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Basin architecture and evolution in the Mount Isa mineral province, northern Australia: Constraints from deep seismic reflection profiling and implications for ore genesis

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ABSTRACT

Deep seismic reflection profiling confirms that the Paleo- to Mesoproterozoic Mount Isa mineral province comprises three vertically stacked and partially inverted sedimentary basins preserving a record of intracontinental rifting followed by passive margin formation. Passive margin conditions were established no later than 1655 Ma before being interrupted by plate convergence, crustal shortening and basin-wide inversion at 1640 Ma in both the 1730–1640 Ma Calvert and 1790–1740 Ma Leichhardt superbasins. Crustal extension and thinning resumed after 1640 Ma with formation of the 1635–1575 Ma Isa Superbasin and continued up to ca. 1615 Ma when extensional faulting ceased and a further episode of basin inversion commenced. The 1575 Ma Century Pb–Zn ore-body is hosted by syn-inversion sediments deposited during the initial stages of the Isan Orogeny with basin inversion accommodated on east- or northeast-dipping reactivated intrabasinal extensional faults and footwall shortcut thrusts. These structures extend to considerable depths and served as fluid conduits during basin inversion, tapping thick syn-rift sequences of immature siliciclastic sediments floored by bimodal volcanic sequences from which the bulk of metals and mineralising fluids are thought to have been sourced. Basin inversion and fluid expulsion at this stage were entirely submarine consistent with a syn-sedimentary to early diagenetic origin for Pb–Zn mineralisation at, or close to, the seafloor. Farther east, a change from platform carbonates to deeper water continental slope deposits (Kuridala and Soldiers Cap groups) marks the position of the original shelf break along which the north–south-striking Selwyn-Mount Dore structural corridor developed. This corridor served as a locus for strain partitioning, fluid flow and iron oxide–copper–gold mineralisation during and subsequent to the onset of basin inversion and peak metamorphism in the Isan Orogeny at 1585 Ma. An episode of post-orogenic strike-slip faulting and hydrothermal alteration associated with the subvertical Cloncurry Fault Zone overprints west- to southwest-dipping shear zones that extend beneath the Cannington Pb–Zn deposit and are antithetic to inverted extensional faults farther west in the same sub-basin. Successive episodes of basin inversion and mineralisation were driven by changes in the external stress field and related plate tectonic environment as evidenced by a corresponding match to bends in the polar wander path for northern Australia. An analogous passive margin setting has been described for Pb–Zn mineralisation in the Paleozoic Selwyn Basin of western Canada.

1. Introduction

As host to several world-class mineral deposits, including Mount Isa, McArthur River and Century (Fig. 1), the Paleoproterozoic–earliest Mesoproterozoic (1800–1575 Ma) rift basins of northern Australia constitute one of the most richly endowed and intensely studied mineral provinces in the world (Broadbent et al., 1998; Duncan et al., 2014; Groves and Bierlein, 2007; Huston et al., 2006; Large et al., 2005; Leach et al., 2005, 2010; Oliver et al., 2008; Pollard et al., 1998). Differences of opinion nevertheless persist about many aspects of basin evolution and its relationship to mineralisation, including the extent to which syn-depositional extensional faults were instrumental in localising fluid flow during successive stages of rifting. In the case of stratiform to stratabound Pb–Zn deposits of the SEDEX or Mount Isa-type, such faults are widely regarded as central to the ore-forming

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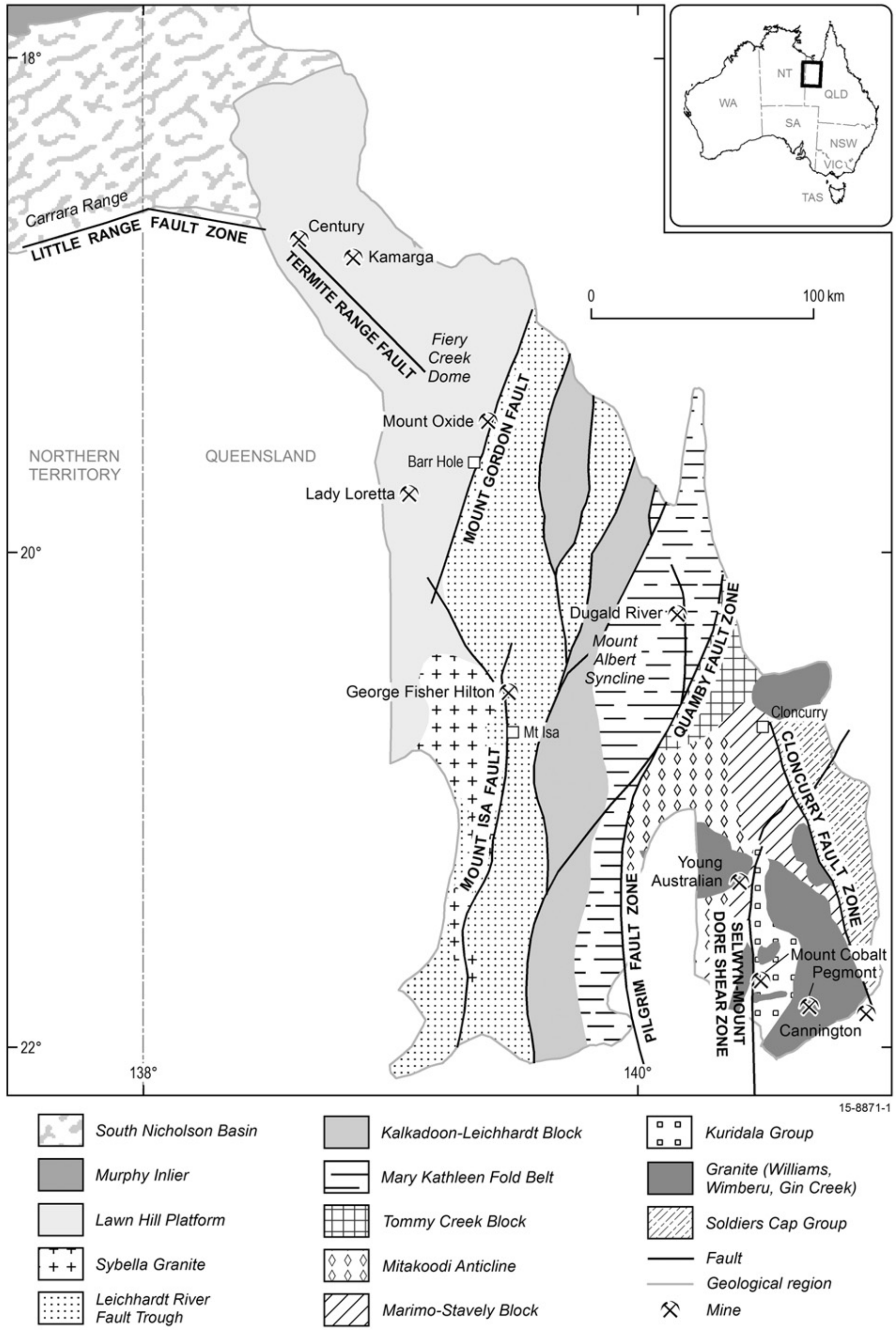

Fig. 1. Simplified geological map for Mount Isa region showing principal tectono-morphological subdivisions and their bounding faults, along with position of main mineral deposits.

process, serving not only as fluid conduits but the principal means whereby connectivity was maintained between the more deeply buried parts of the basin (where the metal-bearing fluids are sourced) and the water–sediment interface where mineralisation is deemed to have actually taken place. Integral to this model of ore genesis is the idea that mineralisation occurred contemporaneously with active rifting and is thus primarily syngenetic or early diagenetic in origin (Betts et al., 2003; Feltrin, 2008; Feltrin et al., 2009; Goodfellow et al., 1993; Huston et al., 2006; Large et al., 2005; Leach et al., 2005). Competing models in which mineralisation occurs later and is decoupled from active rifting have yet to gain the same level of support but typically involve basin inversion or some other form of post-rift deformational process as the principal driver of fluid flow and ore genesis (Broadbent et al., 1998; Hobbs et al., 2000; Zhang et al., 2006). In these models, preservation of the original rift-basin geometry and extensional faults is commonly assumed with the latter acting as the principal conduits along which the mineralising fluids were introduced. However, as with most rift basins, crustal architecture is far from simple and incorporates faults of more than one generation and orientation. At least three phases of extensional faulting and rifting, and as many episodes of post-rift deformation, are currently identified in the Mount Isa region (e.g. Blake, 1987; O'Dea et al., 1997; Betts et al., 2006; Gibson et al., 2012). There is consequently little agreement about the direction and duration of rifting during any one period of basin development let alone which faults or generation of structures were the most important in controlling fluid flow at the time of mineralisation. A better understanding of the geodynamic evolution and kinematic framework of the Mount Isa region is called for.

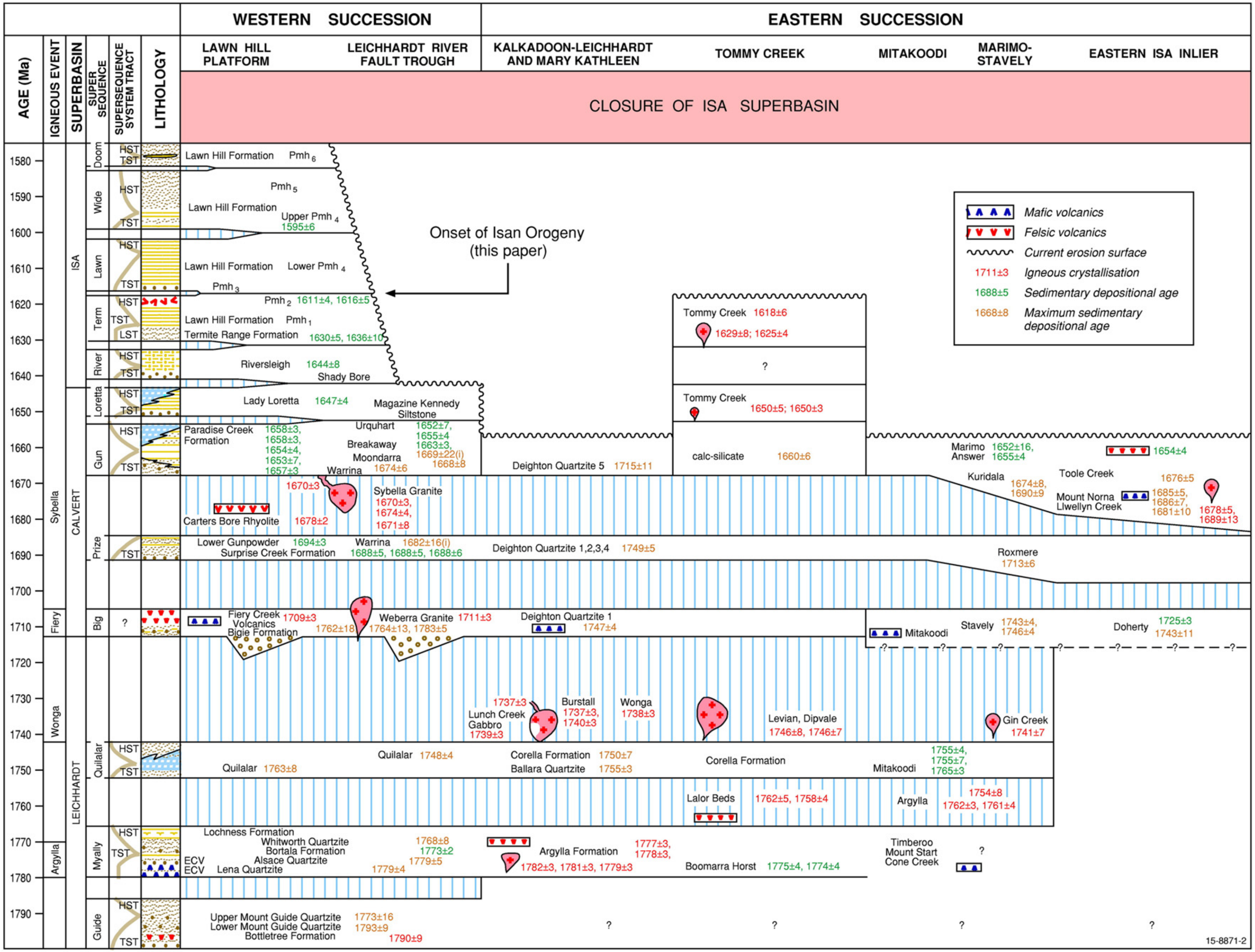

Fig. 2. Event chart for Mount Isa mineral province for interval 1800–1575 Ma. Regional stratigraphy is shown both as traditional lithostratigraphic units and supersequences. Note that the Gun and Loretta supersequences are included here in the Calvert Superbasin contrary to earlier interpretations.
Modified after Southgate et al. (2013).

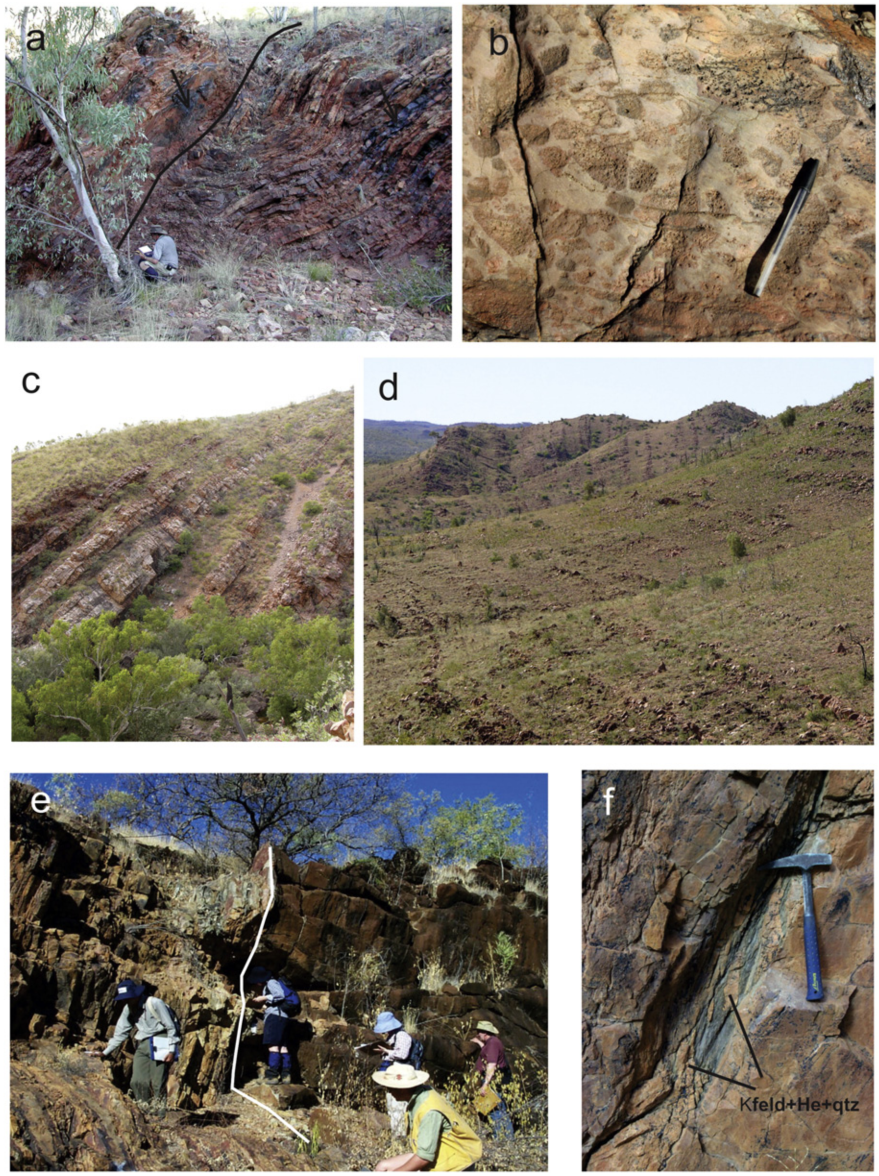

Fig. 3. (a) Thrust fault associated with basin inversion in lowermost Gun Supersequence. Fluid flow along the thrust plane has resulted in Cu carbonate (not visible) and Mn staining development in both footwall and hangingwall of the structure; (b) fragmented pillow lava in sedimentary matrix consistent with extrusion of Eastern Creek Volcanics into a shallow-water fluviatile environment; (c) fining-upward sequences of shallow-marine sandstone and siltstone in Prize Supersequence; (d) overturned and steeply-dipping turbidite-dominated sequence in middle Kuridala Group. Note total absence of mafic dykes and sills; (e) contact between dark, near-shore dolomitic syn-rift sandstone of uppermost Prize Supersequence and shallow-marine post-rift sandstone and siltstones of Gun Supersequence; (f) orthoclase ± quartz ± hematite ± carbonate veining developed along cleavage in siltstone of Myally Supersequence (Police Creek Siltstone).

To this end, a deep seismic reflection survey of the Mount Isa region was undertaken in 2006 to better elucidate crustal architecture and the tectonic processes that shaped basin evolution. This survey was conducted through a collaborative arrangement under the auspices of the Predictive Mineral Discovery Co-operative Research Centre (PmdCRC), involving the Australian Government's Geoscience Australia (Onshore Energy Security Program), and Queensland Government's Smart Exploration Initiative and Zinifex (now OzMinerals), and complements the results of an earlier seismic survey undertaken in 1994 through the Australian Geodynamic CRC (MacCready, 2006). An interpretation of the new survey results has already been released (Geological Survey of Queensland, 2011) but it was very much of a preliminary nature and does not contain the same level of detailed basin analysis presented here. Data acquisition was by the National Research Facility for Earth Sounding (ANSIR) with processing carried out at Geoscience Australia. The processed data and uninterpreted images are available for free download from the Geoscience Australia website at: http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_a05f7892-ee53-7506-e044-00144fdd4fa6/L180+Mt+Isa+Deep+Crustal+Seismic+Survey%2C+QLD%2C+2006.+Stacked+and+migrated+data+and+images+for+lines+06GA-M1+to+06GA-M6.

2. Regional geology of Mount Isa mineral province

The Mount Isa mineral province (Fig. 1) developed along the eastern margin of the North Australian craton and preserves a 200 Myr record (1800–1575 Ma) of crustal thinning, continental rifting and sedimentary basin formation linked at depth to magmatic intrusion and the formation of mid-crustal extensional shear zones (Gibson et al., 2008; Holcombe et al., 1991; Passchier, 1986; Passchier and Williams, 1989; Pearson et al., 1991; Withnall and Hutton, 2013). Continental rifting was initiated in ≥1840 Ma crystalline basement and produced three vertically stacked sedimentary basins (1790–1740 Ma Leichhardt, 1740–1640 Ma Calvert and 1635–1575 Ma Isa superbasins), separated

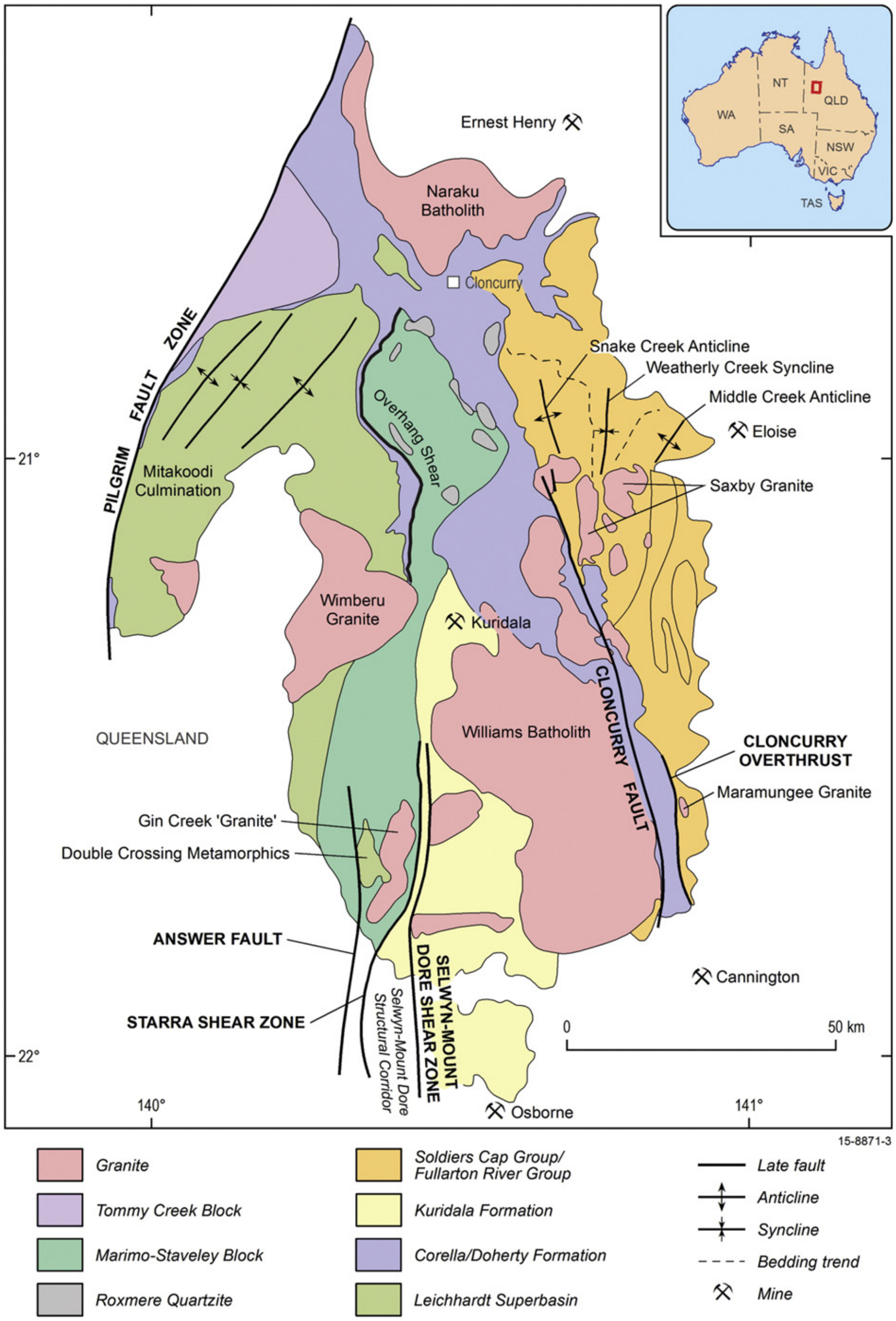

Fig. 4. Simplified geological map for the eastern succession, including previously mapped major folds, faults and shear zones. Note position of strongly mineralized Selwyn-Mount Dore structural corridor in south.

by major regional unconformities, and within which the overall depositional environment progressively changed from fluviatile–lacustrine to open marine (Fig. 2) (Jackson et al., 2000; Southgate et al., 2000a). A back-arc basin or intracontinental setting has generally been favoured as the most likely tectonic environment for basin formation although further refinements of this interpretation have recently been proposed in which intracontinental rifting (Leichhardt Superbasin) was superseded by a fully developed rifted continental margin (Calvert and Isa superbasins) following breakup of the Nuna supercontinent (Betts et al., 2006, 2008; Gibson et al., 2008, 2012).

All three superbasins were deformed and metamorphosed during the polyphase 1600–1500 Ma Isan Orogeny (Fig. 2) although the intensity of deformation and metamorphism varies markedly across the province and rarely exceeds greenschist facies conditions in rocks making up the Lawn Hill Platform and neighbouring Leichhardt River Fault Trough (Fig. 1). These two regions form part of the western succession or fold belt (Blake, 1987) in which crustal shortening associated with the Isan Orogeny is limited and largely confined to open folding and thrust faults with minor displacements (Fig. 3a). Original, pre-orogenic crustal architecture related to all three superbasins is consequently well preserved (Betts et al., 1998, 2006; Derrick, 1982; Eriksson et al., 1983; Gibson et al., 2012; Jackson et al., 2000) and interpreted to be the result of extensional processes operating in an overall strike-slip (Feltrin et al., 2009; Scott et al., 2000; Southgate et al., 2000b) or rift-sag tectonic regime (Betts and Lister, 2001; Betts et al., 1998; Gibson et al., 2008, 2012; Withnall and Hutton, 2013). Separating these rocks from the eastern succession (Fig. 1), and serving as a window on basement beneath this less intensely deformed

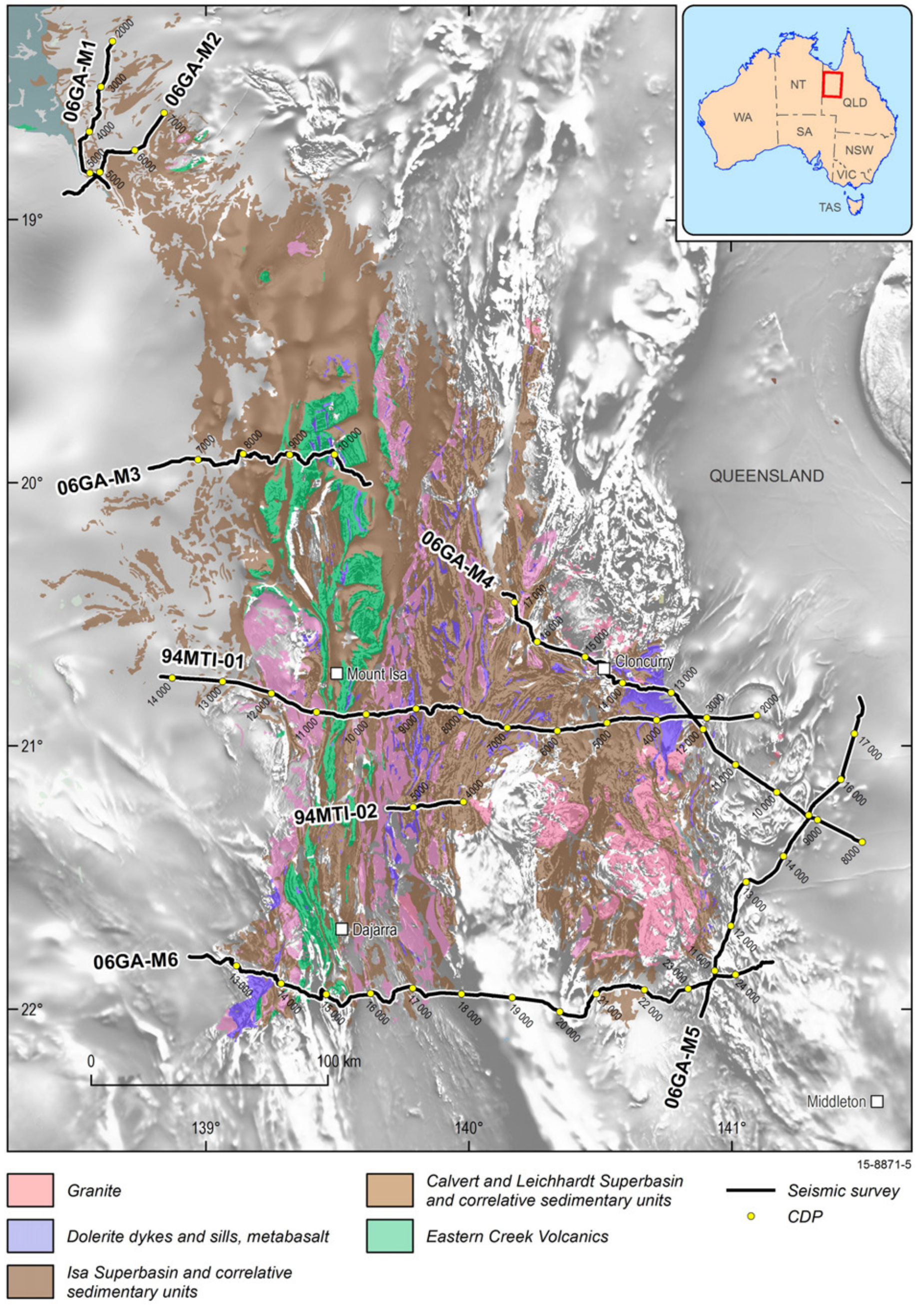

Fig. 5. Aeromagnetic image of Mount Isa region (courtesy of Geoscience Australia) with exposed regional geology superimposed, along with 2006 and earlier 1994 seismic survey lines. Highlighted in colour are the regionally extensive Eastern Creek Volcanics and correlatives (green), granites (red) and main sedimentary units (various hues of brown). Magnetic image shows that the Mount Isa mineral province extends eastwards for some distance under cover and is not limited to the area of mapped bedrock.

structural domain, is a fault-bounded strip of exposed crystalline basement represented by the north–south-trending Kalkadoon–Leichhardt Block.

In contrast to their western counterparts, rocks in the eastern succession (Fig. 4) have been much more tightly folded and subjected to greater amounts of shearing and thrusting, culminating in formation of a west-vergent fold and thrust belt (Beardsmore et al., 1988; Betts et al., 2006; Giles et al., 2006; O'Dea et al., 2006; Rubenach et al., 2008). Beardsmore et al. (1988) further suggested that the deep water, mainly turbidite-dominated Soldiers Cap/Fullerton River Group (Fig. 4) is entirely allochthonous, comprising a series of thrust sheets emplaced from the east. Along with other parts of the eastern succession, including turbidites in the correlative Kuridala Group (Beardsmore et al., 1988; Withnall and Hutton, 2013), these rocks have been extensively intruded by post-orogenic granites (Fig. 4) making up the 1550–1500 Ma Williams and Naraku batholiths (Page and Sun, 1998; Pollard et al., 1998; Wyborn, 1998). Metamorphic grades in this fold and thrust belt locally reach upper amphibolite facies conditions (Foster and Rubenach, 2006; Rubenach et al., 2008) but, except for a well-documented example of an inverted half-graben in the Mitakoodi Culmination SE of Cloncurry (Blenkinsop et al., 2008; O'Dea et al., 2006; Potma and Betts, 2006), much less is known about the original basin geometry prior to deformation accompanying the Isan orogeny. These issues are best addressed through an analysis of the seismic data but before doing so we first give a brief account of the depositional history and structural controls on sedimentation in each of the three superbasins.

3. Basin history and evolution

Regional structure in the Mount Isa region is dominated by N–S to NNW-striking faults and shear zones overprinted by a younger generation of structures trending west–east, NW–SE or NE–SW (Betts et al., 1998, 2006; Betts and Lister, 2001; Gibson et al., 2008; 2012; O'Dea et al., 1997; Potma and Betts, 2006). The former resulted from ENE–WSW-directed extension during formation of the Leichhardt Superbasin (Bain et al., 1992; Blake, 1987; Eriksson et al., 1983; Gibson et al., 2008; O'Dea et al., 1997) whereas the other structures are mainly of Calvert-age and have been variously attributed to NW–SE crustal extension on the Lawn Hill Platform (Betts et al., 1998; Southgate et al., 2006) and ENE–WSW extension south of the Mount Gordon Fault Zone based on the orientation of half-graben and stretching lineations in 1670 Ma syn-extensional granites (Gibson et al., 2008). This phase of basin history is thought to have been coeval with plate convergence along the southern margin of the North Australian Craton (Betts and Giles, 2006; Betts et al., 2002; Giles et al., 2002; Scott et al., 2000) until terminated by accretion of the Warumpi terrane at ca. 1640 Ma (Scrimgeour et al., 2005). A further 40 Myr of syn- and post-rift sedimentation then followed (Fig. 2) before the Isa Superbasin came to a close at ca. 1575 Ma (Southgate et al., 2000a).

3.1. Leichhardt Superbasin (1790–1740 Ma)

The Leichhardt Superbasin is best known from the southern Lawn Hill Platform and Leichhardt River Fault Trough (Fig. 1) where some 5–7 km of continental flood basalts (Eastern Creek Volcanics; Fig. 5) and syn-rift sediments accumulated in an elongate, fault-bounded basin 50–80 km wide (Bain et al., 1992; Blake, 1987; Derrick, 1982; Eriksson et al., 1983; Gibson et al., 2012; Jackson et al., 2000; Scott et al., 2000). Faults bounding this basin typically strike NNW and dip steeply to both the east and west. Hangingwall displacements on these structures range from 100s of metres to several kilometres but vary considerably along the length of the trough indicating that this feature is not a single basin but a train of highly asymmetric overlapping half-graben, each oriented north–south and up to 70–130 km long. These dimensions are comparable to modern intracontinental rifts such as the one in East Africa (Bosworth, 1992; Rosendahl, 1987) and appear to have been similarly controlled by pre-existing fabrics in the underlying basement. In the Mount Isa region, these mainly strike NW or NNE as evidenced by gneissic foliation in the adjacent Kalkadoon–Leichhardt Block and the large number of mafic dykes intruded along these foliations (Gibson et al., 2008). Despite such extensive fault control, topographic relief during development of this superbasin was subdued with no direct sedimentological evidence for deep water depositional environments. Rather, fluviatile to lacustrine environments predominated, during the course of which cross- and trough-bedded quartzite and feldspathic sandstone were deposited (Guide and Myally supersequences; Fig. 2) with local incursions into evaporitic or shallow marine conditions (Derrick, 1982; Eriksson et al., 1983; Jackson et al., 2000).

Syn-rift basaltic rocks of the 1780–1775 Ma Eastern Creek Volcanics were extruded under subaerial or shallow water conditions (Fig. 3b) and form part of a large bimodal igneous province represented in the eastern succession by mafic and felsic volcanics, including rhyolites and ignimbrites of the 1780 Ma Argylla Volcanics and 1760 Ma Bulonga Volcanics (Neumann et al., 2009a; Withnall and Hutton, 2013). This province also includes slightly younger basaltic lava flows of the Marraba Volcanics which, together with the Argylla and Bulonga volcanics, make up the deeper syn-rift component of the Leichhardt Superbasin in the eastern province, including the Mitakoodi Culmination (Fig. 4). The Marraba Volcanics are locally interstratified with stromatolitic dolostone and overlain by shallow-water quartzites and sandstones of the Mitakoodi Quartzite (Fig. 2). The Mitakoodi Quartzite is similarly of syn-rift origin and includes horizons of pillow basalt (Wakefield Metabasalt member) no different in composition to the underlying Marraba Volcanics. Overlying the Mitakoodi Quartzite is the so-called Overhang Jaspilite (Fig. 2), which contains even greater amounts of stromatolitic dolostone and grades upward into carbonaceous shale, indicating that by 1760 Ma the locus of basin formation and syn-rift magmatism had not only shifted eastwards but was by now centred over continental crust that had sufficiently thinned to induce subsidence and a change in depositional environment from fluviatile to shallow marine.

Active rifting in the Leichhardt Superbasin ceased no later than ca. 1740 Ma with intrusion of post-kinematic granites and gabbro (Fig. 2). This was followed shortly thereafter by an episode of thermally-induced subsidence, leading to further inundation and burial of syn-rift sequences beneath a transgressive, post-rift blanket of fluviatile-shallow marine sediments (Blake, 1987; Derrick et al., 1980; Jackson et al., 2000). Clean, well-sorted quartzites (Quilalar Formation, Ballara Quartzite) and well-bedded platform carbonate sequences (Corella Formation, Staveley Formation, Doherty Formation) make up the bulk of this post-rift sequence.

3.2. Calvert Superbasin (1730–1640 Ma)

Rifting in the Calvert Superbasin commenced with the deposition of fanglomerates and redbeds (Big Supersequence) in fault-angle depressions and a rejuvenation of bimodal magmatism represented by the 1730–1710 Ma Fiery Creek Volcanics and 1710 Ma Weberra Granite on the Lawn Hill Platform and the intrusion of 1730–1725 Ma syn-extensional rhyolitic dykes and sills farther east (Hutton and Sweet, 1982; Jackson et al., 2000; Neumann et al., 2006). Several cycles of upward-fining, mainly siliciclastic sedimentation (Prize Supersequence; Figs. 2 & 3c) followed in the west, during the course of which the depositional environment on the Lawn Hill Platform changed from near-shore to deltaic or shallow marine (Hutton and Sweet, 1982; Southgate et al., 2000a) and magmatic activity became progressively more subdued except for < 50 cm syn-sedimentary peperitic intrusions (Lambeck et al., 2012) dated at ca. 1690 Ma (Page et al., 2000). With further rifting and deepening of the sedimentary basin, thinly laminated carbonaceous shale and rhythmite became more widely developed across the western succession whereas carbonate rocks continued to dominate the depositional environment further outboard. This phase of rifting culminated in the west with intrusion of the 1678 Ma Carters Bore Rhyolite and 1670 Ma syn-extensional Sybella Batholith (Fig. 2).

Accompanying or immediately following the cessation of deposition in the Prize Supersequence (Fig. 2), the main depocentre shifted eastward and turbidite deposition commenced in the region now occupied by the Soldiers Cap Group and its correlatives in the Kuridala Group (Fig. 3d). Individual turbidite beds are frequently carbonaceous towards their tops and were laid down in a deep-water environment off the continental shelf. These rocks have no obvious lateral or temporal equivalent in the western succession and have been extensively intruded by basaltic dikes and sills, including variably metamorphosed dolerite with highly evolved, Fe-enriched compositions (Williams, 1998; see also Baker et al., 2010). A tonalite from one of the more strongly fractionated basaltic sills in the Llewellyn Formation yielded a magmatic age (Rubenach et al., 2008) identical to 1685 Ma detrital zircon ages obtained from its host rocks (Neumann et al., 2009b), indicating that sedimentation, crustal thinning and basaltic intrusion were all coeval in the older parts of the Soldiers Cap and Kuridala groups. Despite having identical detrital zircon populations, younger turbidites in the Soldiers Cap Group (Mount Norna Quartzite) probably postdate deposition of the Prize Supersequence, and like the overlying Toole Creek Volcanics, could be a temporal equivalent of carbonaceous slates in the ca. 1655 Ma Marimo Slate and younger Gun Supersequence (Fig. 2). The Toole Creek Volcanics and their black slate correlatives would also appear to mark an important turning point in basin evolution, signalling not only a deepening of the depositional environment but the onset of thermal subsidence and passive margin conditions following breakup of the Nuna supercontinent (Betts et al., 2008; Gibson et al., 2012). An abrupt influx of juvenile material into the sedimentary basin at ca. 1655 Ma (Lambeck et al., 2012) is probably linked to these same events, brought about by an upsurge in basaltic magmatism accompanying the final stages of continental rupture to form a rifted continental margin.

3.3. Isa Superbasin (1640–1590 Ma)

The Isa Superbasin succession is best represented on the Lawn Hill Platform (Fig. 1) where it comprises 8 km of rhythmically-bedded turbidites, carbonaceous shales and stromatolitic dolostone deposited in a shallow to deep water marine environment (Hutton and Sweet, 1982; Krassay et al., 2000a). These rocks make up the River, Term, Lawn, Wide and Doom supersequences (Fig. 2), and except for higher grade calc-silicate rocks and carbonaceous schists hosting rhyolitic sills, flows and volcaniclastic rocks dated at 1610–1620 Ma in the Tommy Creek Block (Fig. 4) immediately north of the Mitakoodi Culmination (Carson et al., 2011; Page and Sun, 1998; Withnall and Hutton, 2013), they have few correlatives outside of the Lawn Hill Platform. Much more widely developed are the underlying Gun and Loretta supersequences (Fig. 2), both of which are currently placed at the base of the Isa Superbasin (Southgate et al., 2000a), but whose stratigraphic affinities may instead lie with the older Calvert Superbasin as suggested by Gibson et al. (2008) and discussed further below. These two units are predominantly made up of thin- to thick-bedded carbonate sequences although the Gun Supersequence also incorporates varying amounts of black carbonaceous shale in addition to several hundred metres of

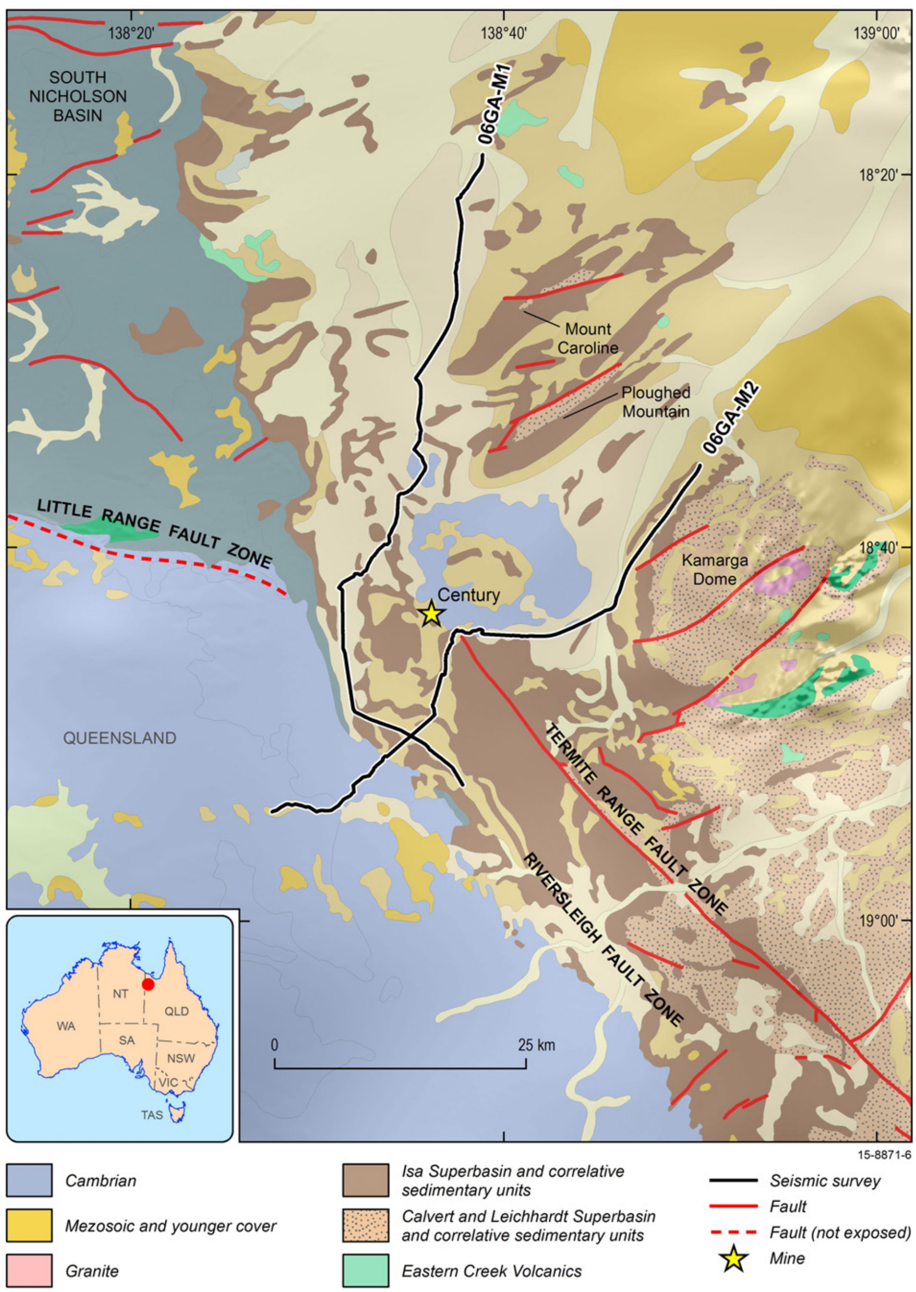

Fig. 6. Geological map for northern part of Lawn Hill Platform showing main structural elements and position of Century Mine relative to Termite Range Fault and seismic lines 06GA-M1 and 06GA-M2.

siliciclastic sandstones and siltstones (Fig. 3e) towards the base of the unit (Southgate et al., 2000b).

The Gun Supersequence is also host to major Pb–Zn and Cu mineral deposits at Mount Isa and Hilton/George Fisher and constitutes one of the most economically important stratigraphic units in the whole of the Mount Isa region. No less importantly in regard to basin formation and evolution, deposition of this unit coincided with onset of a basin-wide marine transgression best documented in rocks of the Lawn Hill Platform (Fig. 3e) but extending south and east through the Leichhardt River Fault Trough into the eastern succession where it is represented by carbonaceous slates of the 1655 Ma Toole Creek Volcanics at the top of Soldiers Cap Group (Fig. 2). Thus, quite apart from uncertainties about its stratigraphic position, there are equally important questions to be resolved about the tectonic significance of this unit and why black shales should be concentrated at this particular stratigraphic level and not be more widely distributed throughout the sedimentary sequence. These and other issues concerning basin evolution, and the extent to which tectonics may have controlled mineralisation, are best addressed through an analysis of seismic data that furnish a more complete picture of crustal architecture and potential fluid pathways.

4. Seismic data acquisition and their interpretation

The 2006 seismic data were acquired along six lines (Fig. 5) with vibroseis using 240 channels and 60 fold data (06GA-M1–06GA-M6). In contrast, data along the older 1994 L138 94MTI-01 profile (Fig. 5) were acquired using explosives and 120 channel, 10 fold data, and an interpretation of the results published a decade or so later (Blenkinsop et al., 2008; MacCready, 2006; O'Dea et al., 2006). Image resolution was generally poor and the data were subsequently reprocessed at Geoscience Australia in 2008 to complement the six new survey lines. These lines are spread across the length of the Mount Isa region and aimed to capture all structural elements down to below the Moho (20 second two-way travel time (TWT) record length), including the top of crystalline basement. CDP lines were used for geological interpretation, and grid referenced to AGD84, AMG Zone 54.

The Mount Isa block has an overall northward regional tilt so that much deeper crustal levels are exposed in the south compared to the north. The southern seismic lines (Fig. 5) consequently sample a much more restricted part of the regional stratigraphy dominated by rocks of the older Leichhardt and Calvert superbasins. Conversely, outcrop

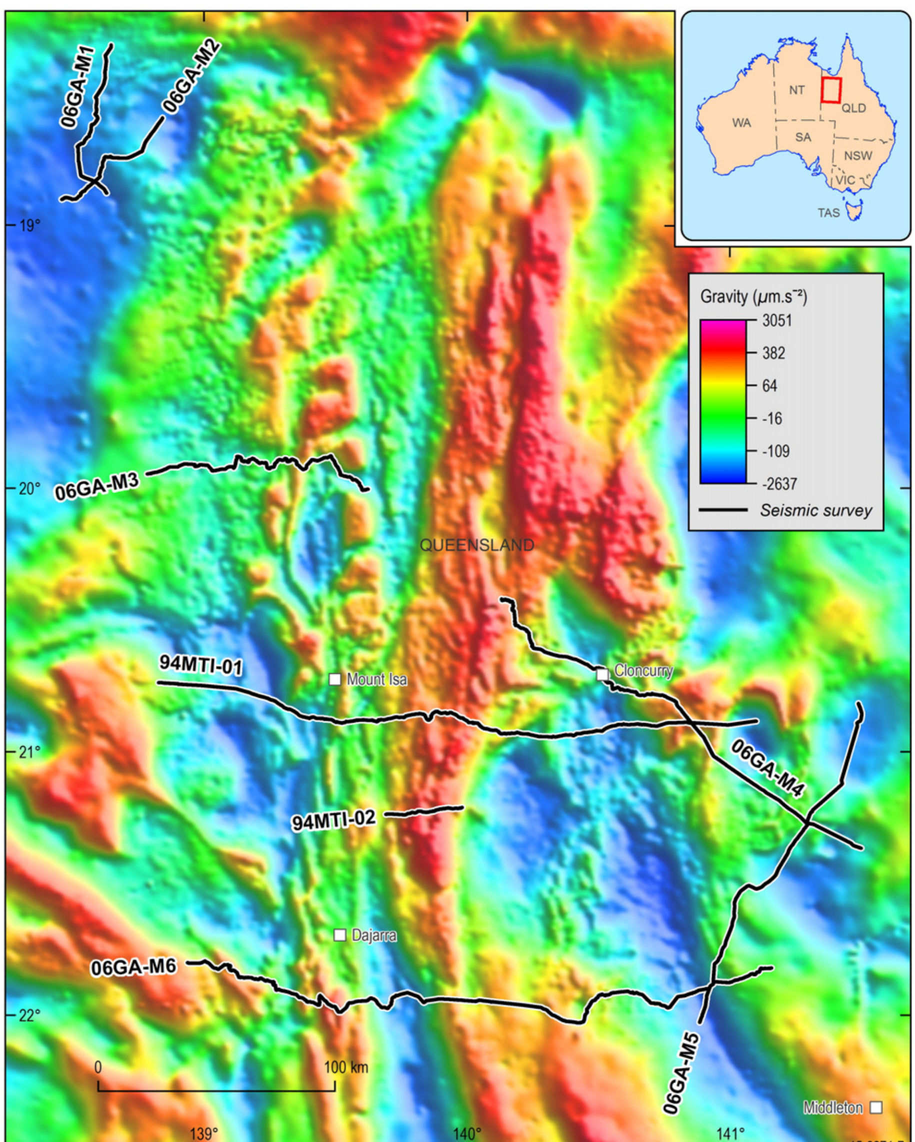

Fig. 7. Regional Bouguer gravity anomaly map of Mount Isa region (Geoscience Australia) showing position and spread of 2006 and earlier 1994 seismic lines.

Table 1
Densities of stratigraphic units employed in gravity modelling.

	Density (g/cm^3)
Post-Cambrian cover rocks	2.2–2.5
Cambrian	2.5–2.55
South Nicholson Group	2.55
Isa Superbasin	2.63–2.65
Calvert Superbasin	2.65–2.67
Fiery Creek Volcanics	2.8–2.9
Leichhardt Superbasin	2.64–2.69
Eastern Creek Volcanics	2.85–2.9
Yeldham Granite	2.64
Altered zone (eastern end 06GA-M6)	2.6
Argylla Formation	2.75–2.8
Doherty Formation and Soldiers Cap Group and correlatives (Kuridala Group)	2.7–2.85
Corella Formation	2.79
Mitakoodi Quartzite	2.77
Granite	2.64–2.69
Mafics	2.85–2.95
Undivided sediments	2.65–2.75
Mt Guide Quartzite	2.72
Oroopo Metabasalt	2.85
Sulieman Gneiss	2.85
Jayah Creek Volcanics	2.9
Plum Mountain Gneiss	2.85
Leichhardt Volcanics	2.68
Marraba Volcanics (mafic)	2.9
Bulonga Volcanics (felsic)	2.75
Marimo Slate	2.75
Undivided basement	2.7–2.8

along the two seismic lines (Fig. 6) on the Lawn Hill Platform (06GA-M1 & 06GA-M2) is overwhelmingly dominated by rocks belonging to the younger Isa Superbasin (Bradshaw et al., 2000; Hutton and Sweet, 1982). In this region, the two older basinal sequences are for the most part deeply buried so that any subdivision into their constituent lithostratigraphic or chronostratigraphic units is largely unconstrained by surface geology. Consequently, rocks making up the deeper stratigraphic levels along both seismic profiles remain largely undivided and the focus in this study has been on the two younger basins where the majority of mineral deposits occur. The older Leichhardt Superbasin nevertheless served as an important source of fluids and metals (Huston et al., 2006; Polito et al., 2006a) and was just as much part of the mineralising system as the other two basins. Unobscured by the other two basins and buried beneath only a thin veneer of Cambrian and younger rocks, its geometry and seismic character are best revealed in the south. Its inclusion makes for a fuller and more comprehensive description of basin architecture. For ease of description, this architecture is described in a series of north–south panels according to the tectonomorphological units shown in Fig. 1, commencing in the west before moving on to the eastern succession where the effects of the Isan Orogeny are greatest and basin geometry least well preserved. For internal division of the basins, attention focussed on the most regionally significant unconformities and their comparison with potential equivalent surfaces identified in reinterpreted older (1986 to 1991) petroleum industry (Comalco) seismic data for the northern Lawn Hill Platform (Bradshaw et al., 2000; Krassay et al., 2000a; Southgate et al., 2000a).

To further constrain and test the revised seismic interpretations, forward modelling of the Geoscience Australia regional gravity dataset (Fig. 7) was undertaken along all seismic transects in the area of exposed geology for which rock property data, and more particularly densities (Table 1), are available (Langbein and Blenkinsop, 2009; Meixner and Chopping, 2009). In almost every case (see below), the gravity models are a good match for the interpreted basin geometries, replicating both the "highs" and "lows" in basin shape. It is nevertheless important to point out that the match is rarely perfect owing to problems in adopting a single density for any one unit subjected to regional as well as local variations in metamorphic grade and magmatic intrusion. For example, density values (Table 1) used for the felsic Bulonga Volcanics (94MTI-01) and sedimentary Soldiers Cap Group (06GA-M6) are likely to be underestimates as both units are extensively intruded by basaltic dykes and sills (now mostly amphibolite). Similarly, crystalline basement is unlikely to be either homogeneous or free from basaltic intrusion, compromising the adoption of a single average density value in the modelling. These shortcomings aside, the gravity modelling and seismic interpretations are in sufficiently good agreement to lend confidence to the basin geometries proposed here. Altogether, more than 1100 line kilometres of seismic data are described. Full details on the gravity modelling methodology are provided in Appendix 1.

4.1. Lawn Hill Platform (06GA-M1–06GA-M3)

Rocks of the Lawn Hill Platform were crossed in three separate seismic lines (06GA-M1; 06GA-M2 and 06GA-M3; Fig. 5). Two of the lines cut across the area around Century Mine and were oriented at high angles to the NNW-striking Termite Range Fault (Fig. 6) and other major structures in the district that might have served as fluid conduits for mineralisation. The third line (06GA-M3) lies just south of the Lady Loretta Pb–Zn deposit and was oriented broadly west–east (Fig. 8) with the intention of imaging structures on either side of the Mount Gordon Fault Zone (Fig. 1), a major NNE-trending strike-slip fault that not only defines the eastern boundary of this structural domain but juxtaposes rocks of the Isa Superbasin against some of the oldest rocks in the abutting Leichhardt River Fault Trough (Eastern Creek Volcanics and Mount Guide equivalents; Fig. 2). In the seismic section (Fig. 8), this fault zone is steeply east-dipping and one of several similarly oriented structures that cut down into the lower crust and partly control distribution of the older Leichhardt-age rocks. Rocks of this age evidently do not extend across the entire Lawn Hill Platform but terminate against the most westerly of the major east-dipping structures. Gravity modelling is consistent with this interpretation (Fig. 8).

Conversely, rocks of the Calvert Superbasin appear to be continuous across the image and are up to ~3 km thick (1 s TWT). Moreover, this thickness is maintained across the section without any evidence of significant thickening into faults, including major structures such as the Russell Creek high strain zone at the western end of the profile. In view of the fact that Calvert-age faults in this region mainly strike WNW–ESE, and thus broadly parallel to the section, this is not unexpected. A notable exception is the east–west-striking Crystal Creek Fault which has rocks of Calvert-age thickening into it and lies wholly within the Leichhardt River Fault Trough (Fig. 8). The Russell Creek high strain zone is a much younger north–south-trending (D2) structure that formed during the Isan Orogeny; it cuts across and disrupts the older WNW–ESE-trending faults and broadly coincides with a zone of asymmetric folding related to shallow-rooted, west-directed thrusting (Fig. 8) as has been observed elsewhere in the Mount Isa region (Fig. 3a). The seismic data make it equally clear that this folding and thrusting is not confined to older parts of the Calvert Superbasin but extends up into the well-bedded carbonates of the overlying post-rift sequence (Gun Supersequence), and Paradise Creek Formation in particular (high amplitude, continuous to semi-continuous reflections; Fig. 8). It may be further concluded from the seismic data along line 06GA-M3 that this thrust-related deformation is linked to more open folding in rocks of the Leichhardt River Fault Trough farther east.

Seismic data from the northern Lawn Hill Platform (06GA-M1 and 06GA-M2) have imaged all three superbasins and reveal a strikingly asymmetric rift basin architecture dominated by variably reactivated extensional faults and less steeply dipping footwall shortcut thrusts (Figs. 9c & 10c). Conspicuously absent is any convincing evidence for a narrow basin bounded by sub-vertical faults that might indicate significant strike-slip faulting or development of a pull-apart basin (Feltrin et al., 2009; Southgate et al., 2000b). Instead, most faults assume a

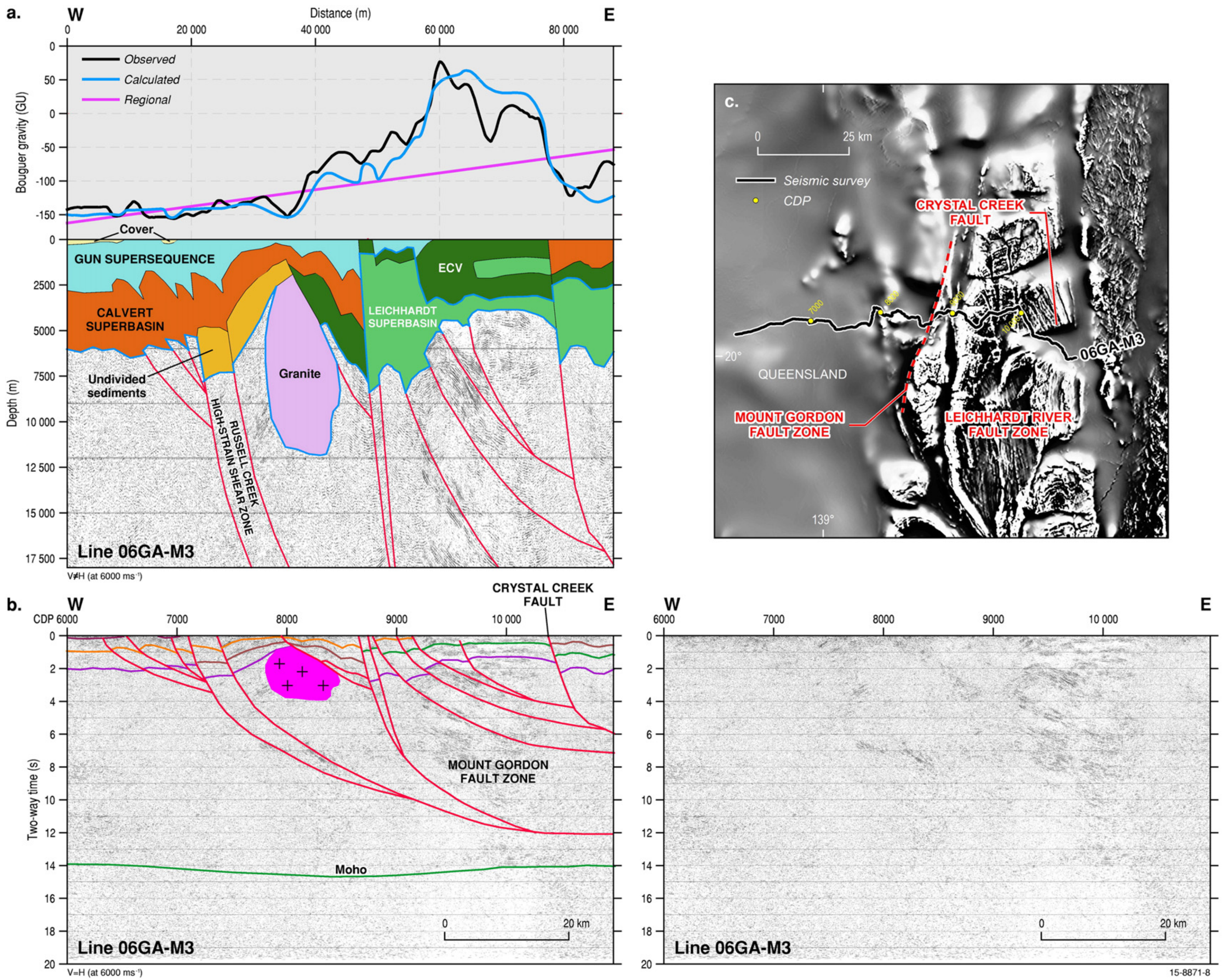

Fig. 8. (a) Forward modelling of gravity data along seismic line 06GA-M3 (image is vertically exaggerated compared to one below); (b) interpreted and uninterpreted seismic images (20 second TWT data); (c) seismic line superimposed upon first vertical derivative of regional aeromagnetic dataset. Magnetic lows over thick sedimentary basin fill contrasts with higher magnetic relief over Eastern Creek Volcanics along spine of the Leichhardt River Fault Trough.

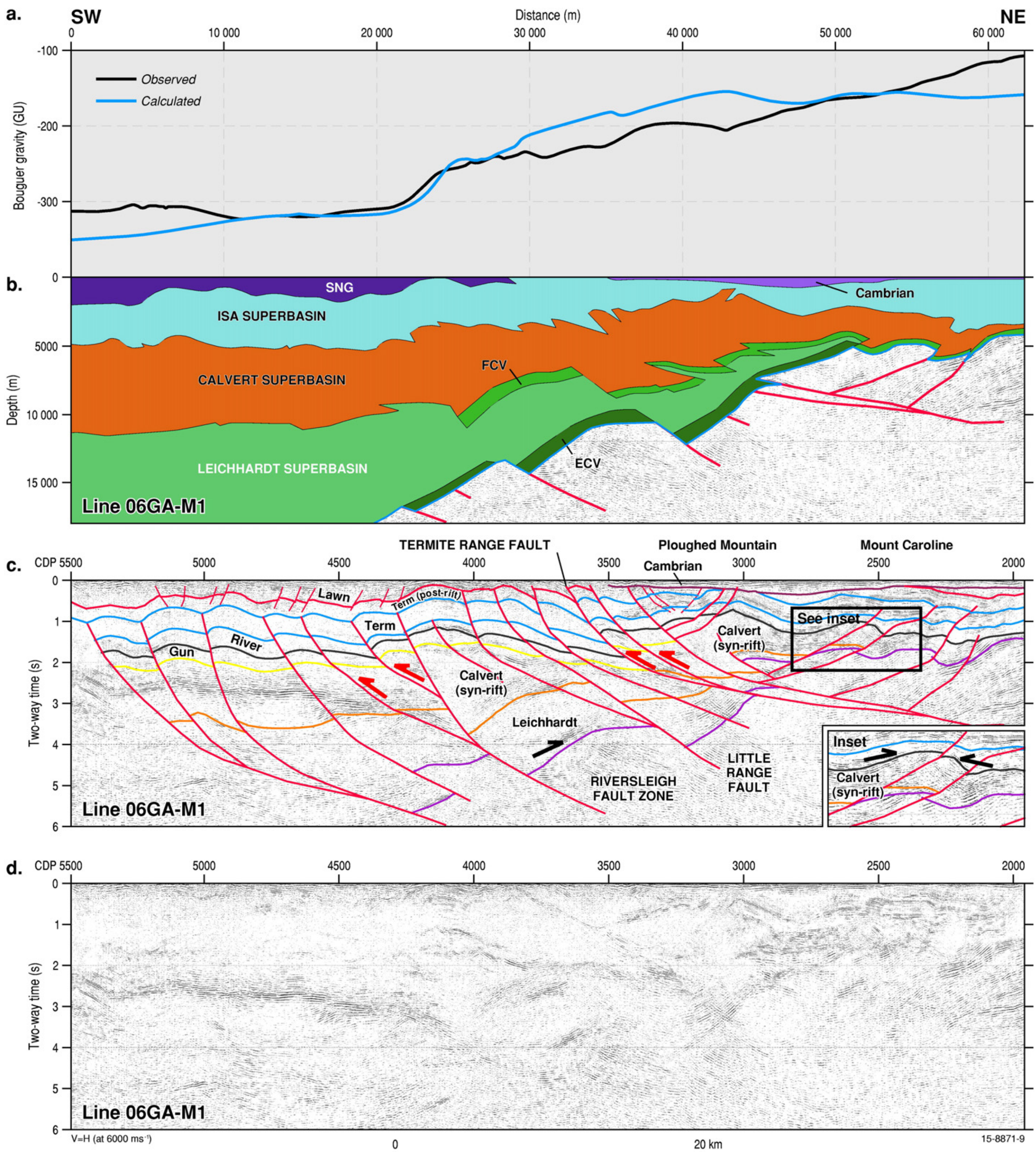

Fig. 9. (a) & (b) Forward modelling of gravity data along seismic line 06GA-M1; (c) more detailed geological interpretation of seismic image (6 second TWT data), incorporating supersequences, unconformities and major structures such as the Termite Range Fault and Riversleigh Fault Zone; (d) uninterpreted seismic image. Basin inversion was accompanied by reactivation of pre-existing normal faults and development of shortcut footwall thrust faults (red arrows; not all marked). Note onlap surface (black arrows; inset) at base of Term/top River Supersequence (black line) and base of Lawn Supersequence (crimson; see inset of Fig. 10) which are taken here as the base of the syn-rift and syn-inversion packages in the Isa Superbasin respectively. Other surfaces identified in the seismic image include top crystalline basement (purple); base Calvert Superbasin/top Leichhardt Superbasin (brown); base River Supersequence/top Gun Supersequence (yellow); top syn-rift sequence/base Gun Supersequence in Calvert Superbasin (green); base post-rift sequence in Isa Superbasin (upper blue); base Cambrian (magenta). SNG — South Nicholson Group, FCV — Fiery Creek Volcanics, ECV — Eastern Creek Volcanics. For position of seismic line see Figs. 5 and 6.

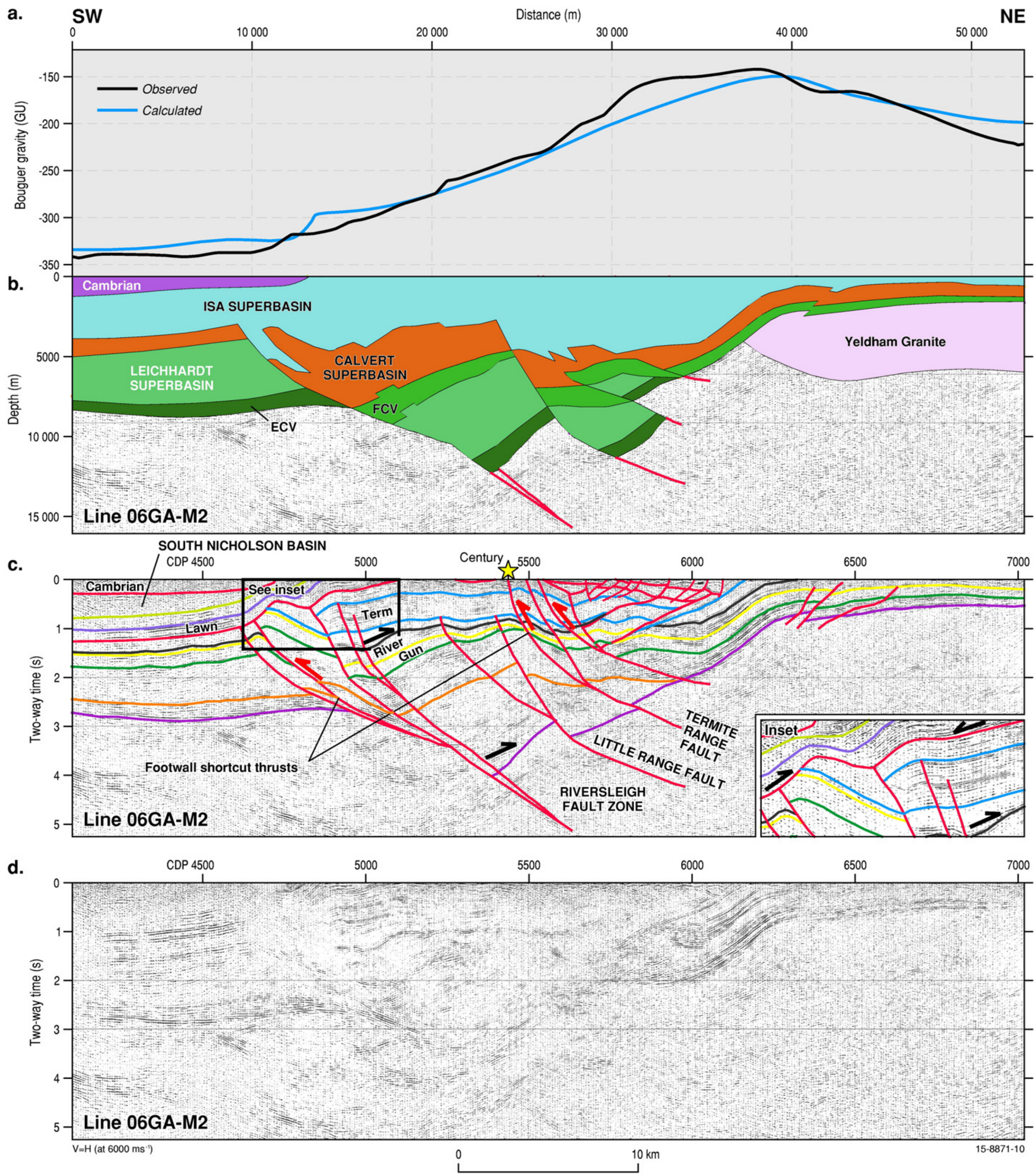

Fig. 10. (a) & (b) Forward modelling of gravity data along seismic section 06GA-M2; (c) & (d) interpreted and uninterpreted seismic images (6 second TWT data). The Termite Range Fault and Riversleigh Fault Zone are common to both this line and 06GA-M1. Note stranded rotated tilt block at depth beneath Century Mine in hangingwall of the Little Range Fault and asymmetric folding east of the Termite Range Fault. Onlap surfaces indicated by black arrows. Colour coding for surfaces is same for Fig. 9 except for following: base Lawn Supersequence (indigo); base South Nicholson Basin/Group (gold). FCV — Fiery Creek Volcanics, ECV — Eastern Creek Volcanics. For position of seismic line see Figs. 5 and 6.

common eastward dip. Basin inversion is most spectacularly developed in the vicinity of the Riversleigh Fault Zone and its associated shortcut thrust (Fig. 10c) but extends to all levels in the basin and across all parts of the platform, including the Kamarga Dome to the east (Fig. 6). A number of west-dipping normal faults of Cambrian age are developed in the uppermost few kilometres of the crust but these are of limited displacement and had no appreciable effect on pre-existing fault attitudes and basin geometry. Consequently, much of the original basin architecture is still preserved, including that of the older Leichhardt Superbasin. This basin has the wedge-like geometry of a half-graben and thickens to the west or southwest, as best determined from line 06GA-M1 (Fig. 9b & c) and supported by the gravity modelling (Fig. 9a). Its formation predates most, if not all, of the normal faulting in the seismic sections east of the Riversleigh Fault Zone as evidenced by an absence of any significant change in sedimentary thickness on either side of any one structure (Fig. 9c). Any normal offset in stratigraphy, or the underlying crystalline basement, on one side of a fault is invariably matched by a commensurate amount of displacement on the other. In contrast, normal faults at the southern end of line 06GA-M1, including the Riversleigh Fault Zone itself, have collectively effected not only a significant downward displacement in basement but a doubling of basin thickness compared to farther east. A comparable thickening of the Leichhardt Superbasin is associated with the unnamed major fault at the western end of profile 06GA-M2, indicating that this structure is common to both seismic lines and has both a significant strike-length and northerly trend. Along with the Riversleigh structure, it is one of the more important structures of Leichhardt-age and, like the former, remained active during subsequent basin-forming events, including deposition of the Calvert and Isa superbasins (Figs. 9c & 10c).

Basin fill for the two younger superbasins is subdivided into syn- and post-rift cycles with an additional syn-inversion component identified at the top of the Isa superbasin (Lawn Supersequence; Fig. 10c inset). The two post-rift sequences are continuous across the seismic sections and form parallel-sided tabular sheets with little or no obvious thickening into intrabasinal faults (Figs. 9c & 10c). They either crop out or have been intersected in drillholes on the Kamarga Dome (Hutton and Sweet, 1982) and correspond to the Gun/Loretta supersequences and uppermost Term Supersequence (Figs. 9c & 10c). Unlike the weakly reflective Loretta Supersequence, the Gun Supersequence is characterised by high amplitude, continuous to semi-continuous reflections (Fig. 10c) that probably indicate a higher proportion of thicker-bedded and coarser-grained carbonate units (cf. Southgate et al., 2000a). These differences aside, the Gun and Loretta supersequences appear to be conformable with respect to each other and belong to one continuous cycle of deposition. Moreover, given their post-rift attributes and singular lack of thickening into extensional faults, they more likely belong with the Calvert than Isa superbasin (Fig. 2) and owe their origin to a combination of post-rift cooling and thermal subsidence.

Compared to the Gun and Loretta supersequences, the syn-rift package in the Calvert Superbasin has a very different seismic character dominated by discontinuous, low to moderate amplitude, almost chaotic reflections in which internal truncations are commonplace. These characteristics are strongly reminiscent of fluviatile to shallow marine sequence making up the Prize Supersequence (Southgate et al., 2000a) which elsewhere in the Mount Isa region is the principal unit of the Calvert Superbasin. This unit attains a maximum thickness of about 5 km adjacent to the Riversleigh Fault Zone, thinning eastwards to less than one kilometre on the Kamarga Dome, and even less farther west (Figs. 9c & 10c). The lower contact with the underlying Leichhardt Superbasin is unconformable and marked by truncation of units in the older superbasin (Fig. 10c). The upper contact is similarly unconformable and can be traced eastwards as far as the Kamarga Dome where the Prize Supersequence is superseded and onlapped by the Gun and Loretta supersequences (Fig. 10c).

The Isa syn-rift sequence comprises rocks of the River and Term supersequences. Both units thicken into the Riversleigh Structure and, except for an abrupt thickening of the former into a structure identified here as the Little Range Fault Zone (Fig. 1), both units become conspicuously thinner eastwards (Fig. 10c). This is particularly evident in the Term Supersequence which varies from 3 to 1 km across the region (Figs. 9c & 10c). It is bounded at its base by a prominent onlap surface (Fig. 10c; inset), as well as a distinctive high-amplitude double reflector (see also Southgate et al., 2000a), and appears to have been deposited on a partially eroded or pene-planated River Supersequence as evidenced by local truncation of its upper stratigraphic units. This would suggest that the River Supersequence was deposited during a period of tectonic instability, possibly involving an episode of syn-depositional uplift and/or basin inversion immediately preceding deposition of the overlying Term Supersequence (Fig. 9; inset). Except for a component of seismically non-reflective rocks at the base of the unit, the remainder of the Term Supersequence is characterised by seismic reflections that are parallel and much more continuous than those in the Prize Supersequence (Fig. 10). This is in keeping with the observation that the bulk of the sequence is made up of turbidites and other deep marine sediments (Andrews, 1998; Hutton and Sweet, 1982; Krassay et al., 2000a). As with the older Prize Supersequence, this syn-rift package becomes increasingly deformed and tightly folded east of the Little Range Fault Zone (Fig. 1). This fault zone lies directly beneath the Century Mine and appears to have undergone little or no reactivation, forming instead one boundary of a rotated tilt block that has retained its pre-deformational position and became stranded at depth during basin inversion (Fig. 10c). This block has been partially overridden by rocks from the east and served as a buffer against which these rocks were shortened, leading to strain partitioning and the development of tight folding and thrusting in its hangingwall rocks (Fig. 10c).

Reactivated normal faults and footwall shortcut thrusts of Calvert- or younger Isa-age accommodated most of the crustal shortening associated with basin inversion. Chief among these structures is the Riversleigh Fault Zone which has undergone only limited amounts of reactivation so that as much as ~6 km (2 s TWT) of the original, normal displacement is still preserved (Figs. 9c & 10c). It has effected a significant offset in crystalline basement and is one of several structures which can be confidently extrapolated from one seismic line into the other. These structures, along with much of the open to tight folding observed in their hangingwalls, strongly resemble the harpoon-like structures described from other inverted sedimentary basins and sand-box experiments (McClay, 1990) and strike mainly NNW–SSE, parallel to the mapped trace of the Termite Range Fault but orthogonal to the northeast-striking, mainly northwest-dipping, structures (e.g. Fiery Creek Fault) previously identified as the principal growth faults in this region from seismic (Southgate et al., 2000a) and potential field data (Betts et al., 2004; Murphy et al., 2011). The Termite Range Fault is itself revealed to be a thrust fault, one of several such structures identified in the seismic data beneath this part of the Lawn Hill Platform (Fig. 10c). It dips much less steeply than the adjacent normal fault and is embedded in the footwall of the above-mentioned stranded tilt block (Fig. 10c).

To the east of the Termite Range Fault, and related folding, are several other thrust faults of opposite dip and vergence (Fig. 10c). They are antithetic to the normal faults farther west and possibly originated on the other side of a crestal extensional collapse structure (see McClay, 1990) which has since been inverted and lies directly below the eastern part of the Termite Range. Inversion on these structures probably occurred about the same time as the footwall shortcut thrusts developed but, unlike the latter, these former normal faults are typically confined to higher stratigraphic levels and in several instances do not cut up section all the way to the surface (Figs. 9c & 10c). Rather, they terminate in and around the level of the River and Term supersequences (Fig. 2). Unlike the other thrust faults, these antithetic structures commonly exhibit variable dips and a staircase geometry of flats and ramps. Both the Ploughed Mountain and Mount Caroline anticlines (Fig. 6) have thrust faults of comparable age developed beneath them but otherwise conform to the same pattern of broad, open folding that accompanied basin inversion farther west (Fig. 9c). As with other thrust faults east of the Termite Range Fault, these two structures are similarly blind but dip in a southerly direction. Previously, both anticlines were thought to be underlain by inverted normal faults dipping northwest (Betts et al., 2004).

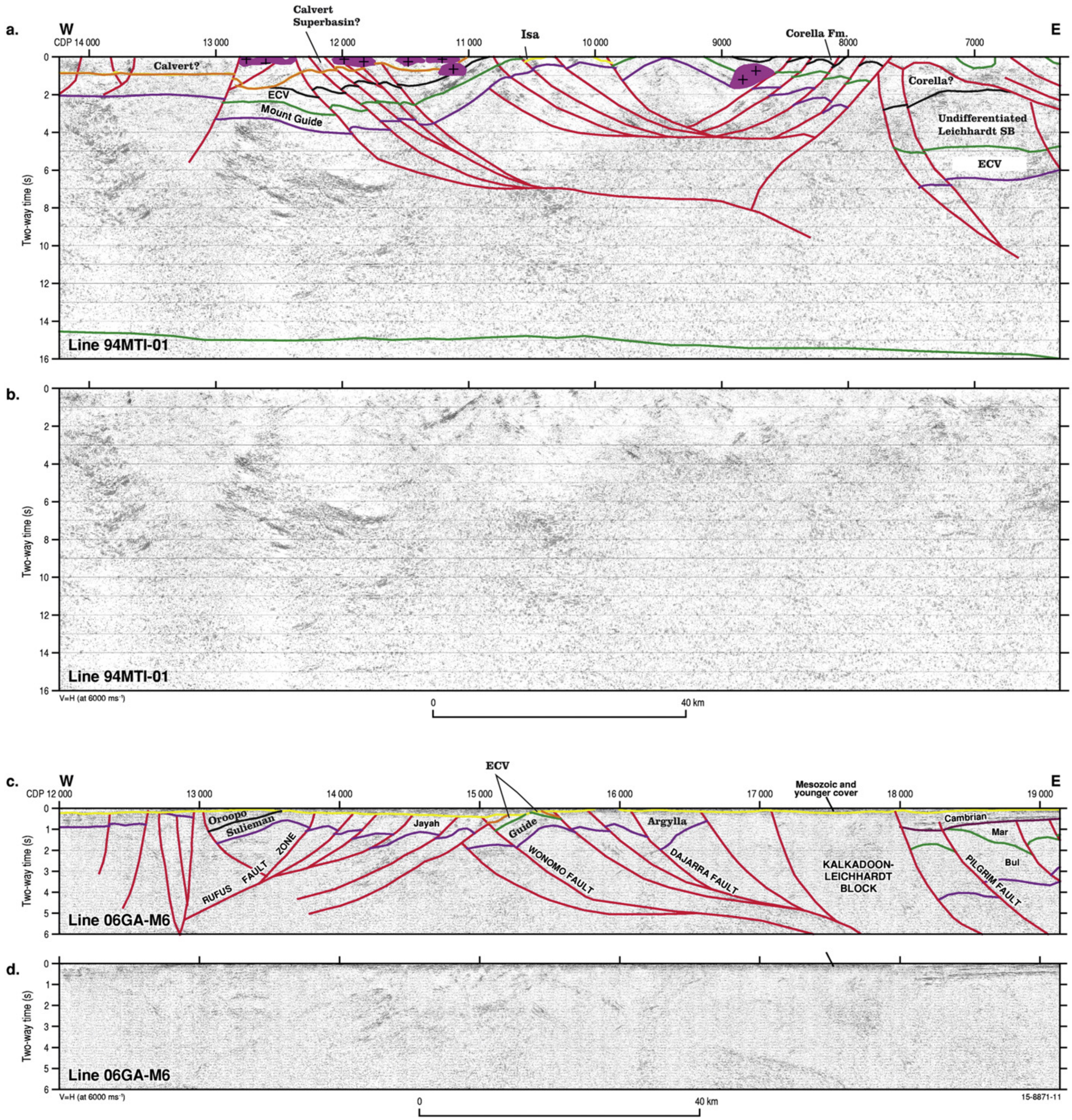

Fig. 11. Interpreted and uninterpreted seismic images for two west–east seismic profiles through the Leichhardt River Fault Trough: (a) & (b) western end of seismic section 94MTI-01 (20 second TWT data); and (c) & (d) western end of seismic profile 06GA-M6 (6 second TWT data). Note extensive granite intrusion in (a) and progressive thinning of Leichhardt Superbasin southwards so that crystalline basement is exposed at the surface along much of 06GA-M6. Both the Eastern Creek Volcanics and basement are often characterised by continuous to semi-continuous high amplitude reflectors precluding unequivocal distinction between these two structural elements in the absence of surface control from outcropping geology. In this paper, basement has been taken where parallel reflectors give way to less continuous or coherent seismic fabrics. Colour coding same as for Fig. 8. For position of seismic profiles and forward modelling of gravity data see Fig. 7.

The syn-inversion component of the Isa Superbasin comprises the Lawn and Wide supersequences and possibly also the overlying Doom Supersequence (Fig. 2). For the two older units, there is a clear and unequivocal inverse relationship between sedimentary thickness and the position of folds and thrusts developed during basin inversion. More specifically, both units thin appreciably over the crest of these structures and thicken away from the folds towards their flanks (Fig. 10c; inset). The Riversleigh Structure and its shortcut thrust are two important cases in point. In the former, rocks making up the core of the fold (Term Supersequence) are onlapped by basal units of the Lawn Supersequence (Pmh_3 or "Balmung Sandstone"; Andrews, 1998) that become progressively younger up-dip whereas in the second case, this onlap relationship is even more pronounced and shared by the overlying Wide Supersequence (Fig. 10c; inset). The latter would also appear to thicken westwards, consistent with material being removed from the growing crestal region of the fold and transported towards its flanks.

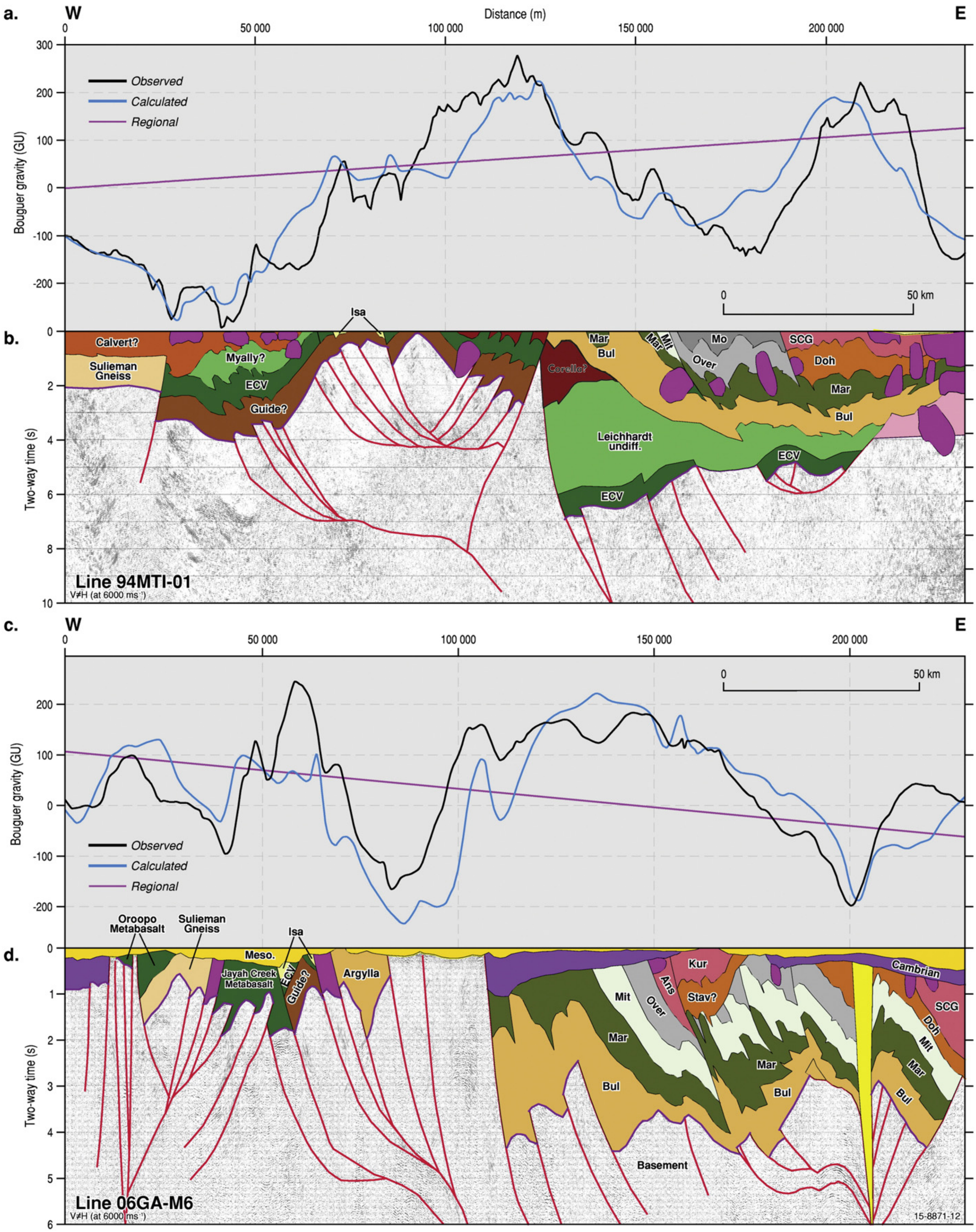

Fig. 12. Gravity models for interpreted seismic data along entire lengths of lines (a) 06GA-M6 and (b) 94MTI-01. Abbreviations same as for Figs. 11 and 13.

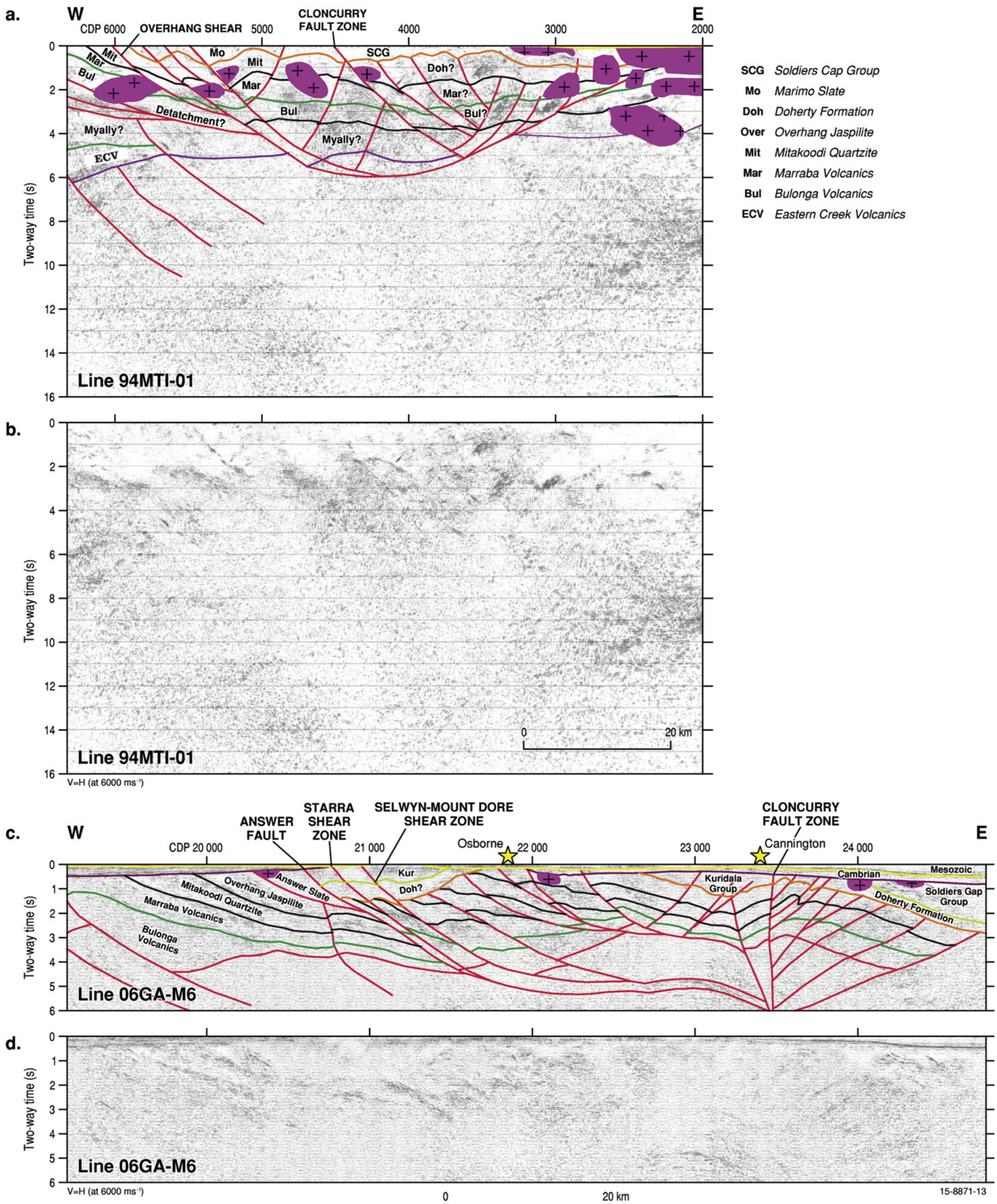

Fig. 13. (a) Interpreted and (b) uninterpreted seismic sections through Mitakoodi Culmination, Marimo Slate Belt and adjacent Soldiers Cap Group at eastern end of line 94MTI-01 (20 second TWT data); (c) & (d) interpreted and uninterpreted sections through same tectonic elements farther south along eastern end of seismic line 06GA-M6 (6 second TWT data). Note west-vergent fold and thrust belt developed east of the Mitakoodi Culmination in (a) and west of the Cloncurry Fault Zone in older rocks of the Leichhardt Superbasin and Selwyn-Mount Dore structural corridor in (c). A now folded detachment in (a) separates 1760 Ma Bulonga Volcanics from an older part of the same half-graben in which basin-fill extends down to basement and includes Eastern Creek Volcanics at its base. Note zone of antithetic reactivated normal faults between the Osborne and Cannington mineral deposits thought here to represent a former extensional crestal collapse structure which subsequently served as a locus for late hydrothermal alteration (this figure). A prominent unconformity (downlap surface) is taken as base of the Doherty/Staveley Formation and Calvert Superbasin; this surface truncates faults and rocks in the underlying Leichhardt Superbasin and extends into seismic line 06GA-M5 (Fig. 15).

A downlap surface developed at the base of the Wide Supersequence is in keeping with this interpretation as is the apparent loss and removal of the underlying post-rift sequence.

4.2. Leichhardt River Fault Trough

Compared to the Lawn Hill Platform, the Leichhardt River Fault Trough has been eroded to deeper stratigraphic levels so that only remnants of the Calvert and Isa superbasins remain. Seismic images are consequently dominated by rocks of the Leichhardt Superbasin, especially the 1780–1775 Ma Eastern Creek Volcanics (Fig. 5). All three seismic lines (06GA-M3, 94MTI-01, and 06GA-M6) are orthogonal to regional strike in the trough and point to deposition of these basaltic rocks in a rift-related environment dominated by north–south-trending half-graben that have since been partially inverted (Figs. 8 & 11). Basin inversion structures are particularly well imaged in the most northerly of the three seismic lines (06GA-M3) where up to 6 km of gently folded mafic volcanics and interstratified sediments (Myally Supersequence; Fig. 2) have been disturbed by post-depositional faulting and preserved in a harpoon-like structure developed immediately east of the Mount Gordon Fault Zone (Fig. 8b). Crystalline basement beneath this structure is similarly complexly faulted and has been reduced to a series of thrust sheets verging west towards the margin of the trough and its former bounding normal fault. A strongly developed fabric in basement rocks beneath these sheets shares the same general eastward dip as the latter but, as with rocks in the overlying Leichhardt Superbasin, becomes increasingly deformed and folded adjacent to the Mount Gordon Fault Zone (Fig. 8b). Farther east this same basement fabric is cut by a south-dipping extensional fault whose position corresponds to the Crystal Creek Fault. This fault juxtaposes folded sediments of Calvert age in the hangingwall against outcropping Eastern Creek Volcanics in the footwall (Fig. 8c).

As is the case farther north, line 94MTI-01 shows the Eastern Creek Volcanics to be cut by a series of east-dipping thrusts or reactivated extensional faults (Fig. 11a) although basin architecture is difficult to discern from the seismic data alone. One set of faults underlies the Leichhardt River Fault Trough but the other extends much farther west and partially underlies granites of the Sybella Batholith (see Fig. 1). These two fault sets also appear to be rooted in two separate detachments but nevertheless appear to have shared a common origin in that both have the Eastern Creek Volcanics preserved in their hangingwalls (Fig. 11a). Formation of both sets of structures at the same time and in a common extensional setting is indicated. Several of these faults also have rocks of the Calvert or Isa Superbasin preserved in their hangingwalls, pointing to a more complicated history involving more than one episode of fault movement. There is a reasonably good fit between the interpreted basin geometry (Fig. 11a) and gravity model (Fig. 12a).

This same history of multiple movement is no less evident for east-dipping structures imaged in line 06GA-M6 farther south (Fig. 11c & d). These include the Wonomo Fault whose folded and inverted hangingwall sequence extends along strike for more than 50 km to the north of the seismic line and encompasses rocks of both the Leichhardt and Calvert superbasins (Fig. 11c). Basin inversion postdates deposition of the younger Calvert-age sediments (Warrina Park Quartzite; Fig. 2) which, along with the underlying Eastern Creek Volcanics, have been juxtaposed against more intensely metamorphosed Jayah Creek Metabasalt (Fig. 11c). Along with the underlying Sulieman Gneiss, this metabasaltic unit makes up the deepest exposed stratigraphic levels of the Leichhardt River Fault Trough in this part of the Mount Isa region and may be a correlative of the Eastern Creek Volcanics.

By far the more obvious feature of this seismic line, however, is the reversal in fault and half-graben polarity on either side of the Wonomo Fault (Fig. 11c). Faults west of this structure are for the most part west-dipping and include the Rufus Fault. It separates Sulieman Gneiss from Oroopo Metabasalt (Fig. 11c) and broadly coincides with the western limits of the Leichhardt River Fault Trough. The Sulieman Gneiss forms basement to the Jayah Creek Metabasalt and probably represents a continuation of the older adjacent crustal block (Arunta and Tennant regions) eastwards beneath this part of the Mount Isa mineral province (Fig. 11c). The zone of fault reversal along the Wonomo Fault has the character of an accommodation zone and is likely to be an area of more intense fracture development with greatly enhanced rock permeability. The relatively poor fit between gravity and interpreted geology at the western end of this seismic section (Fig. 12b) is unexplained but may reflect a higher than usual density in crystalline basement owing to gabbroic intrusion.

4.3. Mitakoodi Culmination and its southern extension

East of the Pilgrim Fault Zone, the Leichhardt Superbasin is host to several large-scale anticlines and synclines making up the Mitakoodi Culmination (Fig. 4), a mid-crustal fold and thrust complex first identified in the original 94MTI-01 seismic line (Figs. 5, 11a) and since attributed to basin inversion accompanying the Isan Orogeny (Blenkinsop et al., 2008; O'Dea et al., 2006; Potma and Betts, 2006). Basin inversion is interpreted to have been driven by northwest-directed thrust faulting rooted in a detachment developed along the interface between basin fill and the underlying crystalline basement (Argylla Detachment) although neither this detachment nor the overlying fold and thrust complex are particularly well imaged (e.g. O'Dea et al., 2006; their Fig. 12). Some similar structure or detachment has been captured in the reprocessed seismic data presented here (Fig. 13a) but it is neither obviously thrust-related nor basement-controlled. Rather, material improvements in image quality over the original seismic dataset, indicate that crystalline basement extends to greater depths than previously supposed and lies buried beneath a considerably thicker pile of syn-rift material (Fig. 13a). The seismic data further indicate that rocks exposed in the core of the fold and thrust complex (Bulonga Volcanics and Marraba Volcanics) make up no more than a fraction of the basinal fill and occur towards the top of the sequence. Moreover, even if the Argylla Detachment were a thrust fault across which stratigraphy were repeated, this would still not account for the bulk of material lying at depth in the half-graben (Fig. 13a). At least some of this material is likely to be metamorphosed basaltic rocks as it has the same seismic character as the Eastern Creek Volcanics (continuous to semi-continuous, high amplitude reflections) and occupies a comparable position at the base of the sequence. Gravity modelling is consistent with the development of high density mafic rocks at depth in this half-graben (Fig. 12b) Indeed, given that the Eastern Creek Volcanics were similarly extruded into half-graben, but erupted up to 20 Myr earlier than either the Bulonga Volcanics or Marraba Volcanics (Fig. 2), it is not unreasonable to conclude that the Eastern Creek Volcanics or some temporal equivalent of the former are represented at depth east of the Pilgrim Fault.

This same combination of mafic and felsic volcanic rocks is also interpreted to be present farther south along seismic line 06GA-M6 (Figs. 13c & d) where basin inversion is even more pronounced and up to ~12 km (~4 s TWT) of the deeper stratigraphic levels of the Leichhardt Superbasin have been brought closer to the surface east of the Pilgrim Fault. This part of the eastern succession has since been buried beneath Cambrian and younger sediments up to nearly 3000 m thick following further extensional faulting in the early Paleozoic and Mesozoic (Fig. 13c) and is therefore not amenable to direct geological mapping. It is therefore not possible to establish with any great certainty whether the interpreted rocks are temporal equivalents of the 1780 Ma Eastern Creek Volcanics and Argylla Formation or the 1760 Ma Bulonga Volcanics and Marraba Volcanics. Aeromagnetic data and modelling of the available gravity data are consistent with either scenario (Fig. 12b). However, as with seismic line 94MTI-01, there is a conspicuous change to more continuous, parallel to semi-parallel reflections in the uppermost part of the syn-rift package that not only serves to subdivide this package into upper and lower units but possibly coincides with entry of the Bulonga Volcanics and Marraba Volcanics into the rock record.

In keeping with the suggestion that these two seismic lines have sampled a common stratigraphy, the volcanic units along both lines are conformably overlain by a 3 km-thick package dominated by parallel, mainly continuous reflections taken here to be quartzites and sandstones of the ca. 1750–1740 Ma Mitakoodi Quartzite (Fig. 2); it is interpreted to continue eastwards beneath younger rocks of the eastern succession, including black slates of the Marimo–Staveley Belt from which it is separated along seismic line 94MTI-01 by the Overhang Jaspilite and east-dipping Overhang Shear (Fig. 13a). This shear zone marks the boundary between the Leichhardt and Calvert superbasins in this part of the eastern succession (Fig. 4) and continues southwards into seismic line 06GA-M6 where it assumes a similar east-dipping attitude and separates poorly exposed black slates (Answer Slate) from an older sedimentary sequence that includes the Mitakoodi Quartzite and also possibly the Overhang Jaspilite (Fig. 13c). Lying between these two older units is a major unconformity along which the Mitakoodi Quartzite is not only truncated but progressively onlapped by elements of the younger overlying unit. This unconformity now dips eastwards but prior to basin inversion would have been west-dipping, consistent with thickening of the Overhang Jaspilite into one of the east-dipping faults identified farther west in the seismic image (Fig. 13c). Total preserved thickness in this unit of the Leichhardt Superbasin is estimated at about 3 km. This is more than the thickness of Overhang Jaspilite farther north, raising the possibility that this segment of the seismic section incorporates more than just the latter and includes carbonates and finer grained siliciclastic rocks of the post-rift Staveley/Doherty Formation and Roxmere Quartzite. Alternatively, this and other syn-rift units exhibit considerable variation in thickness along strike as is expected if they had been deposited in different sub-basins or even one and the same sub-basin.

4.4. Marimo–Staveley fold and thrust belt

Bounding the Mitakoodi Culmination on its eastern side (Fig. 13a), and extending south into line 06GA-M6 (Fig. 13b), is a west-vergent fold and thrust belt comprising inverted basinal sequences of both the Calvert and Leichhardt superbasins. Major faults typically dip eastwards and are of at least two generations. The older generation is entirely confined to the Leichhardt Superbasin and does not extend upward into the overlying Kuridala or Soldiers Cap groups. Rather, together with stratigraphy in their host rocks, this generation of faults is truncated at the contact with the overlying Calvert Superbasin. An angular unconformity evidently exists between the two superbasins in this region along which a significant component of the Mitakoodi Quartzite and Marraba Volcanics has been lost to erosion. This unconformity and related truncation are most obvious in seismic line 06GA-M6 (Fig. 13c) east of the Selwyn-Mount Dore structural corridor (Fig. 4) although some similar relationship is also evident between faulting and stratigraphy in Leichhardt Superbasin rocks farther north along the eastern segment of line 94MTI-01 (Fig. 13a). This would suggest that the Leichhardt Superbasin had already undergone at least one phase of basin inversion and deformation before the Kuridala and Soldiers Cap group rocks had even been deposited. Although the age of this deformational event cannot be determined directly from the seismic section, it cannot be any younger than the 1690 Ma depositional ages obtained from detrital zircon in both the Kuridala and Soldiers Cap groups (Neumann et al., 2009b). Nor is it likely to have occurred much later than 1740 Ma because migmatite and granite of the same age (Magee et al., 2012; Neumann et al., 2009a; Page and Sun, 1998) post-date early deformation and basin inversion in the exposed and dominantly psammopelitic Double Crossing Metamorphics (Fig. 4) a few kilometres to the north of seismic line 06GA-M6. Although once thought to be part of the underlying crystalline basement (Blake, 1987) these metasedimentary rocks are now known from detrital zircon studies to be a higher grade and more intensely deformed part of the Leichhardt Superbasin (Magee et al., 2012; Withnall and Hutton, 2013). Their most likely correlatives in the still buried, but similarly tightly folded and faulted rocks of the Leichhardt Superbasin farther south along line 06GA-M6 are the Mitakoodi Quartzite or Marraba Volcanics (Fig. 13c), both of which incorporate significant amounts of psammopelitic sediment in their type sections (Mitakoodi Culmination). Thus, far from being a separate geological unit, the Double Crossing Metamorphics have simply undergone greater amounts of uplift and unroofing compared to other parts of the Leichhardt Superbasin and serve as a window on what lies at depth farther south along strike. This is in keeping with the observation that rocks of the Leichhardt Superbasin along line 06GA-M6 (Fig. 13c) still retain some vestige of their original post-rift cover (Staveley Formation), indicating that they were either never subjected to the same amount of crustal shortening as the Double Crossing Metamorphics or, more likely, basin inversion was not uniform along strike and was greater in the thicker and originally more deeply buried parts of the basin to the north.

The second generation of east-dipping structures includes the Overhang Shear along seismic line 94MTI-01 (Fig. 13a) and three major shear zones to the south along seismic line 06GA-M6 (Fig. 13c). The Starra and Selwyn-Mount Dore shear zones (Adshead-Bell, 1998; Beardsmore et al., 1988; Duncan et al., 2014) both lie within the intensely mineralised (iron-oxide–copper–gold) Selwyn-Mount Dore structural corridor (Fig. 4) and define its western and eastern boundaries respectively (Fig. 13c). Unlike the older generation of faults and shear zones in the Leichhardt Superbasin, these two structures cut upward all the way to the surface and disrupt stratigraphy in the Calvert Supergroup (Fig. 13c). The third, and most westerly of the three structures, similarly breaches the surface and is interpreted to be a southern continuation of the unnamed structure that juxtaposes the Double Crossing Metamorphics against Answer Slate along strike to the north (Fig. 4). This structure is labelled here (Fig. 13c) as the Answer Fault after the Answer Mine located along its trace, and like the other two structures, preserves a record of extensional faulting that subsequent basin inversion and thrust faulting failed to completely erase. Instead, normal fault offsets and the original wedge-like geometry of the Calvert-age sedimentary basin are widely preserved with the result that it is not uncommon for thrust faults to have the oldest rocks located in the footwall as opposed to the hangingwall, as is the case along parts of the Selwyn-Mount Dore Shear Zone where the ~1740 Ma Staveley Formation is overridden by younger ≤1690 Ma rocks of the Kuridala Group (Duncan et al., 2014).

Notwithstanding evidence from the seismic data that the Selwyn-Mount Dore corridor served as a locus for extensional faulting during Calvert time, some of these same faults preserve a record of earlier activity extending all the way back to Leichhardt time (Fig. 13c), pointing to an even more complex history of multiple reactivation and basin inversion. Thrust faulting along the Selwyn-Mount Dore corridor post-dates deposition of the adjacent Kuridala Group and Answer Slate, and is only one manifestation of this history. Moreover, not all of this thrust faulting need date from the Isan Orogeny; some occurred later as evidenced by an increasing number of geochronological ages from the Selwyn-Mount Dore corridor ranging from 1585 Ma through to 1500 Ma (Duncan et al., 2011; Rubenach et al., 2008). Interestingly, this structural corridor is also broadly coincident with a change in depositional environment from platform to deeper-water turbidite sediments that approximates to the original shelf break or head of the continental slope. It is therefore not unexpected that this already highly deformed zone should serve as a locus for thrusting, strain partitioning, and iron oxide–copper–gold mineralisation during and subsequent to peak deformation and metamorphism accompanying the Isan Orogeny at 1585 Ma (Adshead-Bell, 1998; Duncan et al., 2011).

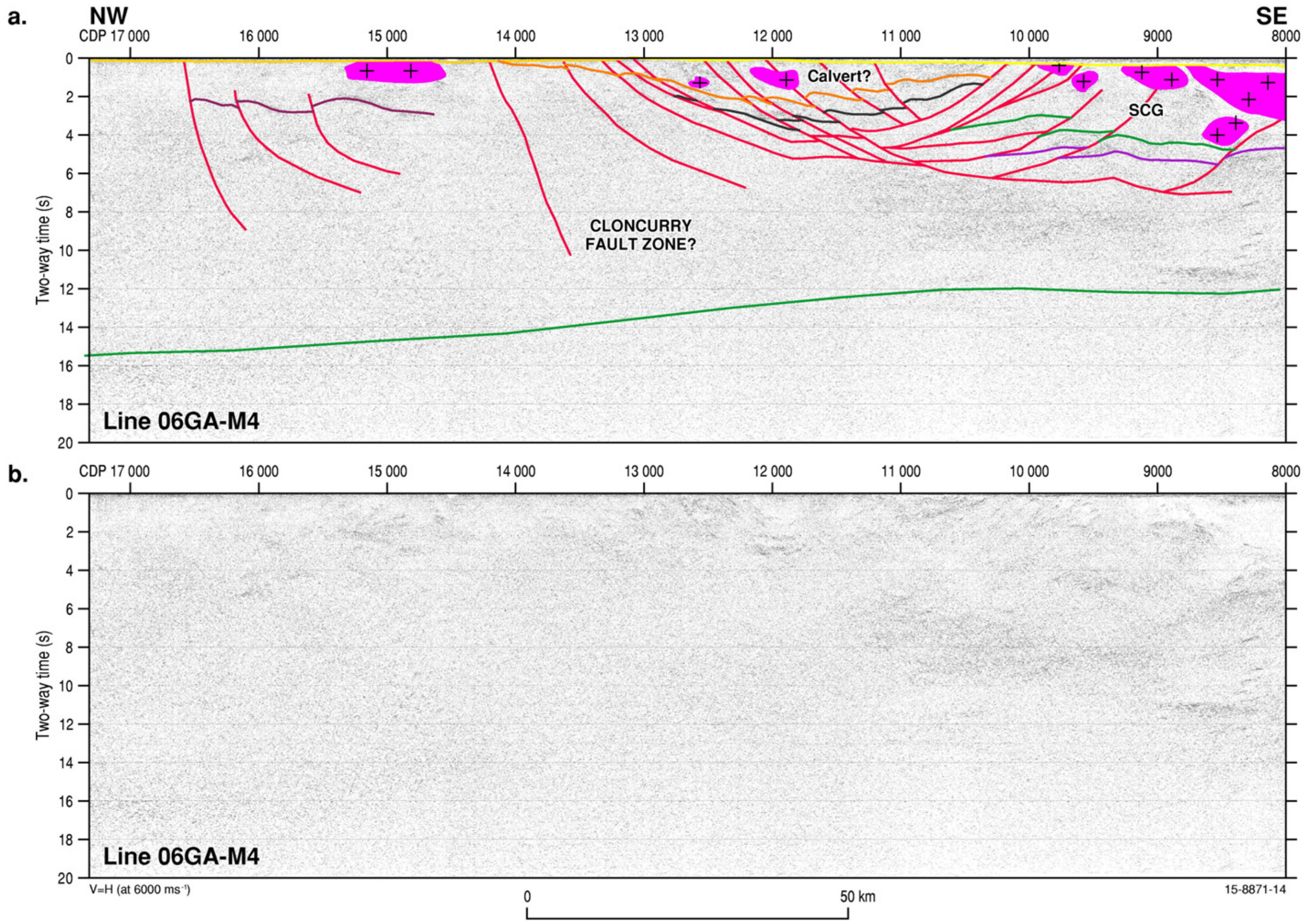

Fig. 14. (a) Interpreted and (b) uninterpreted seismic image (20 second TWT data) for profile 06GA-M4. Owing to poor image quality, only limited interpretation was undertaken on this profile. Note extensive intrusion of Soldiers Cap Group rocks by post-orogenic granites of the Naraku and Williams batholiths (see Fig. 4). The Moho is indistinct and interpreted to coincide with the last few remaining reflectors towards the bottom of the section.

Despite reactivation during the Isan Orogeny, fault and basin geometries in the Leichhardt and Calvert superbasins west of the Cloncurry Fault Zone are strongly asymmetric, reflecting their original shape and origin as half-graben (Fig. 13c). Gravity modelling (Fig. 12b) is consistent with this interpretation and replicates the overall eastward shallowing of half-graben and their underlying crystalline basement. A grossly similar inverted basin geometry (harpoon structure) is replicated in gravity modelling along line 94MTI-01 (cf Figs. 12a and 13a) except that faults along this seismic profile commonly extend no higher than the Staveley and Doherty formations. This is in keeping with the observation made elsewhere in this paper that both syn- and post-rift components are represented in the Leichhardt and Calvert superbasins. In the case of the Leichhardt Superbasin, the post-rift component is restricted to the Staveley and Doherty formations. Moreover, despite comprising different sedimentary facies (dominantly siliciclastic versus more calcareous protoliths) and lying on either side of the Cloncurry Fault Zone, these two geological units appear to be lateral equivalents of each other both as mapped at the surface (Withnall and Hutton, 2013) and in the seismic data (Fig. 13c). Similarly, turbidite-dominated sequences of the Soldiers Cap Group (Fig. 3d) appear to be laterally continuous with the Answer Slate (94MTI-01) and Kuridala Group (line 06GA-M1) on the other side of the Cloncurry Fault Zone (Fig. 13). Together, these units make up a 3 km-thick syn- to post-rift sequence. Along with older parts of the sequence, these rocks have been strongly deformed into a series of asymmetric anticlines and synclines with wavelengths of several kilometres (e.g. Snake Creek Anticline). They are also host to several large granite plutons that not only post-date folding and basin inversion but, in a few instances, are located along or close to inverted extensional faults (Fig. 13a), pointing to a possible structural control on granite intrusion during emplacement of the much younger 1550–1540 Ma Williams Batholith (Fig. 4). A similar pattern of asymmetric folding linked to reactivated east-dipping extensional faults has also been observed in surface outcrops (Blenkinsop et al., 2008; Giles et al., 2006).

4.5. Cloncurry Fault Zone and Soldiers Cap Domain

Except for their western ends, seismic lines 06GA-M4 and 06GA-M5 (Figs. 14 & 15) lie almost exclusively in the area dominated by Soldiers Cap Group and its continuation eastwards under Mesozoic cover rocks of the Eromanga Basin (Fig. 4). Both lines cross the Cloncurry Fault Zone but data quality is disappointingly poor in both cases with few reflections of any significance developed at middle to lower crustal depths, especially along profile 06GA-M4 where the fault zone is ill-defined but interpreted here to be subvertical to steeply east-dipping (Fig. 14a). It corresponds at the surface with a steeply-dipping shear zone, separating Soldiers Cap Group to the east from brecciated calc-silicate rocks of the Staveley Formation in the Marimo–Staveley Belt to the west. Soldiers Cap Group along this seismic line is up to 3 km thick and underlain by calc-silicate rocks of the Staveley Formation. Faults with opposing dips cut through both units in the central part of the seismic section and typically flatten out at depth (Fig. 14a). A few

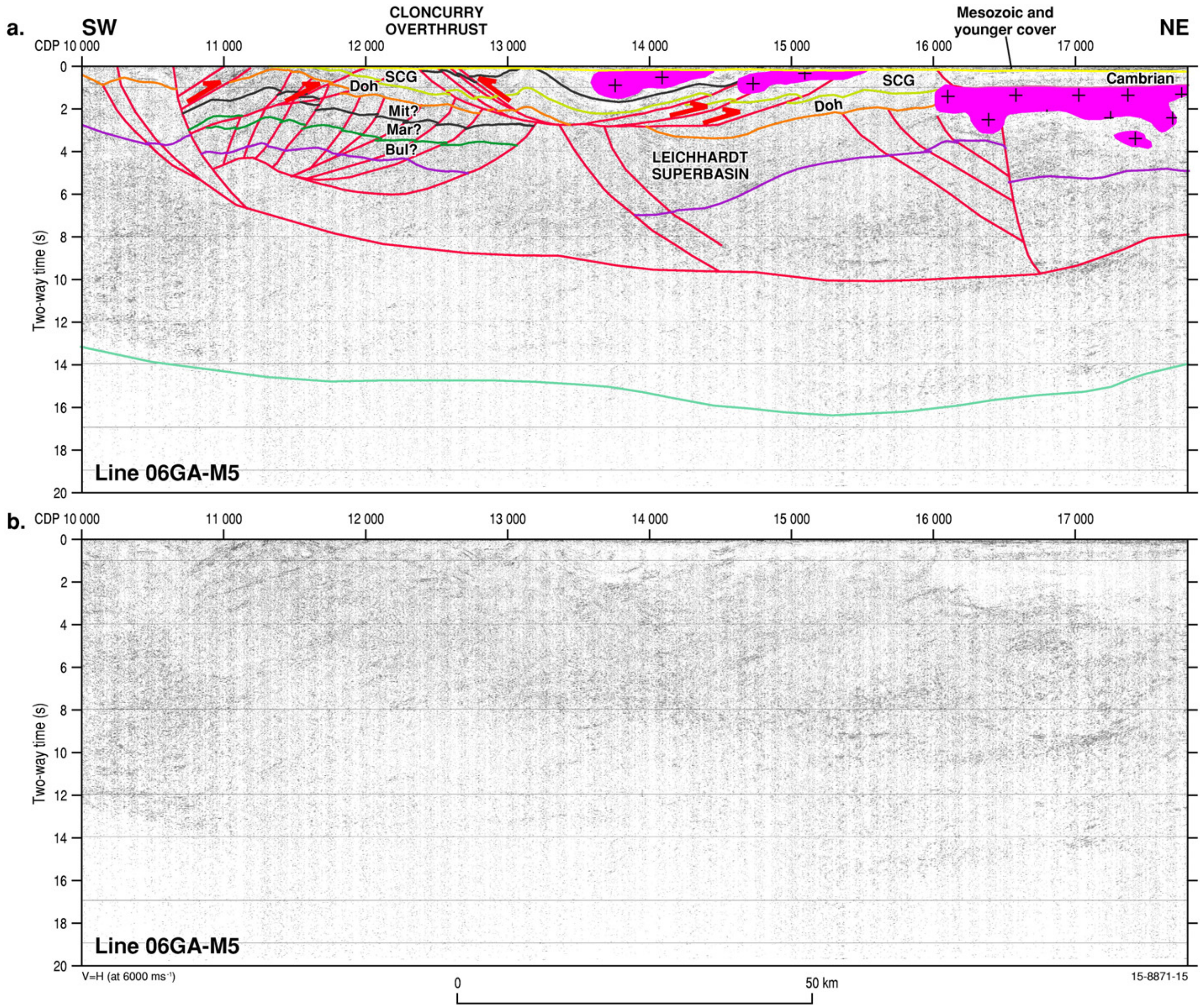

Fig. 15. (a) Interpreted and (b) uninterpreted seismic images (20 second TWT data) for profile 06GA-M5, including Soldiers Cap Group east of the Cloncurry Fault Zone. Although weakly defined, reflections in the mid- to upper crust have opposing dips across large tracts of the section consistent with development of two or more separate sub-basins. An upper crustal section of inferred post-rift age is extensively intruded by granite and underlain by inverted half-graben of opposing polarity. Note truncation of older Leichhardt-age structures and geological units at base of Calvert Superbasin. The prominent east-dipping detachment at mid-crustal levels appears to be a more deep-rooted expression of the Cloncurry Fault Zone.

may even reverse dip and be continuous with faults of opposing dip as might be expected in the case of a seismic line oriented parallel or sub-parallel to the primary growth faults. In this case, basin fill would increase away from the bounding extensional faults towards the centre of the depocentre as is observed. Moreover, any extensional fault transected by the seismic line would be concave upward and have a trace that is continuous across the section. The faults imaged in the central part of line 06GA-M4 satisfy these criteria and consequently are likely to strike NW–SE, parallel to both the seismic line and regionally extensive D1 structures (e.g. Toole Creek Syncline) mapped in Soldiers Cap Group (Ryburn et al., 1988). In so far as these faults are restricted to the upper part of the seismic section and occur in rocks of Staveley Formation or younger age, they cannot be any older than the Calvert Superbasin. Conversely, geological units and more widely spaced faults at deeper crustal levels more likely belong with the older Leichhardt Superbasin and are truncated by the younger Calvert age structures (Fig. 14a). Moreover, even though both sets of faults share a common history of reactivation, the older structures are more obviously growth faults into which the associated geological units consistently thicken. Post-dating reactivation, and in some cases cutting across faults of either age, are several large granite plutons whose size and frequency increases eastwards in tandem with overall deepening of the sedimentary basin. Some of the larger granites in this and the other seismic sections (e.g. 06GA-M5) are up to 3 km thick and have a pancake-like shape (Figs. 14a & 15a).

Seismic lines 06GA-M6 and 94MTI-01 both terminate east of the Cloncurry Fault Zone but provide conflicting information on both its character and attitude. In the north, this structure appears to be an east-dipping reactivated extensional fault (Fig. 13a) whereas farther south, along line 06GA-M6, it is sub-vertical and part of an upward-diverging network of faults that bears more similarity to positive flower structures developed during strike-slip faulting (Fig. 13c). This same sub-vertical fault zone is also evident along strike to the north in line 06GA-M5 where it similarly serves as the western limits of an inverted eastward-deepening half-graben of Leichhardt age (Fig. 15a). Inverted extensional faults in this half-graben are west-dipping and terminate against the Cloncurry Fault Zone in both seismic lines. No less importantly, folds and thrust faults on either side of the fault zone have opposing asymmetries; east or northeast-verging structures predominate in the Soldiers Cap Group and the underlying Staveley or Doherty Formations (Fig. 15a) whereas structures in the Marimo–Staveley Belt farther west are overwhelmingly west-verging (Fig. 13a). This pattern of reactivated extensional structures with opposing dips is not dissimilar to that observed on either side of the Termite Range Fault (Fig. 10), suggesting that much the same deformational processes have been at work and that this part of the eastern succession is similarly underlain by an extensionally collapsed crestal structure that has been subsequently inverted. The Cloncurry Fault Zone overprints this earlier inverted basinal geometry and divides the one basin into two structurally distinct parts. It is clearly an important structural boundary and may even have influenced the location of the original crestal structure although it is difficult to determine from the seismic data alone whether juxtaposition of these two structural domains is original and unambiguously dates from the time of basin inversion or was imposed subsequently during an entirely separate tectonic event (see also Austin and Blenkinsop, 2008). A late-stage origin is consistent with the observation that the Cloncurry Fault Zone shares the same steep to subvertical attitude as brittle D4 faults (e.g. Trepell Fault Zone) cutting through the mine sequence at Cannington (Bodon, 1998) although this is unlikely to provide more than a minimum age for its inception because elsewhere along its trace, the D4 structures overprint an earlier mylonitic fabric of D3 or older age (Austin and Blenkinsop, 2008). As with so many other structures in the Mount Isa region, the Cloncurry Fault Zone is a reactivated structure whose history and relationship to Pb–Zn mineralisation have been masked by later deformational events. Notwithstanding such uncertainties, a sharp drop in gravity values across this fault zone in line 06GA-M6 is consistent with late brecciation, hydrothermal alteration and concomitant reduction in rock density (Fig. 12b).

East of CDP 13200 along line 06GA-M5, basin polarity in rocks of Leichhardt age abruptly switches and inverted extensional faults resume their dominant eastward dip (Fig. 15a). These faults cut down to lower crustal depths where they merge into a single detachment surface that underlies the central part of the section. Coincidently, this part of the section shows a doubling of thickness in the overlying Calvert Superbasin, including more than 6 km in rocks of the Soldiers Cap Group. Rocks of this group dominate the upper part of the seismic section but despite the marked increase in thickness, inverted extensional faults are conspicuously absent from this unit. Instead, the most obvious structure is the west-verging Cloncurry Overthrust which not only disrupts stratigraphy but is associated with a thickening of sedimentary units making up the lowermost part of Soldiers Cap Group (Fig. 15a). Either this thickening is entirely due to crustal shortening or the Cloncurry Overthrust is superimposed on extensional faults reactivated in the opposite sense during thrusting. Conversely, the underlying Staveley or Doherty Formation shows little or no variation in thickness, except where repeated by thrust faults (Fig. 15a). A post-rift age is therefore assumed for these two units whereas most, if not all, of the overlying Soldiers Cap Group more likely has a syn-rift origin, as with its Kuridala Group correlatives west of the Cloncurry Fault Zone (Fig. 13c). During subsequent basin inversion, Soldiers Cap Group along with the underlying Staveley and Doherty formations were asymmetrically folded at the kilometre-scale and locally thrust westwards over older rocks of the Leichhardt Superbasin. Folding and the emplacement of one sub-basin over another is most spectacularly developed in the Cloncurry Overthrust where crustal shortening was accommodated on several shortcut thrusts developed at the leading edge of the overriding half-graben.

4.6. Crustal thickness and Moho

Although 20 s TWT seismic data were collected along all seven survey lines described in this paper, only four sections down to the Moho are included here (Figs. 8, 11, 13, 14, 15). Together, they make up nearly a complete west–east transect through the Mount Isa region and show that the Moho, while not easily identified in all sections, varies in depth from 40 to 51 km (14–17 s TWT) and is far from flat. Rather, it may have up to 8 km of topographic relief in any one section (e.g. 06GA-M5; Fig. 15). Moreover, some of this relief appears to be linked to changes in thickness in the overlying basins, indicating that it may be an original feature inherited from continental rifting. Why the Moho is not more conspicuously defined is not known although it may be related to basaltic intrusion at depth so that there is no significant difference in density or acoustic properties between mantle and lower crustal rocks.

5. Discussion

Despite having been metamorphosed and deformed during the Isan Orogeny, basin architecture in the Mount Isa region is still largely preserved as evidenced by the seismic data presented here. This is no less true of the most intensely deformed rocks making up the eastern succession where basin inversion was widely accompanied by folding and thrusting (e.g. line 06GA-M6) as it is on the Lawn Hill Platform where basin inversion is more limited and was more often accommodated on footwall shortcut thrusts than through the reactivation of pre-existing extensional faults (06GA-M1). Most of these faults dip uniformly east or northeast, and evidence in support of major strike-slip faulting or the development of pull-apart basins (Feltrin et al., 2009; Southgate et al., 2000b) is conspicuously absent. Nor is there any compelling evidence in the seismic data to support suggestions (e.g. Beardsmore et al., 1988) that the Soldiers Cap Group is allochthonous. Rather, this turbidite-dominated unit and its correlatives in the Kuridala Group were deposited in half-graben off the continental shelf and represent a more outboard part of the same superbasin as rocks farther west. They have undergone only limited amounts of displacement from their original site of deposition and there is no need to appeal to large-scale crustal displacements or nappe-like structures in the eastern succession to explain their presence.

Similarly missing from the seismic profiles is any compelling evidence for the slab of west-dipping basaltic material thought to have been tectonically emplaced into the middle crust from deeper levels during east-directed crustal stacking (Drummond et al., 1998; MacCready et al., 1998, 2006). Rather, the west-dipping, high velocity mid-crustal layer in question equates here with mafic volcanic rocks forming the more deeply buried parts of westward-thickening half-graben, best developed along lines 06GA-M6 and 94MTI-01 and supported by gravity modelling (Fig. 12). Moreover, any master detachment fault at the base of these sequences dips east instead of west as exemplified by line 06GA-M5. Indeed, as interpreted here, there is no reason to suppose that any of the rocks imaged along seismic line 06GA-M5 represent anything more than the more outboard component of a rifted continental margin sequence (Gibson et al., 2012). The weight of evidence supports crustal thinning rather than thickening. Equally significantly, the seismic data give no indication that the Soldiers Cap Group and its associated deep water turbidite sequences terminate or thin eastwards. Rather, these rocks appear to continue uninterrupted beneath rocks of the Eromanga Basin, obviating the need for any crustal boundary or suture along the eastern margin of the Mount Isa region (c.f. Korsch et al., 2012).

Basin analysis, combined with sequence stratigraphy (Southgate et al., 2013), reinforce the idea of a progression from intracontinental rifting through to formation of a rifted continental margin. It seems equally probable from the seismic data that the current subdivision of Mount Isa rocks into two dominantly rift-related superbasins

(Leichhardt and Calvert superbasins) followed by thermal sag (Isa Superbasin) is oversimplified. Instead, the same cycle of syn-rift faulting and half-graben development followed by deposition of post-rift sediments is common to all three basins. For the Leichhardt Superbasin, syn- and post-rift fractions have long been recognised with quartzites and carbonate rocks of the Quilalar and Corella formations comprising the latter (Blake, 1987; Jackson et al., 2000). In contrast, no equivalent post-rift sequence has previously been identified in the Calvert Superbasin even though the unconformity and marine transgression at the base of the Gun Supersequence represents a regionally important boundary and overall deepening of the sedimentary environment (Southgate et al., 2000a). Instead, this boundary was taken as the base of the overlying Isa Superbasin, and the Gun Supersequence interpreted as a renewal in rifting brought about by the onset of strike-slip faulting (Southgate et al., 2000b). Based on the seismic data, the Gun and succeeding Loretta supersequences have been reinterpreted here as part of the Calvert Superbasin (Fig. 2) and attributed to thermal sag, a possibility first alluded to by Southgate et al. (2000b) but thought unlikely given their preference for a depositional environment dominated by strike-slip faulting.

Conversely, very little of the Isa Superbasin owes its origin to thermal sag. Both the River and lower Term supersequences are characterised by abrupt changes in thickness across former extensional faults (Bradshaw et al., 2000; Krassay et al., 2000a) consistent with deposition during rifting whereas at least two of the three younger supersequences (Lawn, Wide and Doom) were all deposited during basin inversion, and thicken away from the anticlinal folds cored by older parts of the Isa Superbasin (Figs. 9 & 10). For the River and Term supersequences, differences in sedimentary thickness both orthogonal and parallel to the main basin-forming faults are substantial and commonly exceed 1 km. Basins hosting the River and lower Term supersequences still preserve their half-graben geometry (Figs. 9 & 10) and mark a return to tectonic instability and coarse siliciclastic sedimentation following an extended period of platform carbonate deposition represented by the Gun and Loretta supersequences that commenced soon after 1670 Ma and concluded no later than 1640 Ma (Southgate et al., 2000a). During deposition of these two units, crustal extension was temporarily arrested and the tectonic environment bore more similarity to a passive or rifted continental margin (Gibson et al., 2008, 2012; Southgate et al., 2013). Development of a hairpin bend in the polar wander path for northern Australia at around 1640 Ma (Idnurm, 2000) further indicates that the return to siliciclastic sedimentation in the River and Term supersequences was probably tectonically driven, and induced by a change in the external stress field or plate tectonic regime (Gibson et al., 2008; Huston et al., 2006; Southgate et al., 2000a). Accretion of the Warumpi terrane against the southern margin of the North Australian Craton at ca. 1640 Ma, following an extended period of plate convergence and back-arc subsidence, has been proposed as the most likely cause of this change (Betts and Giles, 2006; Betts et al., 2006; Giles et al., 2002; Scott et al., 2000; Scrimgeour et al., 2005) although it is not unknown for rifted continental margins to undergo episodes of basin inversion and uplift long after thermal subsidence and seafloor spreading have commenced (Holford et al., 2014). Significantly, a comparable passive margin setting has been proposed for the Paleozoic Selwyn Basin of western Canada (Goodfellow et al., 1993) which, though younger, is similarly well endowed in sediment-hosted, SEDEX-style Pb–Zn deposits (e.g. Howards Pass) and thus serves as a good analogue for the Paleo- to early Mesoproterozoic sedimentary basins of northern Australia (Large et al., 2005; Leach et al., 2005). Moreover, as with the bulk of sediment-hosted mineralisation in the Mount Isa region, SEDEX-style Pb–Zn mineral deposits in the Selwyn Basin are concentrated towards the stratigraphic top of the basin in carbonaceous shales and siltstones, which came to dominate the sedimentary environment once open marine conditions had become established. This would suggest a common origin and geodynamic setting for sediment-hosted Pb–Zn mineralisation in both northern Australia and the Selwyn Basin, raising questions about the extent to which syn-extensional as opposed to post-rift processes were responsible for fluid flow and ore formation. More specifically, while there is every indication that mineralisation is linked to periods of profound tectonic change, it is equally clear that the majority of deposits post-date active rifting, and are hosted by the post-rift component of their respective sedimentary basins. This would suggest that basin inversion played a far more important role in ore formation than has previously been supposed. Moreover, in the case of the Mount Isa region, this happened more than once as evidenced by the concentration of mineralisation at the top of both the Calvert and Isa superbasins.

5.1. Case for mineralisation during basin inversion

Based on the seismic data presented here, both the Lawn and Wide supersequences (Lawn Hill Formation) were deposited during basin inversion and thus during the initial stages of the Isan Orogeny. In keeping with this interpretation, folds and thrusts associated with inversion are dominantly west-vergent (Figs. 9 & 10) and thus share the same sense of tectonic transport as structures of Isan age farther east in Soldiers Cap Group and its correlatives (Figs. 13 & 15). They also share the same dominant northerly (D2) trend. It is equally evident from the ca. 1620 Ma and 1595 Ma maximum depositional ages (Fig. 2) of the Lawn and Wide Supersequence (Page et al., 2000; Page and Sweet, 1998) that basin inversion and orogenesis were under way much earlier than previously supposed and long before formation of the Century deposit at 1575 Ma (Carr et al., 2004). A 1610 Ma or younger age is generally accepted for onset of the Isan Orogeny with metamorphism peaking between 1600 and 1570 Ma (Giles and Nutman, 2002; Rubenach et al., 2008). This would imply that mineralisation at Century, deposition of its host rocks (Wide Supersequence) and basin inversion are all different manifestations of the Isan Orogeny as previously surmised (Andrews, 1998; Broadbent et al., 1998; Hobbs et al., 2000; Zhang et al., 2006). This is consistent with other suggestions that deposition of the uppermost part of the Isa Superbasin occurred during a period of reverse displacement on the Termite Range Fault (Andrews, 1998; Broadbent et al., 1998; Krassay et al., 2000b). Although long thought to be the principal fluid conduit for mineralisation at Century (Broadbent et al., 1998; Hobbs et al., 2000; Ord et al., 2002), the Termite Range Fault lies directly beneath the mine site and is interpreted here to be a footwall shortcut thrust rather than a strike-slip (Feltrin et al., 2009) or reactivated normal fault. It is therefore unlikely to be a long-lived structure as previously supposed (Betts, 1999; Hobbs et al., 2000) but a much younger feature that formed during crustal shortening owing to “lock-up” on the more steeply-dipping and less favourably oriented pre-existing extensional faults. A component of strike-slip displacement at this stage cannot be completely discounted although this is considered here to be neither necessary nor sufficient to explain most aspects of fault and basin geometry in the seismic profiles.

Partitioning of strain into footwall shortcut thrusts during basin inversion is even more obvious west of the Termite Range Fault, indicating that this process is more widely developed across the region and may have profoundly influenced fluid flow through the creation of new fluid pathways and the disruption of existing fault networks. Equally importantly, most of these shortcut thrusts are no less deeply penetrating than their neighbouring reactivated extensional faults, invariably rooting down into them at depth (Figs. 9 & 10) and thereby increasing the density and connectivity of the fault network. Further focussing fluid flow was the imposition of a dynamically-induced permeability accompanying cleavage and shear fabric development along fault surfaces and the limbs of tightly asymmetric or overturned folds in the footwalls of these same faults. Numerical models coupling fluid flow to deformation have already demonstrated that fault networks are important in promoting a strong upward fluid flux during basin inversion but have generally assumed that the fluid pathways were predominantly reactivated extensional faults (Zhang et al., 2006). Particularly effective in promoting fluid flow in these models was the increase in porosity and permeability wrought by hydrofracturing (Zhang et al., 2006) which, in many respects, is not too dissimilar to the situation described here where basin inversion was accompanied by the formation of new structures and fluid pathways, as well as the reactivation of pre-existing ones. Petrographic studies (Polito et al., 2006b) have further demonstrated that the chemical breakdown and dissolution of common clastic minerals during diagenesis results in increased porosity and permeability while at the same time releasing metals into the basinal fluids (e.g. Pb from feldspar). Moreover, these processes are more effective following deep, rather than shallow, burial as would have been the case at Century during and subsequent to basin inversion as its host rocks continued to be buried during deposition of younger sediments of the Wide and Doom supersequences.

Conversely, given that the Lawn and Wide supersequences were both deposited under marine conditions, there is no reason to suppose that thrusting and basin inversion were ever accompanied by subaerial exposure and erosion. Rather, basin inversion and fluid expulsion at this stage were entirely submarine, consistent with a syn-sedimentary to early diagenetic origin for mineralisation at, or close to, the seafloor. Importantly, mineralisation is not only tectonically driven but dynamically linked to the growth of hangingwall anticlinal structures which provided both a future source of sediment and a topographic head to further drive fluid flow. In this respect, mineralisation at the Century deposit exhibits characteristics of both Mississippi- and SEDEX-style deposits, as has been previously observed (Broadbent et al., 1998; Hobbs et al., 2000), and there is no compelling reason for it to be assigned to one category or the other. Moreover, unless there was a change from open marine to non-marine conditions during or subsequent to deposition of the Doom Supersequence, any fluids involved in mineralisation are likely to have been entirely intra-basinal and comprise a mixture of recycled seawater and brine released from deeper structural levels during inversion, particularly where thrust faulting was accompanied by breaching of regional seals. Significantly, Century is located in an area where the intensity of folding and thrusting is not only high, but there is greater fault connectivity between the near-surface host rocks and deeper parts of the underlying sedimentary basins from whence metals may have been sourced. Antithetic thrust faults with opposing north- to northwest dips developed beneath Ploughed Mountain and Mount Caroline (Fig. 6) just east of seismic section 06GA-M1 (Fig. 10) are similarly deeply tapping, but either do not extend upward into the Lawn, let alone Wide, Supersequence or sample a more limited range of potential source rocks, including a greatly thinned Calvert Superbasin, and little to no Leichhardt Superbasin (Fig. 9).

Carbonates and carbonaceous rocks of equivalent age to the host rocks at Century are virtually unknown in the eastern succession, except for a small part of the Tommy Creek Block, north of the Mitakoodi Culmination (Fig. 4). No major Pb–Zn mineral deposit has yet been identified in the Tommy Creek Block although it is host to 1610–1620 Ma rhyolitic lava flows and volcaniclastic rocks (Page and Sun, 1998; Carson et al., 2011), indicating that by the time the Lawn Supersequence was being deposited, this crustal block may already have been emergent and could have supplied some, if not all, of the silicic volcanic detritus observed (Andrews, 1998; Hutton and Sweet, 1982) in tuffaceous sandstones at the base of this supersequence (Balmung Sandstone; Krassay et al., 2000b). Notwithstanding the dearth of rocks younger than 1610 Ma, parts of the eastern succession were nevertheless extensively mineralised during the Isan Orogeny and thus during the same event that led to crustal shortening and basin inversion on the Lawn Hill Platform. Iron-oxide–copper–gold deposits dated at 1594 $\pm$ 8 Ma and 1568 $\pm$ 7 Ma along the Starra Shear Zone and Selwyn-Mount Dore corridor (Duncan et al., 2011) are an important case in point. Other deposits hosted by this structural corridor include the Pegmont and Osborne Cu deposits (Fig. 13c), both of which are extensively underlain by inverted half-graben in which metabasaltic rocks (Marraba Volcanics) are the most likely source of metal. Much the same timing and relationship to deformation accompanying the Isan orogeny have been proposed for the Cu lodes at Mount Isa and George Fisher in the Leichhardt River Fault Trough (Perkins, 1997) although this interpretation is by no means universally accepted with other researchers favouring a syn-extensional or syn-genetic origin for both the Cu and spatially-related Pb–Zn mineralisation (McGoldrick and Keays, 1989; Oliver et al., 2006). Differences in mineralisation aside, fluid flow in the Selwyn-Mount Dore structural corridor was accompanied by widespread sodic–calcic alteration (Duncan et al., 2011), and given its age relative to basin formation in its host rocks, is unlikely to be the result of either syn-extensional or syngenetic processes. Rather, a syn-deformational, syn-inversion model for mineralisation and related fluid flow may apply more widely. If this is indeed the case, then it raises a number of important questions, not least of which is the extent to which other regionally extensive alteration events in the Mount Isa region may be similarly attributed to basin inversion. These include potassic alteration at 1640 Ma and for which there are confirmed links to Pb–Zn mineralisation elsewhere in northern Australia (e.g. McArthur River) (Cooke et al., 1998; Huston et al., 2006).

5.2. Case for basin inversion at 1640 Ma

Potassic alteration, resulting in the formation of orthoclase–quartz $\pm$ sericite $\pm$ hematite $\pm$ dolomite $\pm$ anatase $\pm$ barite or chlorite–orthoclase–quartz mineral assemblages, is best documented for 1730–1725 Ma mafic rocks to the north of Mount Isa in the Tawallah Group of the McArthur Basin (Cooke et al., 1998), a temporal equivalent of the Calvert and Leichhardt superbasins. Based on paleomagnetic data, potassic alteration in this basin is reported to have occurred at 1640 Ma and thus synchronously with Pb–Zn mineralisation at McArthur River (Cooke et al., 1998). It is equally clear from the hairpin bend at 1640 Ma in the polar wander path for northern Australia (Idnurm, 2000) that this alteration did not occur in isolation but was linked to tectonic events affecting the whole of northern Australia and extending southwards into the Mount Isa region. The most obvious legacy of this event in both the rock record and seismic data is the major unconformity (onlap surface) developed at the base of the Term Supersequence (Fig. 10c), coupled with a return to coarse siliciclastic sedimentation at the base of the underlying River Supersequence (Shady Bore Quartzite). This would seem to indicate an interval of uplift and erosion accompanying or immediately following the cessation of carbonate deposition in the underlying Gun and Loretta supersequences at around 1640 Ma or shortly after. An increase in tectonic instability around this time has been proposed before and variously attributed to an episode of north–south-directed (D1) folding and thrusting (Betts, 1999; Betts et al., 2006; Gibson et al., 2008) or strike-slip faulting (Southgate et al., 2000b) linked to plate convergence and terrane accretion along the southern margin of the north Australian Craton (Betts and Giles, 2006; Betts et al., 2002; Giles et al., 2002; Scott et al., 2000; Scrimgeour et al., 2005). Moreover, in common with McArthur River, there is no reason to suppose that these same tectonic events were not a driver for fluid flow in the Mount Isa region. Orthoclase $\pm$ quartz $\pm$ hematite $\pm$ carbonate veining similar to that observed at McArthur River occurs widely throughout rocks of the Leichhardt and Calvert superbasins along the Leichhardt River Fault Trough (Gibson et al., 2005), and is commonly observed lying along the D1 cleavage (Fig. 3e), indicating that it is no older than the potassic alteration observed at McArthur River and may even be the same age. Significantly, this veining is particularly well developed towards the top of the Leichhardt Superbasin where it is hosted by redbeds (Lochness Formation) containing a high proportion of feldspar from which at least some of the potassium may have been sourced. Conversely, no such veining appears to have developed in rocks of the Leichhardt River Fault Trough younger than 1640 Ma (Isa Superbasin) or along the later Isan D2 cleavage even where the D1 and D2 fabrics occur together and the older cleavage is overprinted by the younger one. Thus, unless there were two quite separate and unconnected episodes of fluid flow at around the same time, it is difficult to avoid the conclusion that the veining developed at McArthur River and farther south in the Leichhardt River Fault Trough are geodynamically linked and a manifestation of the same hydrothermal event, further emphasising that the period around 1640 Ma was a time of fundamental tectonic change, involving not only a reorganisation of the external plate forces but regional-scale fluid pumping and migration. By the same token, few mineral deposits are hosted by the immediately overlying River and Term sequences, despite a return to widespread rifting and syn-sedimentary normal faulting.

Although rocks hosting the Mount Isa/George Fisher and Lady Loretta Pb–Zn deposits were similarly deformed during the D1 event, the case for mineralisation during basin inversion is more tenuous and complicated by arguments over the age of the overprinting Cu lodes in the former as already stated. More specifically, some researchers have argued that all mineralisation in the Mount Isa deposits is the result of syn-deformational replacement processes accompanying the Isan Orogeny (Perkins, 1997, 1998) whereas others have proposed that Pb–Zn mineralisation occurred much earlier and most likely during or immediately following deposition of the host rocks (Oliver et al., 2006). Lending strong support to this second interpretation are sulphide Pb model ages (Carr et al., 2004) strikingly similar to maximum depositional U/Pb ages obtained from detrital zircon in tuffaceous interbeds (Page et al., 2000). Mineralisation at the Mount Isa/George Fisher deposit is consequently estimated to have occurred between 1655 Ma and 1650 Ma, and thus much too early for basin inversion at 1640 Ma or later deformation linked to the Isan Orogeny. This same conclusion also applies to the Lady Loretta deposit whose mineralisation and host rocks are thought to be only marginally younger at ca. 1647 Ma (Carr et al., 2004; Page et al., 2000). A syn-extensional origin might therefore appear more compatible with the age data were it not for the fact that all three Pb–Zn mineral deposits are hosted by the Gun Supersequence which, from the seismic data presented here, is interpreted to form part of the Calvert post-rift package and mark the onset of thermal subsidence and passive margin conditions. The alternative is to argue that crustal shortening commenced before 1640 Ma and was already well advanced before the close of sedimentation in the Gun or immediately overlying Loretta Supersequence. A late syn-sedimentary to syn-inversion (syn-deformational) age for Pb–Zn mineralisation is therefore not precluded. In support of this interpretation, it is worth noting that the Gun Supersequence is completely missing from the seismic section beneath Mt Caroline (Fig. 9c). Instead, its place has been taken by the River Supersequence which not only onlaps directly onto the underlying Prize Supersequence but appears to have been deposited during or subsequent to the folding developed at deeper levels in the Calvert Superbasin. Moreover, this folding is not completely replicated at higher stratigraphic levels in the Term Supersequence (Fig. 9; inset), indicating that this phase of crustal shortening occurred early and predates deposition of the latter. Although its age is not well constrained, detrital zircons from the Term Supersequence indicate a maximum depositional age of ca. 1630–1635 Ma (Page et al., 2000) requiring any such crustal shortening to be no younger than this and a possible manifestation of the same 1640 Ma D1 deformational event identified elsewhere in the Mount Isa region.

Unlike most other Pb–Zn mineral deposits in the Isa region, mineralisation at Cannington is both older (Pb model age ca. 1665 Ma; Carr et al., 2004) and of the Broken Hill- rather than SEDEX-type (Huston et al., 2006). It lies within the same fold and thrust belt as the Osborne and Pegmont Cu deposits and is only marginally younger than the Prize Supersequence or 1670 Ma Sybella granites emplaced towards the end of rifting in the Calvert Superbasin (Fig. 2). A late rift to early post-rift age is therefore assumed with fluid flow facilitated by the location of Cannington between two opposing sets of reactivated normal faults which, together, originally formed a zone of (crestal) extensional collapse in which fracture density and rock permeability might be expected to have been high during and subsequent to basin formation. Residual heat and an elevated geotherm possibly helped drive fluid flow consistent with the observation that this deposit is hosted by Soldiers Cap Group rocks formed around the time that crustal extension in the Calvert Superbasin was at its peak and basaltic magmatism had not yet ceased. A sub-vertical fault zone of probable strike-slip origin (Cloncurry Fault Zone) disrupts these rocks in the vicinity of the mine but likely post-dates both mineralisation and deposition of its host rocks. A sharp drop in gravity values across the fault zone (Fig. 12b) is interpreted to be due to a decrease in rock density following late-stage brecciation and/or hydrothermal activity. Such late brecciation has been observed in surface exposures of the fault zone (Austin and Blenkinsop, 2008) while late-stage dextral strike-slip faulting has been recorded in the mine (Bodon, 1998; Walters and Bailey, 1998).

6. Conclusions

In common with their Paleozoic analogues in western Canada (e.g. Howards Pass) and Alaska (Red Dog), world class sediment-hosted mineral deposits in the Calvert and Isa superbasins of northern Australia formed in a rifted or passive continental margin setting. Moreover, contrary to most existing models for ore genesis in these SEDEX-style mineral deposits, mineralisation is rarely, if ever, hosted by the syn-rift basinal sequences, occurring instead towards the top of their respective sedimentary basins, in either the post-rift or syn-inversion fraction. These fractions contain a higher proportion of carbonaceous rocks compared to the underlying syn-rift sequences and served as an impermeable seal or chemical trap during fluid flow that was largely tectonically driven and accompanied by basin inversion. Existing models favouring mineralisation in an intracontinental rift setting have placed undue emphasis on crustal extension to generate not only a network of faults active at the time of basin formation to facilitate and focus fluid flow (Hobbs et al., 2000; Ord et al., 2002) but higher levels of heat flow and magmatic activity to provide both a potential source of metals and the energy to drive the mineralising system (Hobbs et al., 2000; Huston et al., 2006; Large et al., 2005; Leach et al., 2010). These requirements were mainly met during formation of the underlying older Leichhardt Superbasin and earlier stages of the Calvert Superbasin and lasted until no later than 1655 Ma by which time rifting was coming to a close and passive margin conditions prevailed across the entire Mount Isa region. Following an episode of crustal shortening around 1640 Ma, rifting resumed until terminated at ca. 1620 Ma by onset of the Isan Orogeny leading to basin inversion and widespread reactivation of the underlying rift template and its network of extensional faults. Sedimentary sequences deposited during basin inversion include the host rocks to the 1575 Ma Century Pb–Zn deposit which not only formed subsequent to the onset of basin inversion but before the Isan Orogeny had concluded. No less importantly, basin inversion during this event was initially entirely submarine consistent with a syn-sedimentary to early diagenetic origin for mineralisation at, or close to, the seafloor.

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Appendix 1. Gravity modelling

Two dimensional gravity modelling was conducted on several interpreted seismic sections in order to test the validity of the proposed basin geometry and crustal architecture (Figs. 8–12). Bouguer gravity grids were downloaded from Geoscience Australia's Geophysical Archive Date Delivery System (GADDS) and imported into the modelling software (ModelVision). Gravity profiles were extracted from the gridded data along the seismic lines. Images of the seismic interpretations were imported into the software and co-located with the gravity profiles. A velocity of 6000 m/s was used to convert the two-way time (TWT) of the vertical axes of the interpreted seismic sections to depth. Polygonal bodies of the interpreted stratigraphy were generated and assigned density values based on mean rock property data for individual stratigraphic units (Table 1). Rock property data (Meixner, 2008) were compiled from several sources (Hone et al., 1987; Meixner and Chopping, 2009) and supplemented by measurements made on samples collected along deep seismic lines 06GA-M1, 06GA-M2 and 06GA-M6 (Langbein and Blenkinsop, 2009). Densities for stratigraphic units that were not sampled for rock property data were assigned the same densities for sampled stratigraphic units with similar lithologies. A regional field was applied to lines 06GA-M1, 06GA-M3 and 94MTI-01, and calculated using a polynomial of degree 1. This regional gravity tilt, across the three lines, is assumed to be from density variations that are off-line, or at a depth beyond the limits of the seismic interpretation. Minor adjustments were made to the polygon densities to improve the fit between the calculated and observed gravity data.

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