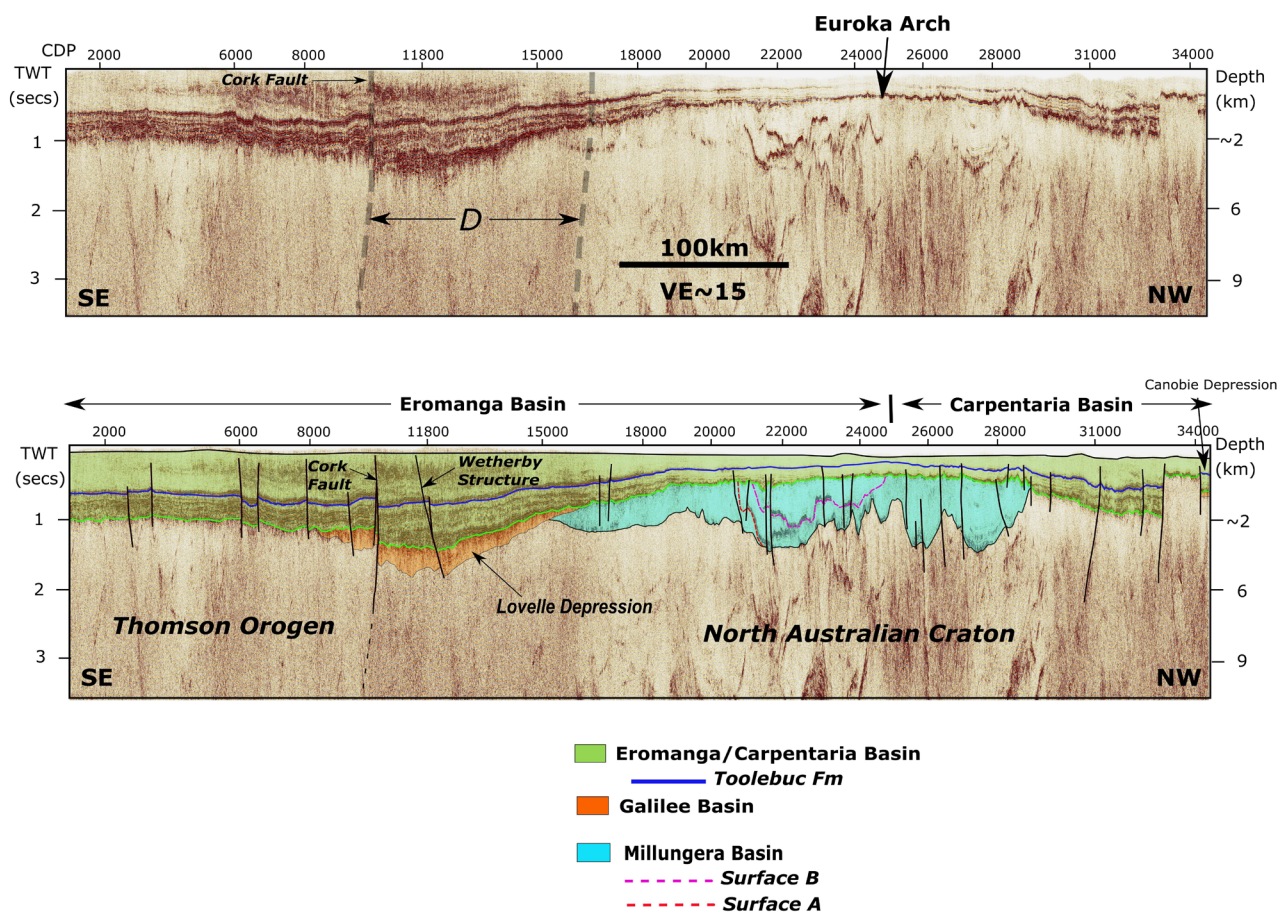


Figure 8. Seismic interpretation of upper crustal cover basins for complete 14GA-CF1 transect showing distribution of Carpentaria and Eromanga Basins divided by Euroka Arch basement high. Loss of resolution within vertical zone labelled “D” appears to affect whole section, rendering interpretation as pre-Eromanga meteorite impact structure unlikely.

4.1.2 Galilee Basin

Early Permian to Triassic sediments of the Galilee Basin are developed in the southern section of the transect adjacent to the Cork Fault and Wetherby structure where they form the **Lovelle Depression** (Figure 2 and Figure 8). The deepest

part of the basin is approximately 1200 m thick and is developed immediately to the north of the Cork Fault. The basin unconformably overlies basement of the Thomson Orogen south of the Cork Fault and undivided Proterozoic upper crust of the NAC north of the Cork Fault. The basin is also interpreted to unconformably onlap onto the southern extent of the Mesoproterozoic? Millungera Basin. Small remnants may exist further north, including Triassic sediments recorded from a drillhole into the Canobie Depression (Williams & Gunther, 1989), but these cannot be resolved in the seismic data. The Galilee Basin is unconformably overlain by Jurassic-Cretaceous strata of the Eromanga Basin.

4.1.3 Millungera Basin

The Millungera Basin was first identified in 2007 following examination of data from the newly-acquired 07GA-IG1 deep seismic survey, which was designed to image crustal linkages between the Mount Isa and Georgetown Provinces. The 14GA-CF1 profile is orthogonal to this northeast-trending section, extending knowledge of Millungera Basin stratigraphy to the northwest and southeast of the 2007 section.

An interpretation of the 07GA-IG1 data has been undertaken by Hutton *et al.* (2010), Korsch *et al.* (2011) and Korsch *et al.* (2012) who identified three major stratigraphic packages with a total thickness of 2.8 - 3.5 km. These packages are not as well imaged in the more recent 14GA-CF1 data, with cross-line extrapolation of these units only being possible for about 6 km north of the 07GA-IG1 intersection (see Figure 9), although the overall basin form can be traced for over 240 km from north to south (see Figure 12).

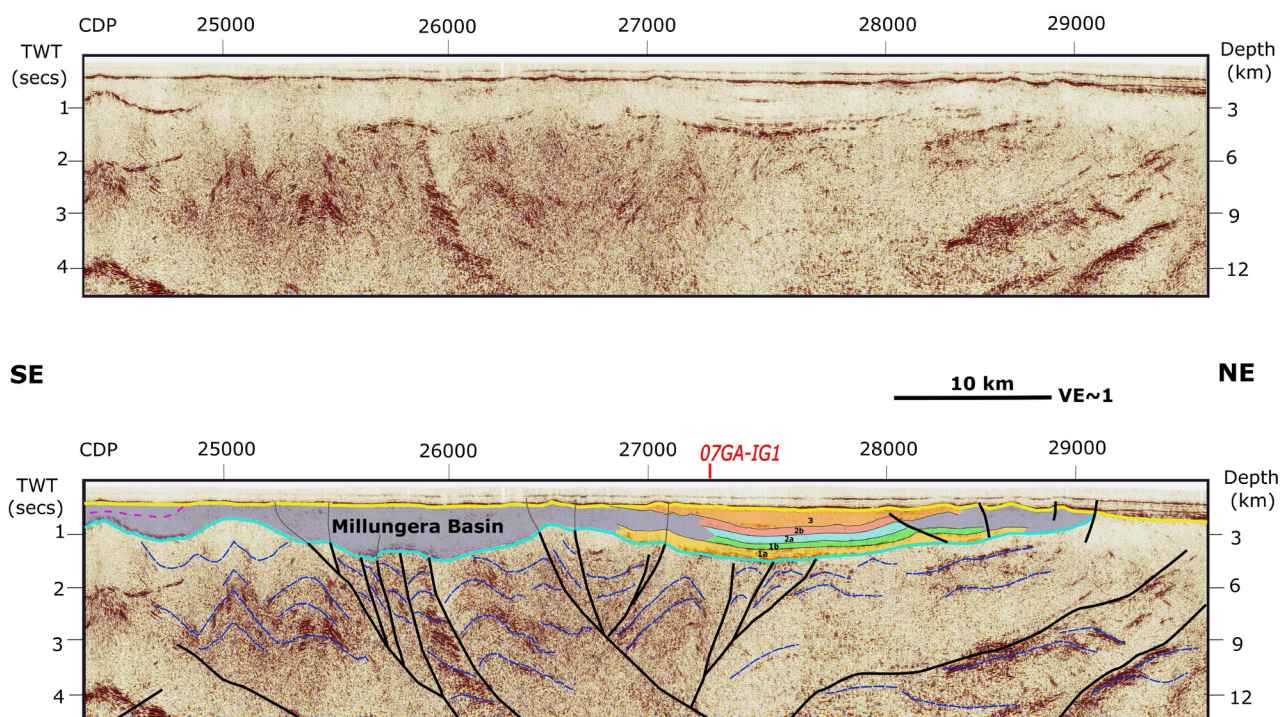


Figure 9. Northern extent of Millungera Basin in 14GA-CF1 profile showing subdivisions identified by Korsch *et al.* (2011) from 07GA-IG1 survey; irregular basal surface reflects palaeo-topography controlled by folds and associated thrusts in Soldiers Cap Group metasediments, lavas and sills.

The 14GA-CF1 profile reveals an unconformable contact with the deformed Julia Creek Basin basement sequence, with strata draped over numerous palaeo-topographic highs defined by thrust and fold culminations (Figure 9).

The southern segment of the basin appears to show a number of onlapping depositional surfaces (shown as Surfaces “A” and “B” in Figure 8), which are in turn onlapped and overlain by the Galilee and Eromanga-Carpentaria Basins. These Millungera Basin units may reflect changing base levels produced by gradual orogenic uplift to the south or west. Some of these sediments have a 2D expression in regional magnetic images (see Figure 10) and may have been sourced from the magnetite-rich rocks of the Eastern Succession, shedding eastwards along valleys confined by tight

basement fold culminations. Withnall & Hutton (2013) proposed a 1500-1400 Ma depositional age for the basin, based on age constraints provided by a ~1530 detrital zircon date (Carson *et al.*, 2011) and an 1100 Ma Rb-Sr illite age (T. Uysal, UQ, unpublished data).

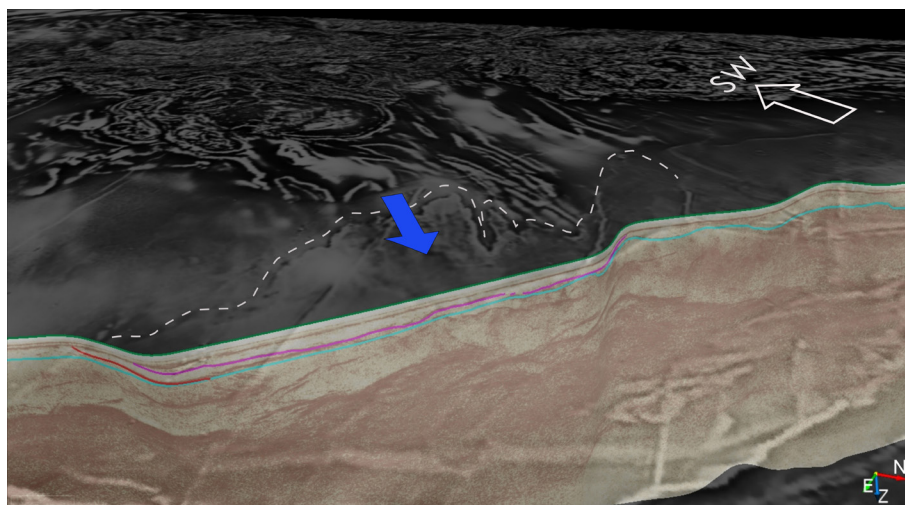


Figure 10. Outline of thin sheet of Millungera Basin strata (white dashes) associated with onlapping depositional surfaces shown in pink and red on seismic profile (refer to Figures 8 and 11b); oblique view to southwest of greyscale magnetic image draped over seismic profile.

4.1.4 Canobie Basement Sequence

Schistose metasediments intersected at the base of the GSQ Dobbryn 1 borehole in the Canobie Depression (close to the far northwestern termination of 14GA-CF1) contain detrital zircons with a maximum depositional age of 1592 \pm 5 Ma (Carson *et al.*, 2011), postdating the Soldiers Cap Group (*i.e.*, Kowanyama Seismic Province equivalents) and the earliest phases of the Isan Orogeny that terminated deposition within the Mount Isa Inlier. However, as no expression of this sequence can be identified in the seismic data, this unit has not been included in the interpretations presented in this report.

4.2 MIDDLE - LOWER CRUST

4.2.1 Kowanyama Seismic Province (Julia Creek Basin)

Upper crustal sequences assigned to the Kowanyama Seismic Province occupy the informally-named **Julia Creek Basin**, an asymmetric feature dominating the central part of the seismic profile. In the plane of the transect, the basin extends for over 300 km, with the deepest segment in the north adjacent to the Mount Isa Province (around CDP 52000), extending to a depth of around 6.5 s TWT (~ 20 km). The basin is dominated by strata considered to be largely subsurface equivalents of the **Soldiers Cap Group** – mainly meta-turbidites with sporadic mafic sills and lava horizons. Outcrop of this unit occurs at the eastern margin of the Mount Isa Inlier south of Cloncurry, and can be traced eastwards in the subsurface using magnetic and gravity images to where it is cut by the 14GA-CF1 transect.

The weakly to moderately reflective **Kowanyama Seismic Province** strata contrast strongly with underlying more reflective seismic basement of the **Numil Seismic Province** (see Figure 11). The basin onlaps the Numil Seismic Province at its southernmost extremity, while its northern extremity is complexly faulted against undivided older NAC crust assumed to belong to the Mount Isa Province (see later discussion on Numil Province affinities) along a low angle southeast-dipping fault system (labelled F3 in Figure 11) that extends to the MOHO.

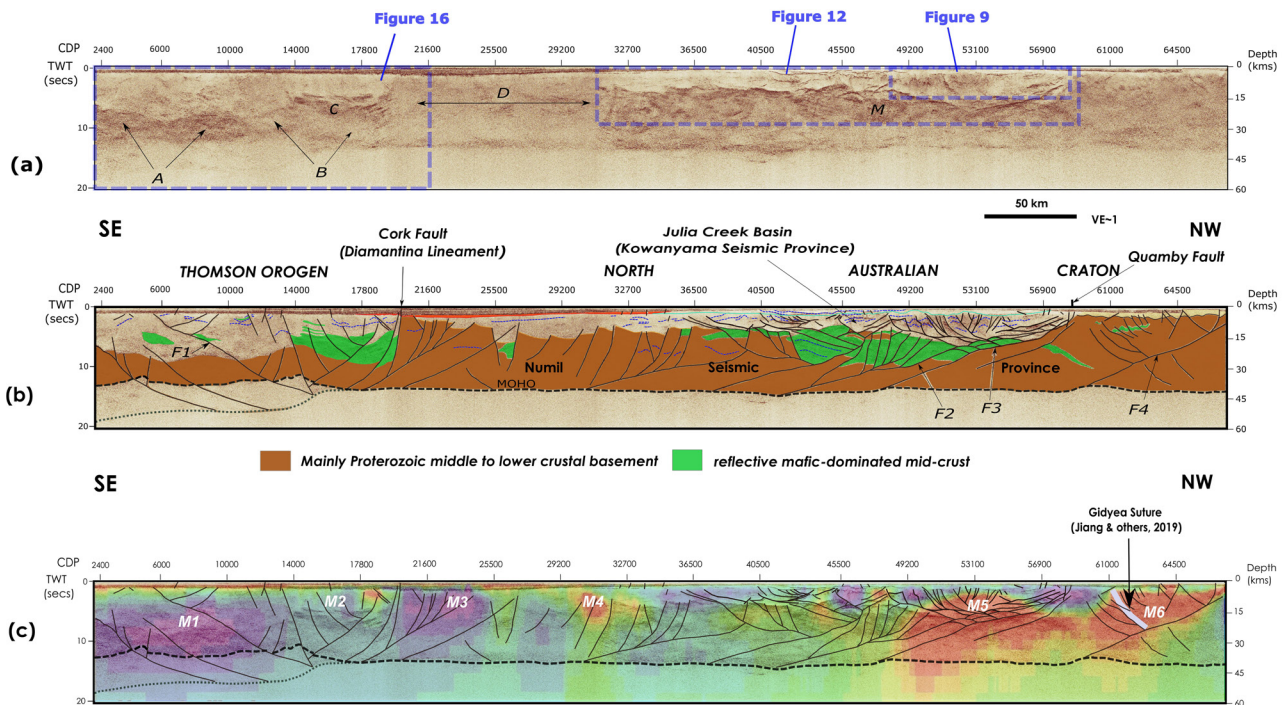


Figure 11. Geological interpretation of 14GA-CF1 deep seismic profile:

(a) Uninterpreted profile showing location of higher resolution figures and selected seismic features discussed in the text;

(b) Interpreted seismic profile showing location of key faults and major crustal subdivisions;

(c) Interpreted seismic profile displaying correlation of seismic features with magnetotelluric data overlay (magnetotelluric data from Jiang et al., 2019).

The faulted northern margin of the Julia Creek Basin appears to represent a master extensional structure facilitating initial basin formation at this location. Significant later inversion and imbrication of both basement and the overlying sedimentary section has taken place along this structure (see Figure 12 and later discussion). Away from this fault, towards the interior of the basin, further shortening is evident as dominantly south-verging open to tight folding and associated thrusts (around CDP 51000), as well as an imbricate fan developed above a basal decollement (around CDP 42200).

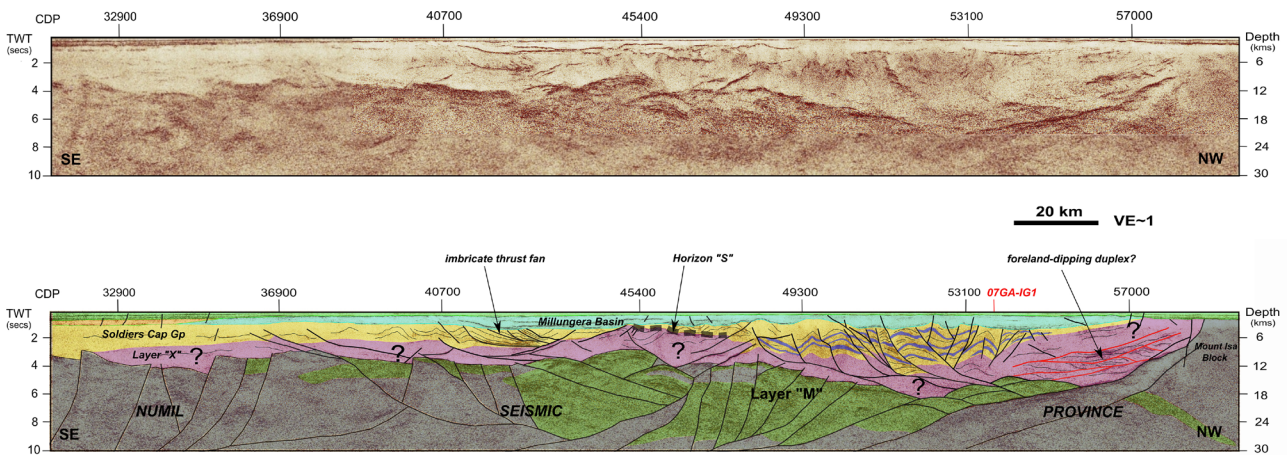


Figure 12. Interpreted crustal profile of the Julia Creek Basin; Kowanyama Seismic Province sedimentary package (pink and orange) overlain by extensive Millungera Basin sequence (aqua); reflective strata interpreted to represent Soldiers Cap Group sequence (orange), while speculative poorly reflective basal layer (pink layer labelled "X") may represent more strongly deformed and metamorphosed equivalent or an even older early Calvert sequence; horizon labelled "S" may represent

remnants of Staveley Formation carbonate platform and/or decollement surface; possible foreland-dipping duplex developed adjacent to northern Mount Isa Province basin margin.

Several reverse offsets of the basement interface below the deformed Soldiers Cap Group sequence are visible in the seismic data. Some of these faults sole out at the MOHO, and may represent original normal faults facilitating crustal thinning during formation of the Julia Creek Basin.

The fault network in the deepest part of the Julia Creek Basin sequence (around CDP 52600) exhibits a flower-type geometry, with a family of north-dipping listric faults (in the south) complemented by several moderate south-dipping faults to the north. These faults may have initiated as syn-depositional normal faults, or alternatively as a later transpressive array produced during Isan Orogeny shortening. Although this segment of the basin contains the best-preserved sequence of reflective strata, with possible marker sequences traceable across faults (see Figure 12), the thickness changes are too ill-defined to demonstrate any syn-depositional character for the faults in this region.

The orientation of these thick-skinned fold/thrust belts in the seismic data is consistent with regional magnetic data images which reveal tight ENE-trending folds of mafic sills and lavas, roughly orthogonal to the transect (Figure 13). These fold trains are interpreted to largely result from a NNW-SSE directed Isan Orogeny shortening event orthogonal to the seismic profile (considered here to most likely represent one of the later D2 events; see Figure 23). This stress direction is consistent with the lack of evidence for this fold/fault style on the intersecting 07GA-IG1 profile, due to its orientation orthogonal to this shortening direction.

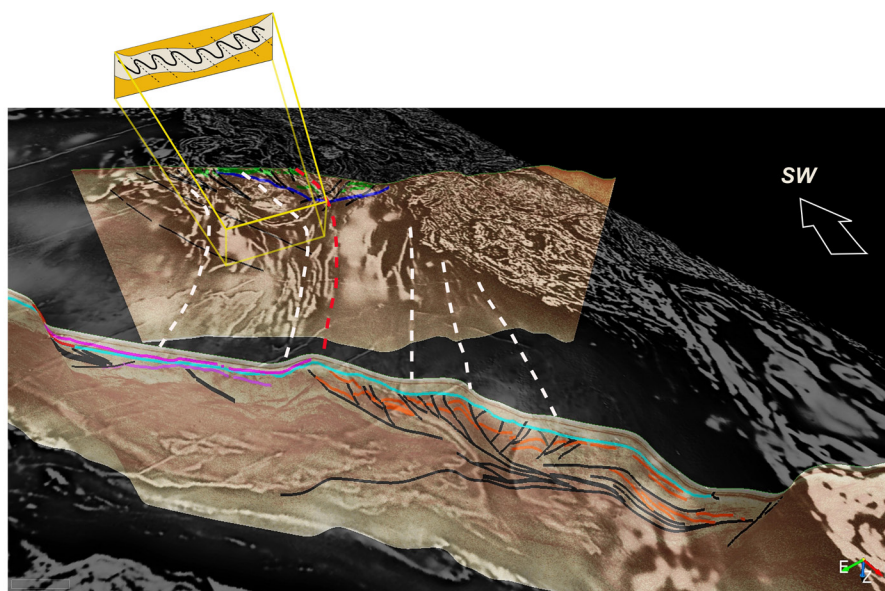


Figure 13. Oblique view of 14GA-CF1 (foreground) and 06GA-M4 profile (background) overlain by greyscale magnetic image; magnetic D2 fold trends extrapolated between sections; red line marks boundary between north and south verging faults on the 06GA-M4 profile; pop-out cartoon shows scale and rheological variation in fold wavelength common in the Mount Isa region – tight meso-scale folds confined within broad regional scale folds of more competent sequences.

No definitive timing relationship can be established between the NNW-SSE D2 event and the crustal imbrication visible in the seismic profiles adjacent to the F2/F3 fault network in the underlying Numil Province and duplex-style deformation of the Kowanyama sequence immediately above the F3 fault. These imbricate-style features are evident also on the 07GA-IG1 profile where imbricated Numil and overlying Kowanyama packages can be tracked through into disrupted Kowanyama sequences subparallel to the F2 and F3 faults (see Figure 14).

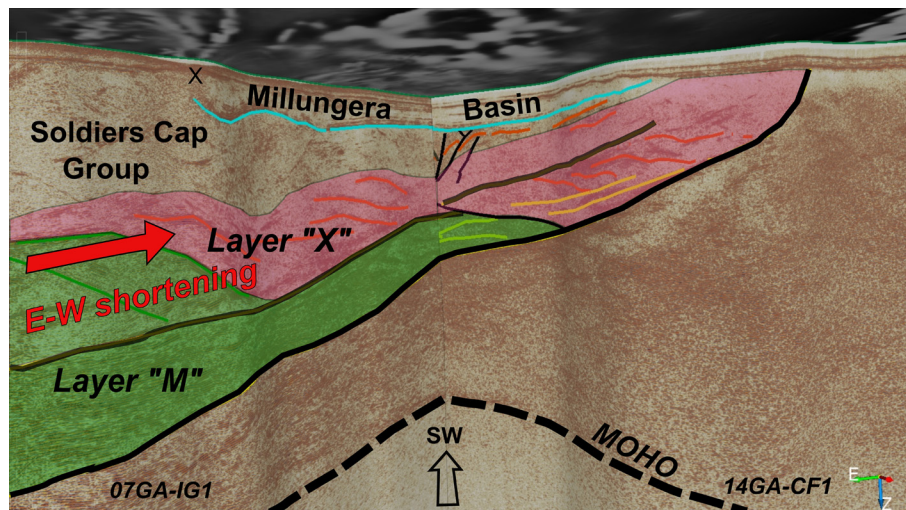


Figure 14. Interpreted intersecting 07GA-IG1 and 14GA-CF1 profiles (on the left and right respectively), showing correlation of speculative basal Kowanyama sequence (layer "X") overlying reflective Numil basement layer "M"; strong imbrication related to west-directed shortening is evident in 07GA-IG1 profile.

The timing of D2? folding and reverse faulting evident on the 14GA-CF1 profile relative to other late Isan events documented from outcrop is uncertain, as several studies of exposed equivalents of this fold style in the Snake Creek-Toole Creek area have yielded conflicting conclusions. Loosveld (1989a, b) and Loosveld & Etheridge (1990) attributed E-W folding to the earliest Isan Orogeny folding event. This conclusion was supported by Giles *et al.* (2006a) who attributed the diversely oriented folds to crumpling in the frontal zone of a northwest propagating nappe, locally refolded still later by N-S folds (*e.g.*, the Weatherly Creek Syncline). However, Abu Sharib (2012) proposed that folds of distinctive orientations in the Cloncurry area were produced by at least three individual deformation events (created by NE-SW, N-S, and E-W to NW-SE directed shortening), with ages supported by monazite dating.

As already mentioned, stratigraphic detail within the Kowanyama sequence is difficult to identify in the 14GA-CF1 profile. The reflective section around CDP 53200 is interpreted as representing Soldiers Cap Group meta-sediments, but, although possible vague stratal repetitions have been interpreted in this part of the section (Figure 12), reliable subdivision into the three constituent formations of the group is not possible. Moreover, a strong discordant reflective horizon, analogous to that identified in the 94GA-MT1 profile by Connors (2019) as carbonates of the Staveley Formation, has not been identified at the base of the inferred Soldiers Cap Group reflective package. The latter is in fact underlain by a significant thickness of material (~2.5 s TWT/ ~7.5 km at deepest point of the basin) whose poorly reflective properties are inconsistent with known carbonate lithologies. The lateral extent of this basal package in relation to the overlying Soldiers Cap Group is difficult to discern throughout the poorly-imaged remainder of the Julia Creek Basin, although the broad association of more poorly reflective material with the lower parts of the basin appears to persist. The speculative distribution of this non-reflective basal package is shown in Figure 12 (designated as Layer "X"), and its possible corresponding distribution on the 07GA-IG1 profile is shown in Figure 14.

A subhorizontal reflector at around 1.5-2 s TWT (~5 km; labelled horizon "S" in Figure 12) is interpreted to cap Layer X between CDP 45600 to 47000 and may represent the remnants of the Staveley Formation carbonate platform, or alternatively a basal decollement facilitating shortening in the overlying sequence.

The nature and origin of the Layer X stratal package is unknown – listric faulting in the upper more reflective sequence generally soils out into very low angle or subhorizontal reflectors, suggesting a rheological contrast and change in thermo-mechanical properties. Layer X may represent a deeper part of the Soldiers Cap Group not known from the succession exposed at the surface, or a change in lithological characteristics of the Soldiers Cap Group with depth resulting from increased metamorphism and deformation. Alternatively, Layer X may represent an older pre-Soldiers Cap Group sequence deposited during the earliest stages of basin development. This would place Layer X presumably within the early Calvert Superbasin age bracket (~1730-1680 Ma), and, if the speculative Staveley Formation "S" reflector is valid, with an upper Staveley-age constraint of ~1715 Ma.

4.2.2 Numil Seismic Province

The Numil Seismic Province is interpreted to form the middle to lower crust extending northwards for around 350 km from the Cork Fault (Diamantina Lineament) to at least the northern edge of the Julia Creek Basin. The province's more reflective character contrasts markedly with the generally more weakly-reflective overlying Kowanyama Province (assigned here to the newly-named Julia Creek Basin).

The Numil Seismic Province broadly comprises a more reflective commonly stratified upper section overlying a more homogeneous less reflective lower section. The two-fold division is best imaged southeast of CDP 53700 where an upper reflective wedge up to 15 km thick extends for over 100 km (labelled “M” in Figures 11, 12, and 15). Continuing further along the profile to the southeast, the reflective stratal patches in the upper layer become more sporadic until the Numil crustal reflectivity becomes mainly uniformly homogeneous (between CDP 36300 and the Cork Fault). Stratification in the upper reflective zones between the Cork Fault (around CDP 19700) and CDP 54000 characteristically exhibits shallow northerly dips with mostly normal (as well as some reverse) offsets across a network of listric south-dipping faults terminating at the MOHO. The latter contact with the underlying mantle is typically strongly reflective and well defined across the province, at a depth of approximately 40 km (~13 s TWT).

The listric-faulted wedges of strongly reflective upper Numil crust in the 14GA-CF1 profile are continuous with a similarly reflective upper Numil layer in the 07GA-IG1 profile (labelled as **Layer M** in Figures 14 and 15).

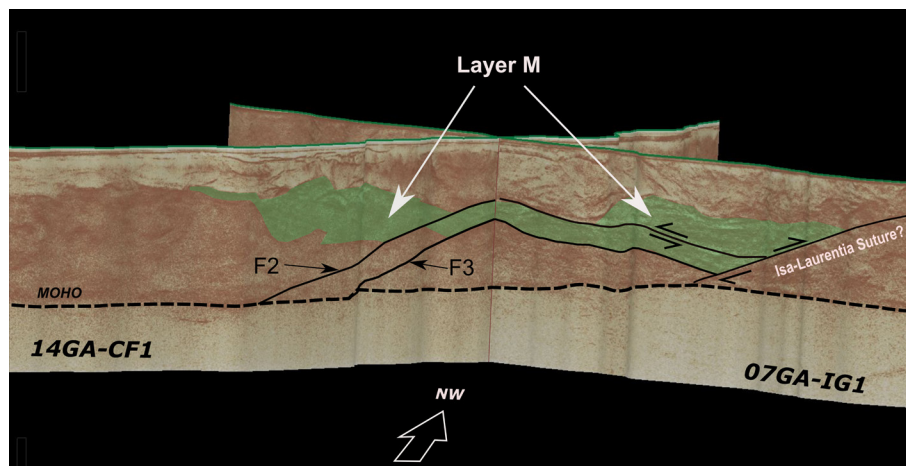


Figure 15. Correlation of reflective upper Numil layer “M” across 14GA-CF1 and 07GA-IG1 profiles; 07GA-IG1 shows west-directed antithetic thrust interpreted by Pourteau *et al.* (2018) above Isa-Laurentia suture.

The latter profile shows Layer M to be attenuated and thinned to the northeast, with some local thickening and inversion along large shallow east-dipping thrust faults. Combining both profiles, it is evident that the Numil crust has experienced a period of early east to southeast-directed extension, significantly greater in the plane of 07GA-IG1 than in the plane of 14GA-CF1. The major extensional master fault bounding the northern margin of the Julia Creek Basin (labelled F3 in Figure 11), can be correlated with a major east-dipping fault in the orthogonal 07GA-IG1 profile, indicating an overall gentle east-southeast dip (see Figure 15). Later inversion along these fault structures is marked by intense imbricate slicing of Layer M lithologies along the northwestern margin of the Julia Creek Basin. These inversion features are interpreted to result from one of the phases of Isan Orogeny shortening (Korsch *et al.*, 2012 and Connors, 2019). Many of these Numil Province faults correlate with inversion features in the overlying Kowanyama Province.

The age and origin of the crustal Layer “M” are uncertain. The layer may represent the remnants of volcanic or volcanic-derived strata developed during earlier periods of extension. Possible scenarios range from collision of Numil Province oceanic marginal basin crust with the Mount Isa terrane during Barramundi-aged subduction, to formation by bi-modal volcanism during Leichhardt Superbasin extension.

4.2.3 Mount Isa Province/northern Numil Seismic Province?

The NAC crustal section north of CDP 54000 to the end of the transect lies in the footwall of the crustal penetrating F3 fault defining the northern margin of the Julia Creek Basin. The mid-crustal profile of this segment of the transect (2-13 s TWT) has similar reflectivity to the remainder of the NAC mid-crust extending to the south, typically with a strongly developed MOHO at similar depths. However, the upper more reflective Layer M of the Numil Province south of CDP 54000 is thinned and dismembered to the north as it approaches the basin-bounding F2 and F3 faults, before effectively disappearing in the remainder of the section (except for rare thin layers; see Figure 11b).

The uppermost ~2000 m of the crust below the thin Carpentaria Basin cover sequence is bland with very little reflective detail visible. This layer is assumed to comprise equivalents of the Soldiers Cap Group, although considerably younger components are implied from ~1590 Ma detrital zircon ages obtained from meta-sediments at the base of the Dobblyn 1 drillhole into the Canobie Depression (Carson *et al.*, 2011).

The complete crustal section of the northern segment of the transect is cut by a moderate southeast-dipping normal fault with possible inversion spawning a family of northeast-dipping reverse faults extending through the hanging wall section to the south. Steeper subsidiary normal faults control graben and half-graben development forming Carpentaria Basin depocentres.

Inspection of the overall seismic character of the NAC mid-crust throughout the complete transect reveals little to distinguish between southern and northern elements. Both are here interpreted as components of the Numil Seismic Province, lacking the deeper more diffuse MOHO and sporadic reflectivity that is more common within the Mount Isa Province. However, the strong gravity and magnetic signatures of the northern segment of the transect are characteristic of the Mount Isa Province to the south across the Quamby Fault. The rationalization of the Mount Isa *versus* Numil Province affinity for this northern section of the profile remains to be resolved.

4.2.4 Winton Impact Structure

Northwest of Winton, the crustal section is poorly resolved in the seismic data for a distance of over 100 km (northeast of the Cork Fault, from CDP 20000 to CDP 30000). This segment of the profile is anomalously bland, although thin Kowanyama crust is interpreted overlying a thick Numil crustal section. The lack of strong reflectivity through this zone (labelled D in Figures 8 and 11a) may be a result of local signal attenuation by overlying cover basins (a relatively thick package of Eromanga Basin sediments and Galilee Basin coal measures) or loss of resolution due to unknown changes in the recording environment. Alternatively, Glikson *et al.* (2016) speculate that the feature results from an asteroid impact in the latest Carboniferous, now reflected at the surface by circular drainage features in the region. However, this timing seems unlikely, as the apparent loss of resolution occurs throughout the whole stratigraphic section, in rocks both older and younger than the Carboniferous (see Figure 8).

4.2.5 Thomson Orogen

The crustal architecture across the Cork Fault in the Longreach region has been the subject of recent studies – Spampinato (2015) using geophysical modelling to investigate the crustal architecture, while Abdullah & Rosenbaum (2018) studied the evolution of the broader Thomson Orogen including an interpretation of part of the 14GA-CF1 deep seismic profile. Both of these studies interpreted the Diamantina Lineament as a crustal-penetrating, southeast-dipping structure, currently expressed at the surface as the steep north-dipping Cork Fault. This report supports this geometry but has further identified the suture as continuing into the mantle to a depth of approximately 50 km (~17 s TWT).

The 14GA-CF1 profile shows the Diamantina Lineament to be associated with dramatic thinning of the Proterozoic crust southeast of the Cork Fault, with the lower crust decreasing in thickness from around 30 km to the north to around 12-14 km to the south of the fault. The poorly reflective Proterozoic character of the lower crust (layer B, Figures 11 and 16) changes along strike to the south where it transitions to more highly reflective crust of uncertain composition (layer A in Figures 11 and 16). The more reflective character of layer A may represent either the development of oceanic crust,

or heavily intruded hyper-extended Proterozoic crust. The base of the lower crustal layer is defined by a generally well-defined MOHO at ~35 km depth (~12.5 s TWT).

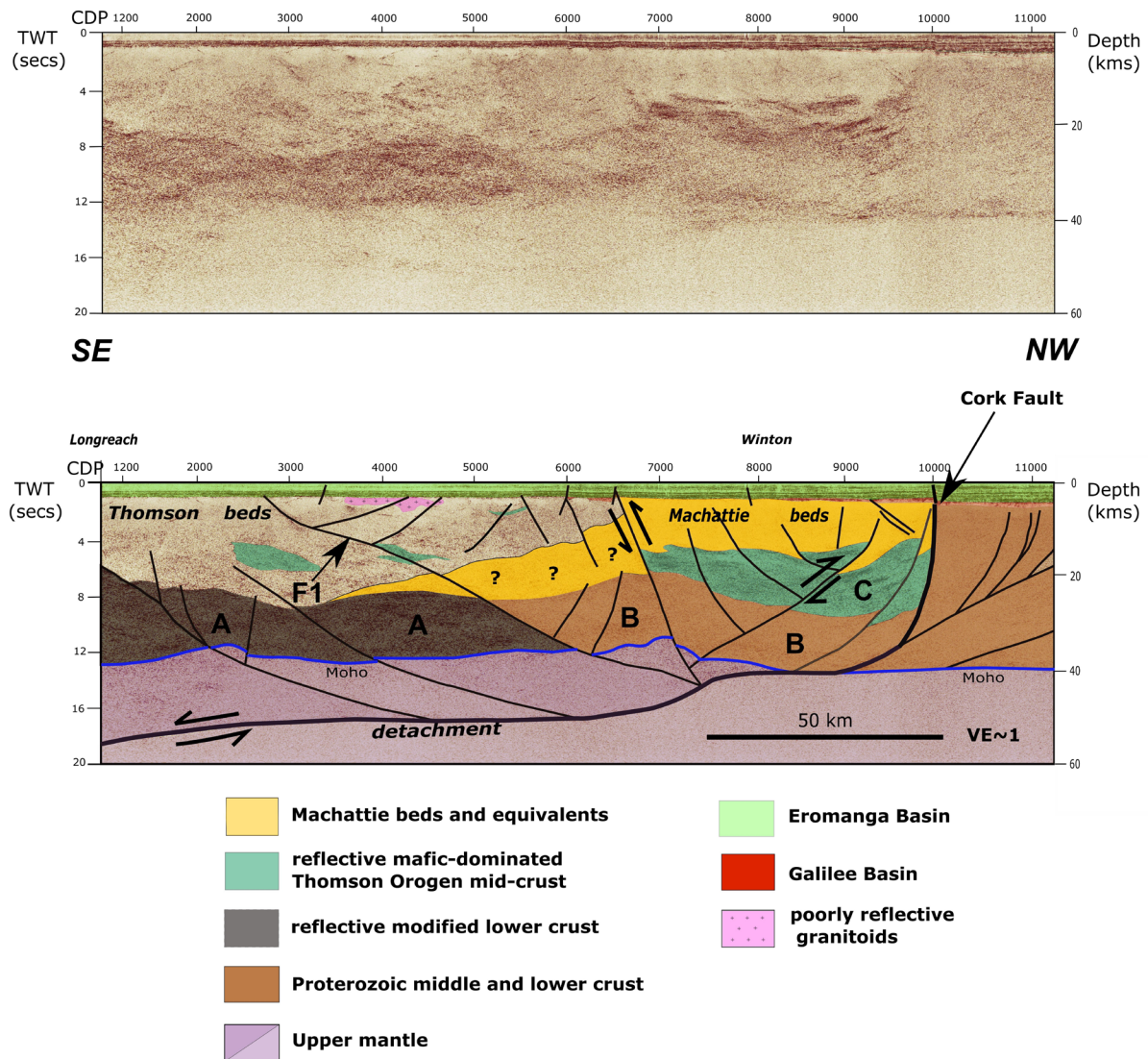


Figure 16. Interpreted seismic profile from the North Australian Craton cross the Cork Fault/Diamantina Lineament into the Thomson Orogen (looking southwest); extended reflective lower crust evident beneath thick meta-sedimentary Thomson Orogen sequence; sub-MOHO surface developed south of the NAC boundary.

The Thomson Orogen crustal section adjacent to the Diamantina Lineament has a rift-like character, with the basal section comprising a 60 km wide wedge of generally reflective strata (layer C of Figures 11 and 16) 3-10 km in thickness, immediately overlying thinned Proterozoic crust (layer B). This wedge thickens towards the Diamantina Lineament, implying its movement as a growth fault during deposition. Extension along the steep-southeast dipping Diamantina Lineament on the northern side of the rift reflects the orientation of pre-existing southeast-dipping faults that segment the Proterozoic lower crust of the NAC bounding the Thomson Orogen to the north. The reflective lower wedge at the base of the rift feature is overlain by a 10 km thick section of moderate to poorly reflective strata.

The southern margin of the Diamantina rift feature is marked by a change in polarity of Thomson Orogen faults, with northwest (rather than southeast) dips predominating. These faults are listric in character slicing the lower reflective crustal Layer A into lozenge-shaped segments. A major whole-of-crust penetrating fault (labelled F1 in Figures 11 and 16) marks an abrupt change in reflectivity in the lower crust between layers A and B (Figures 11 and 16), and may mark a crustal break coinciding with the development of oceanic crust. The northwest-dipping series of extensional faults at

the southern end of 14GA-CF1 are interpreted to sole out on the master detachment lying at around 10 km beneath the MOHO (Figures 11 and 16).

Thomson Orogen basin fill at the southern end of the seismic profile is imaged as around 20 km of poorly to moderately reflective section which in turn is capped by the strongly parallel reflections of the Galilee and Eromanga cover basins up to 2 km thick.

There is no evidence of widespread orogenic deformation visible in the seismic profile, although there is some inversion evident along earlier extensional structures. In particular, pop-up features are visible in the centre of the Diamantina “rift”, possibly associated with dextral transpression along the Diamantina Lineament as indicated by large-scale asymmetric inflections of regional magnetic linears to the south of the Cork Fault. Moreover, reverse faulting along the southern rift margin has juxtaposed older rift sequences against younger successions to the south (see discussion below).

4.2.5.1 Age and affinities of Thomson seismic packages

Knowledge of the subsurface Thomson Orogen in northwest Queensland has only become available from the few exploration and stratigraphic boreholes that have penetrated basement through the thick Permo-Triassic cover sequences. On the basis of recent studies of these core samples, Carr *et al.* (2014), have proposed four new informal subdivisions of the subsurface succession – the **Machattie beds**, the **Betoota beds**, the **Thomson beds** and the **Maneroo Volcanics**. The Machattie beds have only been described from two drill holes (GSQ Machattie 1 and HPP Goleburra 1) immediately south of the Diamantina Lineament and comprise moderately-dipping quartz-feldspar-lithic sandstone and pebbly sandstone and interbedded laminated to thin-bedded shale and siltstone. The remainder of the succession to the south has been assigned to the widely sampled **Thomson beds** (moderately to steeply-dipping deep marine meta-sediments) or locally, the coarse fluvial meta-sediments of the **Betoota beds** (recorded from DIO Betoota 1).

These units can be grouped into two broad provenance (and age) categories based on detrital zircon spectra – (1) the **Thomson and Betoota beds** displaying a “**Pacific-Gondwana**” signature (typical of many sediments along the Pacific Gondwana margin in Antarctica and eastern and central Australia) characterized by 1300-900 Ma zircon populations and maximum depositional ages of ~495 Ma, and (2) the **Machattie beds** dominated by Grenvillian-age (1300-900 Ma) zircons with a significant peak at ~1180 Ma and lesser peak at ~1070 Ma and a maximum depositional age of ~626 Ma (Purdy *et al.*, 2016; Cross *et al.*, 2018).

This two-fold subdivision has also been identified from Thomson Orogen sequences exposed in the Charters Towers and Anakie Provinces to the east (Fergusson *et al.*, 2001, 2007; Purdy *et al.*, 2016). Units with Grenvillian-age sources form an older package of rocks (Cape River Metamorphics and lower parts of the Argentine Metamorphics in the Charters Towers Province, and the Bathampton Metamorphics in the Anakie Province). The younger Pacific-Gondwana signature has been identified from the upper Anakie Metamorphic Group (Wynyard Metamorphics) and a variety of other units in the region (Fergusson *et al.*, 2001, 2007; Purdy *et al.*, 2016).

The Grenville-sourced provenance package is thought to pre-date the late Cambrian **Delamarian Orogeny** affecting outboard sequences in southern and eastern Australia, while the Pacific-Gondwana provenance package is thought to post-date this event. However, the orogeny had little deformational effect across western Queensland, except for some Delamarian transpressional inversion proposed for the sequences adjacent to the Diamantina Lineament (Spampinato, 2015; Abdullah & Rosenbaum, 2018).

The upper Diamantina “rift” sedimentary package is thought to have been derived largely from the west, where **Petermann Orogeny** uplift at ~580-530 Ma exposed Grenville-age source material within the **Musgrave Province** (Purdy *et al.*, 2016).

Further south, outside the Diamantina “rift”, the poorly reflective Thomson Orogen package mainly records a younger Pacific-Gondwana signature derived from sources presumably isolated from drainage systems fed from the Musgrave

Province. However, as the sequence has not been comprehensively sampled at depth, the presence of unrecognized Grenville-sourced material at the southern end of the seismic profile and at depth cannot be ruled out.

The reflective wedge visible at the base of the Diamantina “rift” underlying the Machattie beds (layer C of Figures 11 and 16) represents the earliest phase of Thomson Orogen basin development visible in the seismic profile. This wedge is interpreted to represent a package of mafic lavas and volcanics formed during vigorous early extension along the northern margin of the Thomson Orogen. As the reflective wedge predates the Neoproterozoic-Cambrian Machattie beds, it is most likely late Neoproterozoic in age. Possible analogues of this proposed mafic magmatism occur to the east, where extension-related mafic schists of the **Bathampton Metamorphics** occur within the exposed Anakie Province of the Thomson Orogen (Fergusson *et al.*, 2009), and to the west along the southern margin of the NAC where the ~600 Ma **Riddock Amphibolite** accompanied early extension within the now exhumed and metamorphosed Irindina Province rift (Wallace *et al.*, 2015). Alternatively, the proposed Diamantina mafics may represent a series of sill-like bodies intruding the Machattie beds in the Early Cambrian (~509-511 Ma) as part of the widespread magmatism associated with the **Kalkarinji Large Igneous Province** (Ware *et al.*, 2018).

5. Integration of crustal conductivity and seismic data

Several of the deep seismic surveys collaboratively undertaken by GSQ and Geoscience Australia have been accompanied by companion deep crustal magnetotelluric (MT) surveys aiming to characterize the crustal conductivity profiles along each transect. This includes the 14GA-CF1 transect (Jiang & Duan, 2018) as well as the earlier 07GA-IG1 survey (Korsch *et al.*, 2012) which intersects the northern half of the 14GA-CF1 transect at almost 90 degrees. MT surveys over the 06GA-M4 and 06GA-M6 transects were undertaken by Quantec Geoscience on behalf of GSQ in 2009 (Gharibi & Killin, 2010).

More recently much of this data has been reworked and updated by Jiang *et al.* (2019) with a focus on understanding the character of the continent-scale Carpentaria Conductivity Anomaly (CCA; see Woods & Lilley, 1979 and Lilley *et al.*, 2003) which trends roughly parallel to the eastern margin of the Mount Isa Province (see Figure 17). These workers concluded that the CCA in the eastern Mount Isa region results from a series of isolated or interconnected conductive bodies.

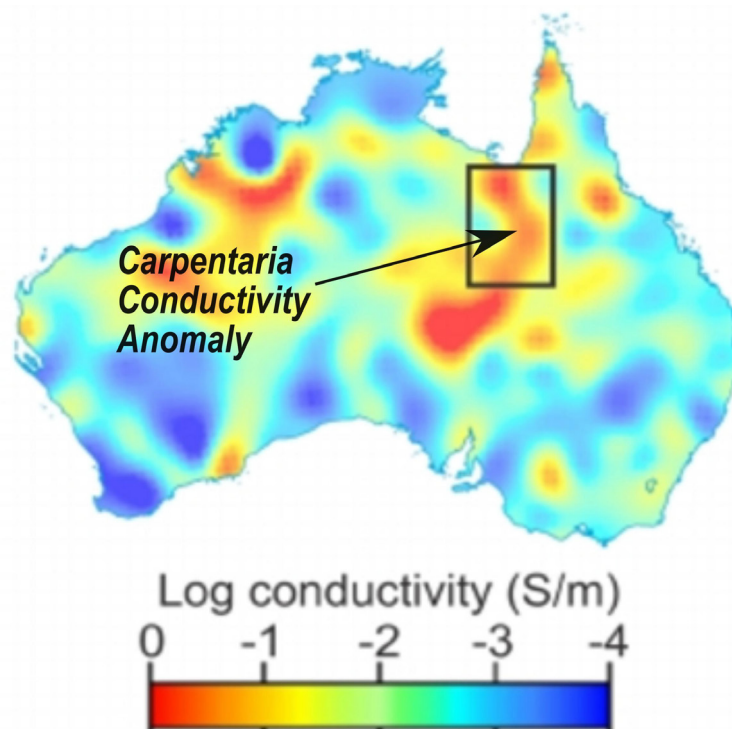


Figure 17. Electrical conductivity structure of the Australian continent showing position of Carpentaria Conductivity Anomaly.

Integration of the revised 3D conductivity profile presented by Jiang *et al.* (2019) with the interpreted seismic profile presented in this report demonstrates a good first order correlation between faults and overall lithologic distributions (refer to Figure 11c above).

The Thomson Orogen is characterized by generally low conductivity (area labelled as M1 in Figure 11c) compared to the adjacent moderately to highly conductive Numil Seismic Province, with the exception of the Diamantina “rift” sequence which is well defined as a belt of slightly higher conductivity (labelled M2 in Figure 11c).

Immediately north of the Cork Fault, the Numil Seismic Province demonstrates a zone of anomalously low conductivity (labelled M3 in Figure 11c), perhaps related to small scattered igneous intrusions evident in regional magnetic data but not resolved in the seismic data. A highly conductive feature at location M4 may be related to fluid movement along steeply-dipping basement faults.

The Julia Creek Basin of the Kowanyama Seismic Province is generally well resolved in the MT data as an upper crustal layer of mainly low conductivity, overlain by a slightly more conductive layer defining the Millungera Basin. However, the MT data highlights the deepest and most structurally complex section of the Julia Creek Basin as a broad zone of strong conductivity overlapping into the underlying Numil Province basement (labelled as feature M5 in Figure 11c). This zone is likely related to long-term deformation-induced fluid flow along the listric, mantle-tapping, basin-bounding F2 and F3 faults (Figure 11b), infiltrating both the footwall and hanging wall. These faults were likely active as master faults during Proterozoic extension and basin formation, as well as later basin inversion events associated with the Isan Orogeny.

The Mount Isa Province basement north of the F2/F3 fault pair also shows strong fault compartmentalisation of conductivity, with the crustal section dominated by a broad zone of high conductivity (M6 in Figure 11c), juxtaposed abruptly against lower conductivity crust across another mantle-tapping listric fault (F4 in Figure 11b).

This region at the junction of the subsurface Mount Isa Province (as defined by regional magnetic and gravity images) and the subsurface Kowanyama Province has been proposed as the location of a major west-dipping palaeo-subduction zone (the Gidyea Suture Zone), most recently by Jiang *et al.* (2019; refer to Figure 11c) who broadly included the feature as part of the Carpentaria Conductivity Anomaly. However, this structure has not been recognized in the 14GA-CF1 data presented in this report (see following discussion).

5.1 Gidyea Suture

The Gidyea Suture Zone, a 10 km wide, west-dipping zone of seismic reflectivity destruction, was identified by Korsch *et al.* (2012) near the western end of the 07GA-IG1 transect. These workers also identified the suture zone in magnetotelluric data and gravity and magnetic inversion modelling. Korsch *et al.* (2012) as well as later workers (*e.g.*, Betts *et al.*, 2016; Jiang *et al.*, 2019) considered the suture to mark a fundamental crustal boundary marking the strongly conductive eastern margin of the Mount Isa Inlier, separating it from contrasting more resistive Numil Seismic Province crust forming basement to the western segment of the Etheridge Province, over 300 km to the east. These authors favoured a model in which the west-dipping suture represented a Paleoproterozoic (~1875-1850 Ma) subduction zone marking the site of ocean basin closure during the widespread 1900-1870 Ma Barramundi Orogeny. Subduction was accompanied by magmatic arc volcanism now represented by the Kalkadoon Granodiorite-Leichhardt Volcanics suite exposed within the core of the inlier to the west.

Betts *et al.* (2016) interpreted the Gidyea Suture Zone to represent mafic and ultramafic oceanic lithosphere entrained between the Mount Isa and Numil Provinces during subduction, while Jiang *et al.* (2019) favoured the zone to represent lithosphere refertilised by fluid dehydration, metasomatism or magmatism during subduction. They viewed the suture as being reactivated during the Isan Orogeny (~1640-1550 Ma), explaining its evident disruption of the whole crustal section, including rocks of the Kowanyama Seismic Province (~1680-1655 Ma) post-dating proposed Kalkadoon-Leichhardt-related subduction by several hundred million years.

This whole-of-crust disruption was confirmed during preparation of this report, which included re-examination of all the deep seismic transects intersecting with or in close proximity to 14GA-CF1. Re-examination of the Gidyea Suture in the 07GA-IG1 profile revealed not only disruption of the Kowanyama Province (mainly Soldiers Cap Group succession of the Julia Creek Basin), but also some east-block-up normal reactivation post-dating deposition of the Jurassic-Cretaceous Carpentaria Basin (see Figure 18).

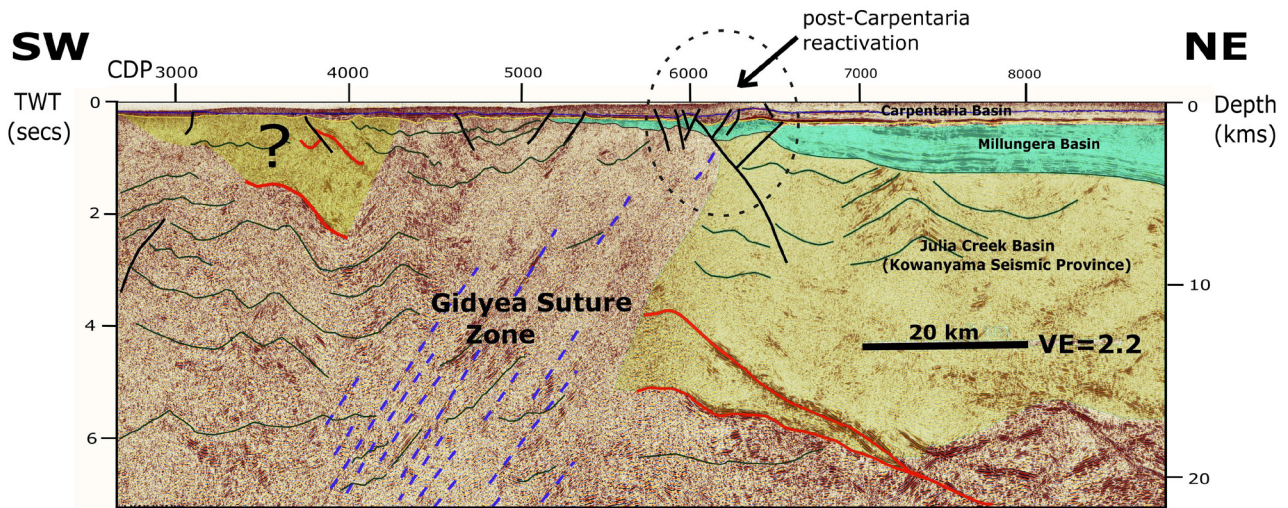


Figure 18. Wide zone of reflectivity disruption defines Gidyea Suture Zone in 07GA-IG1 seismic profile; disruption of sheared base of the Kowanyama Province and Isan Orogeny fold trends is evident in the profile; Millungera Basin post-dates major movement and is interpreted to onlap as a thin veneer across the deformed zone, although both Millungera and Carpentaria Basins experienced much younger localized reverse fault offsets.

Disruption of the sheared base of the Kowanyama Province occurs over a broad 10 km wide zone characterised by fabric development parallel to the fault envelope, overprinting Isan Orogeny fold trends (refer to see Figure 18). The disruption appears to largely predate deposition of the Millungera Basin, interpreted in Figure 18 to onlap as a thin veneer across the deformed zone, and postdate Isan Orogeny folding events. Despite the obvious dramatic expression of the suture in the 07GA-IG1 seismic profile, extrapolation of this structure north and south of this survey has proved enigmatic. No such wide west-dipping structure with internal fabric development is visible in the 14GA-CF1 profile at the concealed margin of the Mount Isa Inlier 55 km to the northeast (see Figure 11 and Figure 19 below). Jiang *et al.* (2019) placed the Gidyea Suture at an inflection in the 14GA-CF1 magnetotelluric profile close to the Mount Isa margin (see Figures 11 and 19) but have not rationalized this with the seismic profiles. Their 3D MT conductivity inversion for this survey better matches the seismic interpretation presented in this report, where no obvious suture was identified (see Figure 11b).

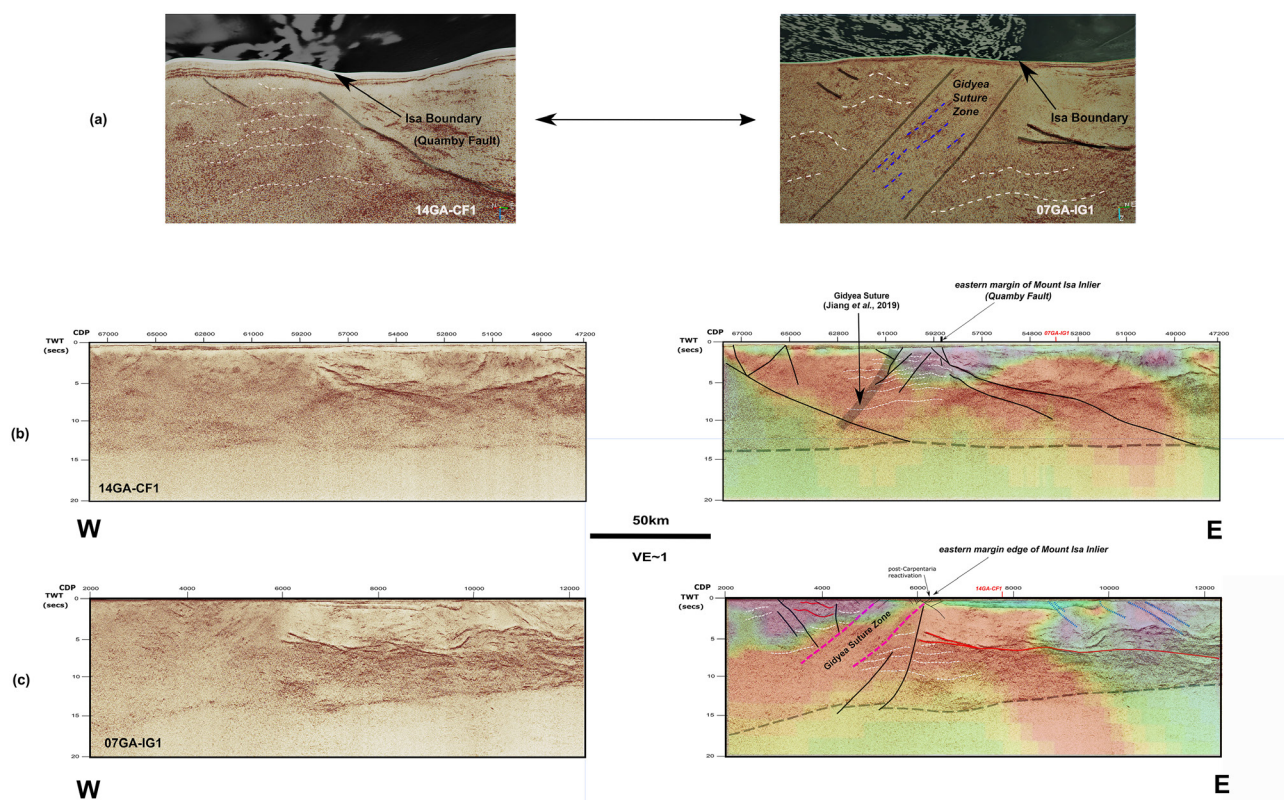


Figure 19. Comparison of equivalent northwestern and southwestern segments of the 14GA-CF1 and 07GA-IG1 deep seismic and magnetotelluric profiles (respectively) showing detail of the eastern margin of the Mount Isa Province:

(a) 3D view of the two contrasting profiles across the eastern Mount Isa Block margin 55 km apart; reflectivity trends marked as white dashed lines, faults in grey, and deformation fabric as blue dashed lines;

(b) Interpretation of northwestern end of 14GA-CF1 profile showing correlation of structures with recent magnetotelluric inversion presented by Jiang et al. (2019); reflectivity trends shown as dashed white lines; position of Gidyea Suture advocated by Jiang et al. (2019) (marked in grey) lacks broad zone of reflectivity disruption and internal fabric development displayed by the suture on the 07GA-IG1 profile;

(c) Interpretation of southwestern end of 07GA-IG1 profile showing correlation of structures with recent magnetotelluric inversion presented by Jiang et al. (2019); reflectivity trends shown as dashed white lines; Gidyea Suture Zone evident as wide zone of reflectivity disruption.

More convincing large-scale, west-dipping seismic reflectivity contrasts are however visible in the 14GA-CF3 and 06GA-M6 deep seismic profiles which traverse the southern Mount Isa Inlier from east to west (Figure 20; see Connors, 2019 and Simpson, 2019).

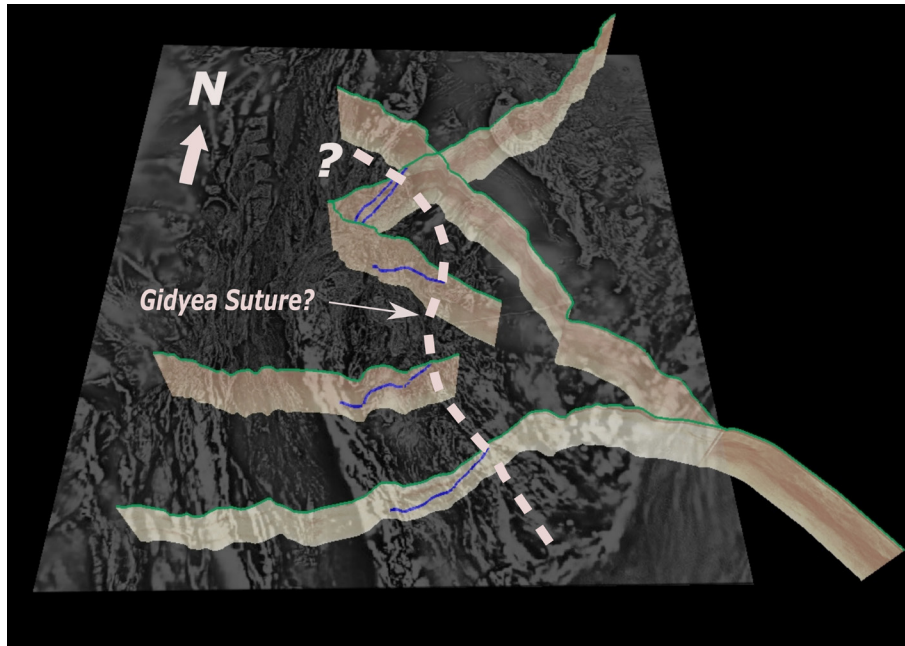


Figure 20. Regional 3D view of deep seismic network (progressing northward from 14GA-CF3 to 06GA-M6, 06GA-M4 and 07GA-IG1, cut by NW-trending 14GA-CF1) showing position of reflectivity contrasts (blue lines) between probable Numil Seismic Province crust and Mount Isa Province crust; dashed white line is speculative surface trace on greyscale regional magnetic image; this contrast has not been identified on the 14GA-CF1 seismic profile.

This contrast between weakly to moderately reflective Mount Isa Province crust to the west and more reflective probable Numil Province crust to the east defines a moderate west-dipping contact in both southern transects. These structures roughly align with the Cloncurry Fault at surface, but further north the contrast is also evident in both the seismic and conductivity profiles of the 06GA-M4 profile (Figure 21).

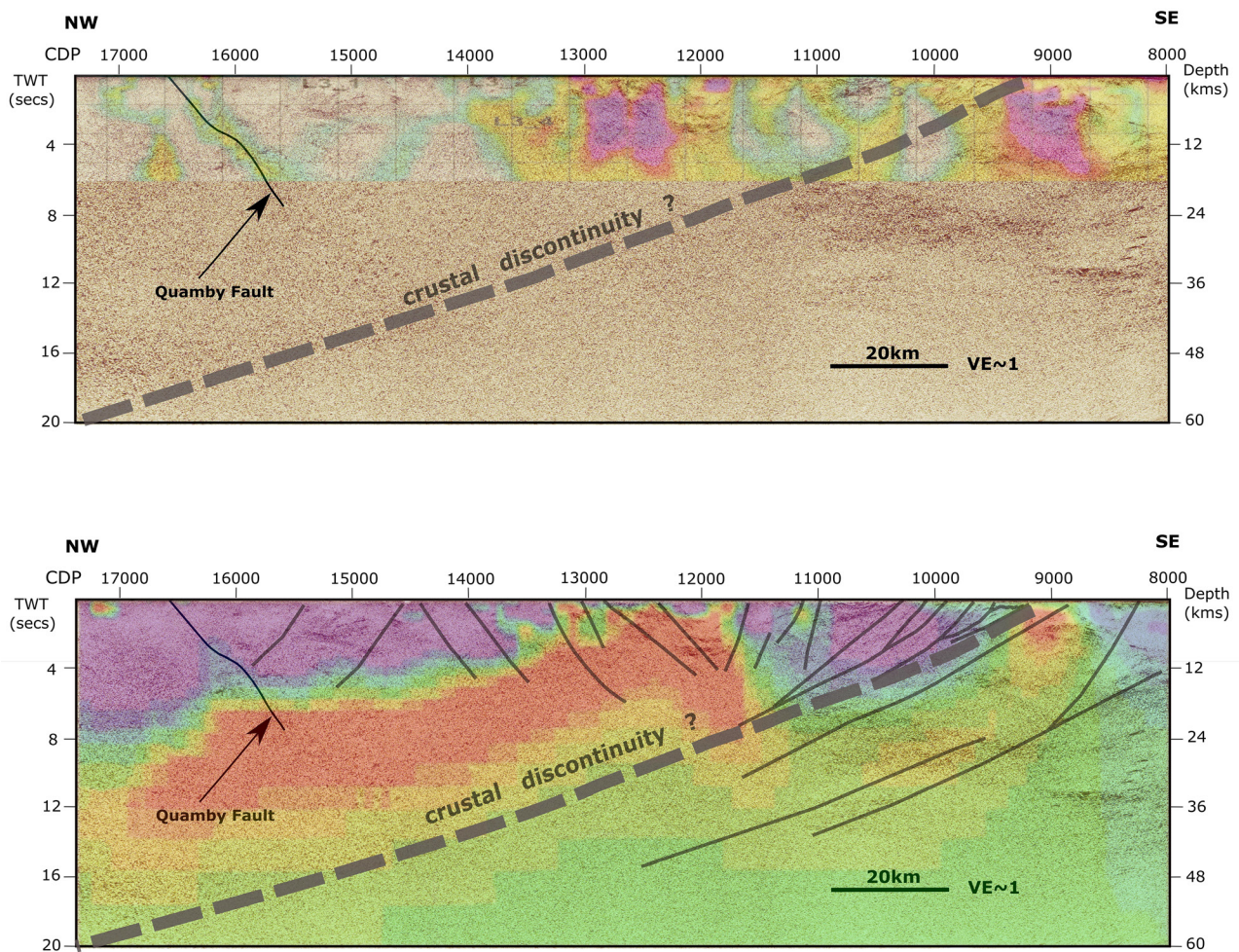


Figure 21. Correlation of seismic and magnetotelluric profiles for the 06GA-M4 deep seismic transect showing selected faults; upper image shows upper crustal magnetotelluric inversion provided by Gharibi & Killin (2010) highlighting a southeast-dipping conductive zone co-incident with the Quamby Fault; lower image shows deep crustal magnetotelluric inversion of Jiang et al. (2019) which is consistent with crustal discontinuity identified in the seismic profile (dashed grey line).

These crustal contrasts, while similar in dip to the Gidyea Suture of 07GA-IG1, differ markedly in terms of seismic character – all other regional seismic surveys show no wide distributed zone of reflectivity destruction and deformation comparable with that of the 07GA-IG1 structure, as well as no obvious younger post-Isan Orogeny reactivation.

The unique seismic character of the Gidyea Suture on 07GA-IG1 may result from extensive reworking of the crust by magmatic or hydrothermal fluids, localized along a short section of the Mount Isa margin. The lack of strong seismic evidence supporting the existence of structures with similar fabric development elsewhere at locations beyond the 07GA-IG1 profile renders the interpretation of the origin of this feature equivocal.

5.2 Quamby Fault

The Quamby Fault has historically been interpreted as a subvertical dextral transcurrent fault that formed in the final stages of the Isan Orogeny. The fault is generally poorly resolved in most seismic transects due to its steeply-dipping nature. However, there are hints in the seismic and magnetotelluric data that the location of the Quamby Fault may partly relate to older features.

In both the 14GA-CF1 and 07GA-IG1 profiles the listric F3 sheared base of the Kowanyama Province has been interpreted here to project to the surface near the Quamby Fault (see Figures 18 and 22), suggesting that the geometry and location of late strike-slip faulting may have been partially controlled by older basin-bounding extensional

structures. Further support for an early extensional component for the Quamby Fault is provided by magnetotelluric data acquired along the 06GA-M4 deep seismic transect (see Figure 21), which indicates a moderate southeast dip for the central section of the fault northeast of Cloncurry (see Figure 22). Further support for the Quamby Fault's role in early basin formation is its contiguous relationship with the Pilgrim Fault, a major basin-margin fault during Leichhardt Superbasin time (and perhaps even earlier periods). The arcuate trace of the Pilgrim-Quamby Fault system also marks the arcuate trace of D2 Isan Orogeny inversion producing major features such as the Duck Creek Anticline (see Figure 23). The fold trains intersected by the 14GA-CF1 seismic profile display a similar arcuate trend on geophysical images, suggesting a common history.

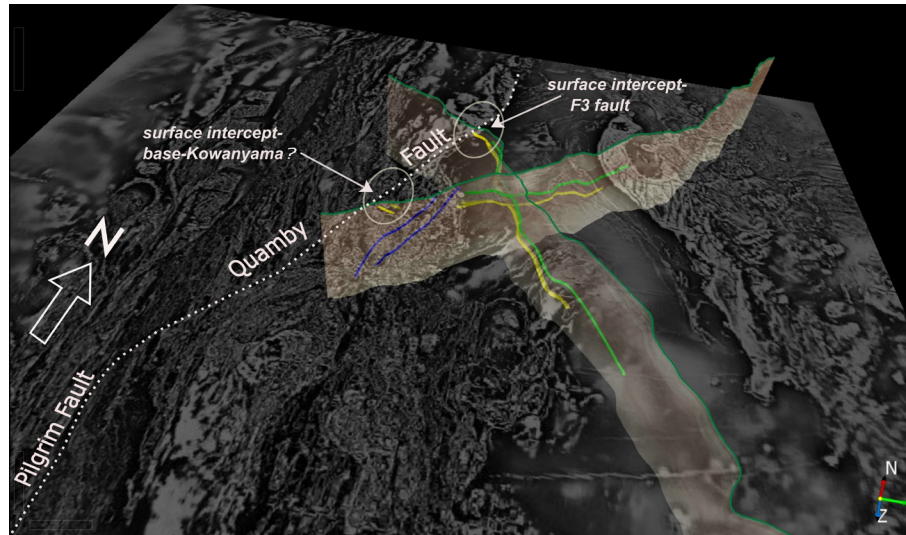


Figure 22. 3D view looking north of greyscale regional magnetic image, showing surface intercepts of sheared base of the Julia Creek Basin (yellow line) on the 07GA-IG1 profile and the equivalent F3 fault (yellow line) marking the base of the Julia Creek Basin on the 14GA-CF1 profile; these intercepts coincide with the Quamby Fault and may infer its geometry at depth.

6. Conclusion

The value of the new geological knowledge revealed by the 14GA-CF1 deep seismic profile is best leveraged by integration of the interpretation with other nearby deep seismic and magnetotelluric datasets, as well as with the regional magnetic and gravity datasets. Comparison of the 14GA-CF1 and orthogonal 07GA-IG1 profiles reveals a number of contrasting characteristics. In particular, the two profiles display two different styles of Isan Orogeny crustal shortening - 14GA-CF1 displays upper crustal folding and reverse faulting generated by a NW-SE directed stress field, whereas the 07GA-IG1 profile displays lower to mid-crustal low angle thrusting and stratal imbrication produced by roughly E-W directed shortening (Figures 14 and 15). There is little definitive indication in the seismic profiles of the relative timing of the two events. The NW-SE event displays arcuate fold trends in the magnetic data, swinging to more northerly orientations against the buttressing Pilgrim and Cloncurry Faults (Figure 23), partly defined by crystalline basement margins. This folding episode has generally been assigned to the broad spectrum of later Isan Orogeny events (collectively included here as D2), perhaps with structures being tightened and locally rotated into N-S orientations against the buttressing faults during the E-W 07GA-IG1 event.

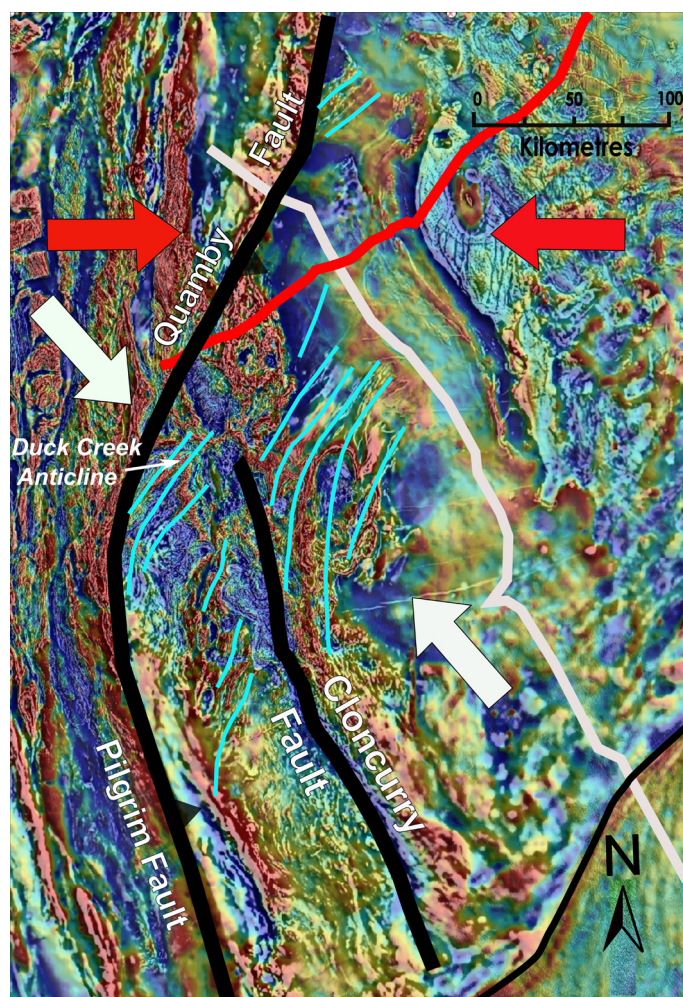


Figure 23. Regional magnetic/gravity image showing (i) location of 07GA-IG1 traverse (in red) and dominant regional shortening direction (in red) identified from structures on that seismic profile, and (ii) the location of the 14GA-CF1 traverse (in white) and dominant regional shortening direction (in white) identified from structures on that seismic profile; major associated D2? fold trends (in pale blue) define arcuate pattern swinging from north-northeast to north-south against major regional buttressing faults (Cloncurry and Pilgrim/Quamby Faults) accompanied by development of high strain fabrics; timing relationships unknown between “red” and “white” events, although doubly-plunging “white” folds may result from interference by later “red” shortening event.

This interpretation contrasts with earlier authors (Loosveld, 1989a, b; Loosveld & Etheridge, 1990; Giles *et al.*, 2006a) who attributed all ENE-trending folding in the Cloncurry area to the earliest Isan Orogeny folding event. However, it is here considered that folds of this type also include an extensive array of later generation folds of the type evident on the 14GA-CF1 profile. It is considered likely that these D2 folding events most likely tightened and re-oriented pre-existing thin-skinned nappe-style D1 folding which was probably restricted to discrete zones in the immediate hanging wall of underlying thrusts (*e.g.*, the Snake Creek Anticline; see Giles *et al.*, 2006a) rather than being pervasively developed throughout the region.

The two differently-oriented D2? shortening events recorded in the 14GA-CF1 and 07GA-IG1 seismic profiles (see Figure 23) appear to represent the effects of two distinct far-field plate collisions. Both events could be related to two phases of amalgamation with an irregular Laurentian plate margin comprising a northeast-trending segment bounding the NAC to the south (essentially parallel to the Diamantina Lineament) contiguous with a north-trending segment to the east of the Georgetown Province. Alternatively, the two events may reflect collisions with two discrete entities - an easterly collision with Laurentia, and a southerly collision with the South Australian craton and/or associated microcontinents.

Further comparison between the 14GA-CF1 and 07GA-IG1 seismic profiles invites a renewed perspective on the nature of the eastern geophysically defined margin of the Mount Isa Inlier. The broad west-dipping zone of reflectivity destruction defining the boundary between the Mount Isa and Numil Provinces in the 07GA-IG1 seismic profile (the Gidyea Suture of Korsch *et al.*, 2012) is not evident in the 14GA-CF1 profile at the Mount Isa Inlier margin 50 km to the northwest. Instead, the Mount Isa margin at this location is defined by a moderately southeast dipping extensional fault, as discussed above. Examination of the remaining suite of deep seismic transects elsewhere across the eastern Mount Isa region has also not resulted in identification of any features of comparable width, reflectivity destruction and internal fabric development to the unique 07GA-IG1 Gidyea Suture. In view of this, the question of whether the Gidyea Suture is part of a continuous structure running the length of the Mount Isa Inlier remains open.

However, re-examination of historical as well as more recent deep seismic datasets has revealed hints of bulk reflectivity contrasts between the Mount Isa Province and possible Numil Province rocks to the east. Likely Isa-Numil contrast boundaries are evident on the 06GA-M6, 06GA-M4 and 14GA-CF3 seismic profiles (see Figure 20) supported in part by magnetotelluric data (see Figure 21). Furthermore, 3D examination of the combined seismic profiles across the eastern Mount Isa region highlight two contrasting crustal styles – sections east of the Cloncurry Fault have typical Numil-type characteristics (strongly-reflective lower and mid-crustal section juxtaposed against an underlying very poorly reflective mantle along a largely sharp flat MOHO), whereas sections further west are characterized by typical Isan-type crust (weakly to moderately reflective upper sections with a diffuse, but relatively deeper, mantle transition; see Figure 24).

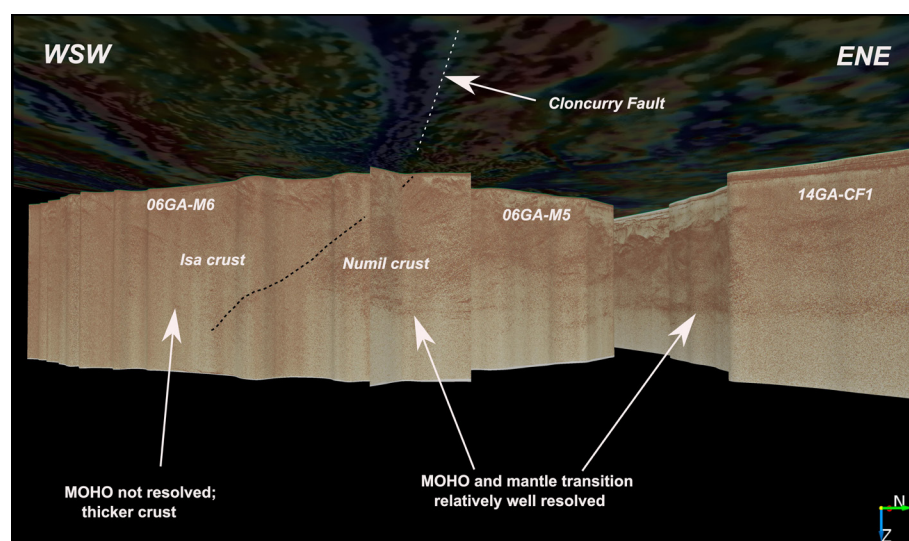


Figure 24. Oblique 3D view of selected seismic transects demonstrating change from Numil to Isan seismic character across west-dipping feature; upper ground level overlay is magnetic/gravity combination image.

Although the seismic data supports the existence of two contrasting crustal styles forming the basement of the eastern Mount Isa region, their origin, timing and significance is uncertain. The seismic contrast may represent an ancient suture between two cratonic blocks, perhaps an old subduction zone related to the Kalkadoon-Leichhardt magmatic arc forming the central crystalline backbone of the inlier (Korsch *et al.*, 2012). Alternatively, the seismic contrast may result from modification of earlier crustal structure by later magmatism and deformation. Numil-type crust displays the sharp MOHO typically found in Archean cratons elsewhere around the globe, thought to be produced by delamination and sinking of dense lithologies at the garnet-in isograd (Abbott *et al.*, 2013). Numil-type crust may therefore represent a stabilized segment of the craton little modified by plutonism and deformation, whereas Isa-type crust may be more similar to modern-day arcs, displaying a diffuse undulose MOHO. The ~100 million year period of Kalkadoon-Leichhardt magmatism and Leichhardt Superbasin volcanism is likely to have modified the pre-existing crustal architecture in a similar way to modern arc volcanism, producing a similar seismic character. In this context, the unexpected Numil-type character of the Isan crust at the northern end of the 14GA-CF1 profile may result from the lack of magmatic reworking more typical of the central Mount Isa Inlier.

Further careful re-assessment of the suite of deep seismic datasets available for the Mount Isa region, together with modelling of newly acquired higher resolution magnetic, gravity and magnetotelluric datasets may allow improved identification of deep crustal boundaries and an enhanced understanding of any role they might play in ore-forming processes within the Mount Isa Eastern Succession.

7. References

- ABBOTT, D.H., MOONEY, W.D., & VAN TONGEREN, J.A., 2013: The character of the Moho and lower crust within Archean cratons and the tectonic implications. *Tectonophysics*, **609**(2013), 690-705.
- ABDULLAH, R., & ROSENBAUM, G., 2018: Devonian crustal stretching in the northern Tasmanides (Australia) and implications for oroclinal bending. *Journal of Geophysical Research: Solid Earth*, **123**, 7108–7125.
- ABU SHARIB, A. S. A. A., 2012: Foliation intersection axes (FIAs) preserved within porphyroblasts: Resolving plan view orthogonal refolding, Eastern Fold Belt, Mt Isa Inlier. *Australian Journal of Earth Sciences*, **59**(4), 571–598.
- ABU SHARIB, A. S. A. A., 2016: Changes in Relative Plate Motion during the Isan Orogeny (1670–1500 Ma) and Implications for Pre-Rodinia Reconstructions. *Acta Geologica Sinica*, **90** (1), 88-105.
- AUSTIN, J.R., BLENKINSOP, T.G., 2008: The Cloncurry Lineament: geophysical and geological evidence for a deep crustal structure in the Eastern Succession of the Mount Isa Inlier. *Precambrian Research*, **163** (1–2), 50–68.
- AUSTIN, J. R., & BLENKINSOP, T. G., 2010: Cloncurry fault zone: Strain partitioning and reactivation in a crustal-scale deformation zone, Mt Isa Inlier. *Australian Journal of Earth Sciences*, **57**(1), 1-21.
- BETTS, P. G., ARMIT, R. J., STEWART, J., AITKEN, A. R. A., AILLERES, L., DONCHAK, P., HUTTON, L., WITHNALL, I., & GILES, D., 2016: Australia and Nuna. Geological Society London Special Publications, 24 (1), 47–81.
- BETTS, P.G. & GILES, D., 2006: The 1800–1100 Ma tectonic evolution of Australia. *Precambrian Research*, **144** (1–2), 92–125.
- BETTS, P.G., GILES, D., FODEN, J., SCHAEFER, B.F., MARK, G., PANKHURST, M.J., FORBES, C.J., WILLIAMS, H.A., CHALMERS, N.C., & HILLS, Q., 2009: Mesoproterozoic plume-modified orogenesis in eastern Precambrian Australia. *Tectonics*, **28**(3), 1-28
- BETTS, P.G., GILES, D., LISTER, G.S., 2003: Tectonic environment of shale-hosted massive sulphide Pb–Zn–Ag deposits of Proterozoic northeastern Australia. *Economic Geology*, **98**, 557–576.
- BETTS, P.G., GILES, D., LISTER, G.S., FRICK, L.R., 2002: Evolution of the Australian lithosphere. *Australian Journal of Earth Sciences*, **49** (4), 661–695.
- BETTS, P.G., GILES, D., MARK, G., LISTER, G.S., GOLEBY, B.R., AILLERES, L., 2006: Synthesis of the Proterozoic evolution of the Mount Isa Inlier. *Australian Journal of Earth Sciences*, **53**, 187–211.
- BLAIKIE, T. N., BETTS, P. G., ARMIT, R. J., & AILLERES, L., 2017: The ca. 1740–1710 Ma Leichhardt Event: Inversion of a continental rift and revision of the tectonic evolution of the North Australian Craton. *Precambrian Research*, **292**, 75–92.
- CARR, P., PURDY, D., & BROWN, D., 2014: Peeking under the covers: Undercover geology of the Thomson Orogen. *Australian Earth Sciences Convention*, Volume **110**: Abstracts. Newcastle, NSW: *Geological Society of Australia*.
- CARSON, C.J., HUTTON, L.J., WITHNALL, I.W., PERKINS, W.G., DONCHAK, P.J.T., PARSONS, A., BLAKE, P.R., SWEET, I.P., NEUMANN, N.L., LAMBECK, A., 2011: Joint GSQ-GA NGA geochronology project Mount Isa region, 2009-2010. *Queensland Geological Record*, **2011/03**
- CARSON, C.J., HUTTON, L.J., WITHNALL, I.W., PERKINS, W.G., DONCHAK, P.J.T., PARSONS, A., BLAKE, P.R., SWEET, I.P., NEUMANN, N.L., LAMBECK, A., 2011: Joint GSQ–GA NGA geochronology project—Mount Isa region, 2009–2010. *Geological Survey of Queensland, Record* **2011/3**.
- CONNORS, K., 2019; Central Eastern fold Belt Solid Geology- Insights from crustal architecture. DNRME New Discovery Program, Technical Workshop. https://smi.uq.edu.au/files/48829/IsaSepD2_03_Connors_EFB%20Solid%20Geo.pdf
- CROSS, A. J., PURDY, D. J., CHAMPION, D. C., BROWN, D. D., SIÉGEL, C. & ARMSTRONG, R.A., 2018: Insights into the evolution of the Thomson Orogen from geochronology, geochemistry, and zircon isotopic studies of magmatic rocks, *Australian Journal of Earth Sciences*, **65** (7-8), 987-1008.
- DE CARITAT, P. & BRAUN, J., 1992: Cyclic development of sedimentary basins at convergent plate margins -1. Structural and tectono-thermal evolution of some Gondwana basins of eastern Australia. *Journal of Geodynamics*, **16**, 241 – 282.

- ERNST, R. E., WINGATE, M. T. D., BUCHAN, K. L., & LI, Z. X., 2008: Global record of 1600-700 Ma Large Igneous Provinces (LIPs): Implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. *Precambrian Research*, **160**(1-2), 159–178.
- FERGUSON, C. L., CARR, P. F., FANNING, C. M., & GREEN, T. J., 2001: Proterozoic–Cambrian detrital zircon and monazite ages from the Anakie Inlier, central Queensland: Grenville and Pacific–Gondwana signatures. *Australian Journal of Earth Sciences*, **48**, 857–866
- FERGUSON, C. L., CARR, P. F., FANNING, C. M., & GREEN, T. J., 2001: Proterozoic–Cambrian detrital zircon and monazite ages from the Anakie Inlier, central Queensland: Grenville and Pacific–Gondwana signatures. *Australian Journal of Earth Sciences*, **48**, 857–866.
- FERGUSON, C. L., HENDERSON, R. A., FANNING, C. M., & WITHNALL, I. W., 2007: Detrital zircon ages in Neoproterozoic to Ordovician siliciclastic rocks, north-eastern Australia: Implications for the tectonic history of the East Gondwana continental margin. *Journal of the Geological Society of London*, **164**, 215–225.
- FERGUSON, C. L., OFFLER, R. AND GREEN, T. J., 2009: Late Neoproterozoic passive margin of East Gondwana: geochemical constraints from the Anakie Inlier, central Queensland, Australia. *Precambrian Research*, **168** (3-4), 301-312
- GHARIBI, M. & KILLIN, K., 2010: Geophysical Survey Interpretation report regarding the Quantec Spartan Tensor magnetotelluric survey over the Mount Isa Project, near Cloncurry, Queensland, Australia. *Report commissioned by Geological Survey of Queensland*, Department of Mines and Energy, Brisbane.
- GIBSON, G. M., CHAMPION, D. C., WITHNALL, I. W., NEUMANN, N. L., AND HUTTON, L. J., 2018: Assembly and breakup of the Nuna supercontinent: Geodynamic constraints from 1800 to 1600 Ma sedimentary basins and basaltic magmatism in northern Australia. *Precambrian Research*, **313**, 148-169.
- GIBSON, G. M., CHAMPION, D. C., HUSTON, D. L., & WITHNALL, I. W., 2020. Orogenesis in Paleo-Mesoproterozoic eastern Australia: A response to arc-continent and continent-continent collision during assembly of the Nuna Supercontinent. *Tectonics*, **39** (2), TC005717
- GIBSON, G. M., HUTTON, L. J., & HOLZSCHUH, J., 2017: Basin inversion and supercontinent assembly as drivers of sediment-hosted Pb–Zn mineralization in the Mount Isa region, northern Australia. *Journal of the Geological Society*, **174**(4), 773–786.
- GIBSON, G.M., RUBENACH, M.J., NEUMANN, N.L., SOUTHGATE, P.N., HUTTON, L.J., 2008: Syn- and post-extensional tectonic activity in the Palaeoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia. *Precambrian Research*, **166**(1–4), 350–369.
- GILES, D., AILLERES, L., JEFFRIES, D., BETTS, P. G., & LISTER, G., 2006a: Crustal architecture of basin inversion during the Proterozoic Isan Orogeny, Eastern Mount Isa Inlier, Australia. *Precambrian Research*, **148**(1-2), 67-84.
- GILES, D., BETTS, P. G., AILLÈRES, L., HULSCHER, B., HOUGH, M., & LISTER, G. S., 2006b: Evolution of the Isan Orogeny at the southeastern margin of the Mt Isa Inlier. *Australian Journal of Earth Sciences*, **53**(1), 91–108.
- GILES, D., BETTS, P.G., LISTER, G.S., 2002: Far-field continental back-arc setting for the 1.8–1.67 Ma basins of north-east Australia. *Geology*, **30**, 823–826.
- GLIKSON, A., R. J. KORSCH, R.J. & P. MILLIGAN, P., 2016: The Diamantina River ring feature, Winton region, western Queensland, Australian Journal of Earth Sciences, **63** (5), 653-663.
- GREENE, D.C, 2010: Neoproterozoic rifting in the southern Georgina Basin, central Australia: Implications for reconstructing Australia in Rodinia, *Tectonics*, **29**, TC5010.
- HENSON, P., NATALIE KOSITCIN, N., & HUSTON., D, 2011: Broken Hill and Mount Isa: linked but not rotated, AusGeo News, 102, Geoscience Australia.
- HUTTON L., FITZELL M., HOFFMANN, K., WITHNALL I., STOCKILL B., JUPP B., DONCHAK P., 2010: The Millungera Basin—new geoscience supporting exploration. *The APPEA Journal* **50**, 727-727.
- HUTTON, L.J., GIBSON, G.M., KORSCH, R.J., WITHNALL, I.W., HENSON, P.A., COSTELLOE, R.D., HOLZSCHUH, J., HUSTON, D.L., JONES, L. E. A., MAHER, J.L., NAKAMURA, A., NICOLL, M.G., ROY, I., SAYGIN, E., MURPHY, F.C. AND JUPP, B., 2009: Geological interpretation of the 2006 Mt Isa seismic survey. In: Camuti, K. and Young, D.(eds) Northern Queensland Exploration and Mining and North Queensland Seismic and MT Workshop. *Australian Institute of Geoscientists Bulletin*, **49**, 137–41.

- IDNURM, M., 2000: Towards a high resolution Late Palaeoproterozoic—Earliest Mesoproterozoic apparent polar wander path for northern Australia. *Australian Journal of Earth Sciences*, **47**(3), 405–429.
- JIANG, W., DUAN, J., 2018: Electrical Conductivity Structure Derived from Magnetotelluric Data in the South-Eastern Mount Isa Region. *Geoscience Australia Record* **2018/04**
- JIANG, W., KORSCH, R. J., DOUBLIER, M. P., DUAN, J., & COSTELLOE, R., 2019: Mapping Deep Electrical Conductivity Structure in the Mount Isa region, Northern Australia: Implications for Mineral Prospectivity. *Journal of Geophysical Research: Solid Earth*, **124**, 10,655–10,671.
- KARLSTROM, K. E., AHÄLL, K. I., HARLAN, S. S., WILLIAMS, M. L., MCLELLAND, J., & GEISSMAN, J. W., 2001: Long lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Research*, **111**(1–4), 5–30.
- KORSCH, R. J., HUSTON, D. L., HENDERSON, R. A., BLEWETT, R. S., WITHNALL, I. W., & COSTELLOE, R. D., 2012: Crustal architecture and geodynamics of North Queensland, Australia: Insights from deep seismic reflection profiling. *Tectonophysics*, **572–573**, 76–99.
- KORSCH, R. J., STRUCKMEYER, H., KIRKBY, A., HUTTON, L., CARR, L., HOFFMANN, K., CHOPPING, R., ROY, I. G., FITZELL, M., TOTTERDELL, J. M., NICOLL, M. G., & TALEBI, B., 2011: Energy potential of the Millungera Basin: A newly discovered basin in north Queensland. *The APPEA Journal*, **51**(1), 295–332.
- LI, Z. X., BOGDANOVA, S. V., COLLINS, A. S., DAVIDSON, A., DE WAELE, B., ERNST, R. E., FITZSIMONS, C. W., FÜCK, R. A., GLADKOKHUB, D. P., JACOBS, J., KARLSTROM, K. E., LU, S., NATAPOV, L. M., PEASE, V., PISAREVSKY, S. A., THRANE, K., & VERNIKOVSKY, V., 2008: Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precambrian Research*, **160** (1–2), 179–210.
- LILLEY, F. E. M., WANG, L. J., CHAMALAUN, F. H., & FERGUSON, I. J., 2003: The Carpentaria Electrical Conductivity Anomaly, Queensland, as a major structure in the Australian Plate. *Geological Society of Australia Special Publication* **22** and *Geological Society of America Special Paper*, **372**, 141–156.
- LOOSVELD, R. J. H., 1989a. The intra-cratonic evolution of the Central Eastern Mount Isa Inlier, Northwest Queensland, Australia. *Precambrian Research*, **44**, 243–276.
- LOOSVELD, R. J. H., 1989b. The synchronism of crustal thickening and low-pressure facies metamorphism in the Mount Isa Inlier, Australia. 2. Fast convective thinning of mantle lithosphere during crustal thickening. *Tectonophysics*, **165**, 191–218.
- LOOSVELD, R. J. H., ETHERIDGE, M. A., 1990. A model for low-pressure facies metamorphism during crustal thickening. *Journal of Metamorphic Geology*, **8**, 257–267.
- MACCREADY T., GOLEBY B. R., GONCHAROV A., DRUMMOND B. J. & LISTER G. S., 1998: A framework of overprinting orogens based on interpretation of the Mount Isa Deep Seismic Transect. *Economic Geology* **93**, 1422–1434
- NEUMANN N. L., GIBSON G. M & SOUTHGATE P. N., 2009a: New SHRIMP age constraints on the timing and duration of magmatism and sedimentation in the Mary Kathleen Fold belt, Mt Isa Inlier, Australia. *Australian Journal of Earth Sciences* **56**, 965–983.
- NEUMANN N. L., SOUTHGATE P. N. & GIBSON G. M., 2009b: Defining unconformities in Proterozoic sedimentary basins using detrital geochronology and basin analysis- an example from the Mount Isa Inlier, Australia. *Precambrian Research* **168**, 149–166.
- NEUMANN N. L., SOUTHGATE P. N., GIBSON G. M. & MCINTYRE A., 2006: New SHRIMP geochronology for the Western Fold Belt of the Mount Isa Inlier: Developing an 1800–1650 Ma Event Framework. *Australian Journal of Earth Sciences* **53**, 1023–1039.
- NORDSVAN, A. R., COLLINS, W. J., LI, Z. X., SPENCER, C. J., POURTEAU, A., WITHNALL, I. W., BETTS, P. G., & VOLANTE, S., 2018: Laurentian crust in northeast Australia: Implications for the assembly of the supercontinent Nuna. *Geology*, **46** (3), 251–254.
- POURTEAU, A., SMIT, M. A., LI, Z-X, COLLINS, W. J., NORDSVAN, A. R., VOLANTE, S., & LI, J., 2018: 1.6 Ga crustal thickening along the final Nuna suture. *Geology*, **46**(11), 959–962.
- PURDY, D. J., CROSS, A. J., BROWN, D. D., CARR, P. A., & ARMSTRONG, R. A., 2016: New constraints on the origin and evolution of the Thomson Orogen and links with central Australia from isotopic studies of detrital zircons. *Gondwana Research*, **39**, 41–56.

- SCOTT, D.L., RAWLINGS, D.J., PAGE, R.W., TARLOWSKI, C.Z., IDNURM, M., JACKSON, M.J., SOUTHGATE, P.N., 2000: Basement framework and geodynamic evolution of the Palaeoproterozoic superbasins of north-central Australia: an integrated review of geochemical, geochronological and geophysical data. *Australian Journal of Earth Sciences*, **47** (3), 341–380.
- SIMPSON, J., 2019: Interpretation of seismic, gravity and MT in the southern Mount Isa Province. DNRME New Discovery Program, Technical Workshop. https://smi.uq.edu.au/files/48832/IsaSepD2_04_Simpson_Isa%20Geophysics%20Interp.pdf
- SOUTHGATE, P. N., BRADSHAW, B. E., DOMAGALA, J., JACKSON, M. J., IDNURM, M., KRASSAY, A. A., PAGE, R.W., SAMI, T.T., SCOTT, D.L., LINDSAY, J.F., MCCONACHIE, B.A. & TARLOWSKI, C., 2000: Chronostratigraphic basin framework for Palaeoproterozoic rocks (1730-1575 Ma) in northern Australia and implications for base-metal mineralisation. *Australian Journal of Earth Sciences*, **47**(3), 461–483
- SOUTHGATE, P. N., NEUMANN, N. L., & GIBSON, G. M., 2013: Depositional systems in the Mt Isa Inlier from 1800 Ma to 1640 Ma: Implications for Zn–Pb–Ag mineralisation. *Australian Journal of Earth Sciences*, **60**(2), 157–173.
- SPAMPINATO, G. P., AILLERES, L., BETTS, P. G., & ARMIT, R. J., 2015: Imaging the basement architecture across the Cork Fault in Queensland using magnetic and gravity data. *Precambrian Research*, **264**, 63–81.
- WALLACE, M. L., JOWITT, S. M., & SALEEM, A., 2015: Geochemistry and petrogenesis of mafic-ultramafic suites of the Irindina Province, Northern Territory, Australia: implications for the Neoproterozoic to Devonian evolution of central Australia. *Lithos*, 234-235, 61-78.
- WARE, B.D, JOURDAN, F., MERLE, R., CHIARADIA, M., HODGES, K., 2018: The Kalkarindji Large Igneous Province, Australia: Petrogenesis of the Oldest and Most Compositionally Homogenous Province of the Phanerozoic. *Journal of Petrology*, **59**, 4, 635–665.
- WILLIAMS, L.J., & GUNTHER, L.M., 1989: GSQ Dobbryn 1 – Preliminary Lithologic Log and Composite Log. *Geological Survey of Queensland Record* **1989/22**
- WITHNALL, I. W., & HUTTON, L. J., 2013: Chapter 2: North Australian Craton In P. A. Jell (Ed.), *Geology of Queensland*, 23–112. Brisbane: *Geological Survey of Queensland, Department of Natural Resources & Mines, Brisbane*.
- WOODS D.V., LILLEY, F.E.M., 1979: Geomagnetic induction in central Australia. *Journal of Geomagnetism and Geoelectrics*, **31**, 449-458.

