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Solid Earth Discussions

Basin inversion and structural architecture as constraints on fluid flow and Pb-Zn mineralisation in the Paleo-Mesoproterozoic sedimentary sequences of northern Australia

George M. Gibson, Research School of Earth Sciences, Australian National University, Canberra ACT 2601, Australia

Sally Edwards, Geological Survey of Queensland, Department of Natural Resources, Mines and Energy, Brisbane, Queensland 4000, Australia

Abstract

As host to several world-class sediment-hosted Pb-Zn deposits and unknown quantities of conventional and unconventional gas, the variably inverted 1730-1640 Ma Calvert and 1640-1580 Ma Isa superbasins of northern Australia have been the subject of numerous seismic reflection studies with a view to better understanding basin architecture and fluid migration pathways. Strikingly similar structural architecture has been reported from much younger inverted sedimentary basins considered prospective for oil and gas elsewhere in the world. Such similarities suggest that the mineral and petroleum systems in Paleo-Mesoproterozoic northern Australia may have spatially and temporally overlapped consistent with the observation that basinal sequences hosting Pb-Zn mineralisation in northern Australia are bituminous or abnormally enriched in hydrocarbons. This points to the possibility of a common tectonic driver and shared fluid pathways. Sediment-hosted Pb-Zn mineralisation coeval with basin inversion first occurred during the 1650-1640 Ma Riversleigh Tectonic Event towards the close of the Calvert Superbasin with further pulses accompanying the 1620-1580 Ma Isa Orogeny which brought about closure of the Isa Superbasin. Mineralisation in all cases is hosted by the syn-inversion fraction of basin fill, contrary to most existing interpretations of Pb-Zn ore genesis where the ore-forming fluids are introduced during the rifting or syn-extensional phase of basin development. Syn-extensional normal faults of Calvert and Isa age are mutually orthogonal, giving rise to a complex compartmentalisation of sub-basins with predominantly NNW and ENE strikes. Basin inversion subsequent to 1640 Ma occurred in a transpressive tectonic regime linked to continent-continent collision accompanied by orogen-parallel extensional collapse and right-stepping strike-slip faulting.

Introduction

Northern Australia and its late Paleoproterozoic-early Mesoproterozoic basinal sequences have long attracted the interest of the minerals and petroleum exploration industries. Besides being the world's single largest repository of sediment-hosted Pb-Zn mineral deposits (Huston et al., 2006; Southgate et al., 2006), these same mineral-rich sequences hold some of the planet's oldest oil (Jackson et al., 1986) along with an unknown quantity of conventional and unconventional gas (Carr et al., 2019; Gorton and Troup, 2018; McConachie et al., 1993). Unsurprisingly, many mineral deposits and their host rocks are bituminous or contain very high proportions of carbon (Andrews, 1998; Broadbent et al., 1998; Hutton and Sweet, 1982; Jarrett et al., 2018; McConachie et al., 1993; McGoldrick et al., 2010), raising the possibility that the petroleum and mineralising systems in northern Australia may have temporally and spatially overlapped and share a common tectonic driver. Such a possibility was first entertained for the 1575 Ma Century Pb-Zn deposit (Fig. 1a) where first hydrocarbons and then a more metalliferous ore-forming fluid are thought to have been sequentially trapped following their expulsion from deeper stratigraphic levels during folding and thrusting accompanying the 1620-1575 Ma Isan Orogeny (Broadbent et al., 1998). In this scenario,

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a small point, but and age range should have an 'en dashes' between the numbers, not a hyphen

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If you are not going to quote the error as well you should put a 'ca.' in front of the age

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basin inversion was not only intimately linked to fluid migration and mineralisation but played a key role in generating the structural architecture that brought the petroleum and mineralising systems together in one place. Seismic reflection images for the Lawn Hill Platform have since shown the Century deposit to be hosted by the syn-inversion fraction of basin fill (Gibson et al., 2017; Gibson et al., 2016) and occur in rocks possessing a structural architecture common to inverted basins the world over, including those currently under exploration for oil and gas in the Irish and North seas and north European continental shelf more generally (Cooper et al., 1984; Hayward and Graham, 1989; Lowell, 1995; Thomas and Coward, 1995; Turner and Williams, 2004). Thus, not only does basin inversion appear to have been a prerequisite for ore formation at Century but the structural architecture cannot have appreciably changed during the transition from a hydrocarbon to mineral system lest the similarities with their more modern European counterparts have been lost during crustal shortening. Such conclusions are difficult to reconcile with most existing models for sediment-hosted Pb-Zn mineralisation in northern Australia where ore formation is interpreted to have been syn-extensional and facilitated by fluid migration along normal faults active at the time of basin formation (Huston et al., 2006; Kunzmann et al., 2019; Large et al., 2005; Leach et al., 2010; McGoldrick et al., 2010). Alternative exploration strategies for this and other types of sediment-hosted Pb-Zn mineralisation in northern Australia may therefore be warranted that better reflect the similarities with the petroleum system and target the structures formed during basin inversion. Here, we make use of publically available industry and government deep seismic reflection data to show that inversion-related structures of more than one generation and style are widely developed in the late Paleoproterozoic-early Mesoproterozoic basin sequences of northern Australia (Figs. 1 & 2), reflecting successive episodes of crustal shortening during the course of which the majority of Pb-Zn deposits were emplaced (Gibson et al., 2017).

Regional geology and basin-forming events of northern Australia

Northern Australia's late Paleoproterozoic-early Mesoproterozoic basinal sequences belong to one of three superbasins (Figs. 2 & 3) which, together with the overlying and younger South Nicholson Basin (Fig. 1a), preserve a 300 Myr history of lithospheric extension interrupted by successive episodes of basin inversion, uplift and erosion (Betts et al., 2006; Blake, 1987; Gibson et al., 2012; Giles et al., 2002; Jackson et al., 2000; O'Dea et al., 1997b; Southgate et al., 2000a; Withnall and Hutton, 2013). The oldest basin inversion event (Fig. 3) occurred subsequent to 1840 Ma and is best expressed by the angular unconformity separating the 6-8 km thick 1790-1740 Ma Leichhardt Superbasin (Fig. 2) from an older underlying ≥ 1870 Ma crystalline basement (Kalkadoon-Leichhardt Block; Fig. 2) variably intruded by foliated 1860-1840 Ma granites (Blake, 1987; Withnall and Hutton, 2013). Clasts of strongly foliated granite and other basement rocks occur widely in conglomerates at the base of the Leichhardt Superbasin (1790 Ma Bottletree Formation) but otherwise its basin fill is only mildly deformed and metamorphosed, and mainly comprises continental tholeiites and rhyolite interstratified with subordinate but still substantial volumes of fluviatile-shallow marine sedimentary rocks. This same cover-basement relationship is also evident on the Murphy Ridge farther north where conglomerates (Westmoreland Conglomerate) at the base of the 1790-1740 Ma Tawallah Group (Fig. 3) in the McArthur Basin (Fig. 1b) similarly rest unconformably on an older deformed basement intruded by 1860-1840 Ma granites (Withnall and Hutton, 2013). As with the Kalkadoon-Leichhardt Block, basement granites on the Murphy Ridge were deformed long before the overlying conglomerate was deposited and likely represent exposed fragments of a much more regionally extensive magmatic belt that is continuous at depth and once lay at or close to the eastern margin of the North Australian Craton. Granites with calc-alkaline compositions occur widely throughout the Kalkadoon-Leichhardt Block (Bierlein et al., 2011) and may originally have formed part of a continental magmatic arc linked to west-dipping subduction beneath the eastern margin of the craton (Bierlein et al., 2008; Korsch et al., 2012). Alternatively, these granites originated in a backarc setting linked to oceanward retreat of a more

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a bit pedantic, but this would only be the case if the Pb-Zn mineralisation was syn-sedimentary. If it was completely replacement, then the mineralising fluid flow could be much later than the development of the structure.. I think that you just need a sentence about the model for ore deposition to complete the logic here.

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You do need to be more focused here. You are not talking about 'Northern Australia'. You are talking about the Mount Isa Province and possibly/probably the eastern McArthur Basin (the northern McArthur Basin has another basin between the Leihardt and the Calvert that is represented by the Goyder Package). And of course you are not referring to northern Western Australia at all......

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Well, if the South Nicholson Basin includes equivalents of the Upper Roper Group (which is likely), then the age range is ca. 1800-1300 Ma! See Yang et al. 2020 (Basin Research) for age constraints on the youngest part of the Roper Group. - so 500 Myr!

Number: 4 Author: a1130525 Subject: Sticky Note Date: 7/04/2020 2:47:48 PM

Suggest you consider adding:

Yang, B., Collins, A.S., Cox, G.M., Jarrett, A.J.M., Denyszyn, S., Blades, M.L., Farkaš, J., Glorie, S. 2020. Using Mesoproterozoic Sedimentary Geochemistry to Reconstruct Basin Tectonic Geography and Link Organic Carbon Productivity to Nutrient Flux from a Northern Australian Large Igneous Province. *Basin Research*. https://doi-org.proxy.library.adelaide.edu.au/10.1111/bre.12450

and maybe

Yang, B., Smith, T., Collins, A.S., Munson, T., Schoemaker, B., Nicholls, D., Cox, G., Farkas, J, Glorie, S. 2018. Spatial and temporal detrital zircon U-Pb provenance of the hydrocarbon-bearing upper Roper Group, Beetaloo Sub-basin, Northern Territory, Australia. Precambrian Research, 304, 140-155.

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after

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The Tawallah Group continues to at least 1710 Ma based on the age of the Tanumbirini Rhyolite a detrital zircon in the overlying Nyanantu Fm of 1705 ± 4 Ma (Page et al. 2000).

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Well, these are similar in age to the Stafford Event in the Aileron Province and both the Pine Creek Orogen and Halls Creek Orogen.. So these probably represent large scale accretionary and collisional orogenesis involving small nuclei of the North Australian Craton - e.g. Worden et al. 2008

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distal arc built along either the southern or eastern margin of conjoined North and South Australian cratons (Betts et al., 2016; Betts et al., 2008; Giles et al., 2002) or eastern margins (Gibson and Champion, 2019; Gibson et al., 2018; Gibson et al., 2008). Regardless of which interpretation is correct, by 1790 Ma lithospheric extension and thinning were well underway and northern Australia was subjected to widespread intracontinental rifting, normal faulting and half-graben formation accompanied at deeper crustal levels to elevated heat flow, low pressure-high temperature metamorphism and bimodal magmatic intrusion (Betts et al., 2016; Betts et al., 2006; Gibson et al., 2012; Gibson et al., 2008; Giles et al., 2002; Giles et al., 2004; Holcombe et al., 1991; O'Dea et al., 1997a; Pearson et al., 1991). Lithospheric extension during this phase of basin formation produced mainly northwest-oriented normal faults and half-graben and continued through until ca. 1740 Ma when backarc extension and rifting in the Mount Isa region and neighbouring McArthur Basin (Fig. 1a) temporarily ceased and gave way to an episode of thermal subsidence accompanied by the deposition of shallow marine quartzite and carbonate rocks (Gibson et al., 2012; Jackson et al., 2000; O'Dea et al., 1997b) .

The Leichhardt Superbasin concluded in a period of renewed tectonic instability variously attributed to onset of a 1730-1710 Ma orogenic event (Blaikie et al., 2017) or a renewal in fault-block rotation and tilting (Gibson et al., 2012; Gibson et al., 2008). Either way, uplift and erosion accompanying this event resulted in the formation of a deeply incised and regionally extensive angular unconformity above which conglomerates and redbeds of the Bigie Formation were deposited (Fig. 3). Their deposition marks the start of the 1730-1640 Ma Calvert Superbasin (Figs. 2 & 3) and corresponds to a resumption in backarc extension, bimodal magmatism and rift-related sedimentation (Gibson et al., 2016; Jackson et al., 2000; Southgate et al., 2000a). Both NW-SE and NE-SW extensional directions have been proposed for the Calvert Superbasin (Fig. 3) and questions remain about the primary orientation of half-graben hosting the bulk of basin fill. In the McArthur Basin, this includes basaltic rocks of the 1730-1720 Ma Peters Creek Volcanics and Top Rocky Rhyolite (Rawlings et al., 2008) whereas farther afield on the Lawn Hill Platform (Fig. 1a), the Calvert Superbasin hosts basalts of the 1710-1705 Ma Fiery Creek Volcanics (Fig. 3) and fluviatile-shallow marine sediments of the 1700-1690 Ma Surprise Creek Formation (Fiery and Prize Supersequences; Southgate et al., 2000). At about the same time that these rocks were being laid down across the Lawn Hill Platform, water depths began to substantially increase farther east in the Mount Isa region so that by 1690 Ma basaltic magmas were being extruded and/or intruded into a deep marine basin filled with turbidites (Black et al., 1998; Foster and Austin, 2008; Gibson et al., 2018; Gibson et al., 2012; Giles et al., 2002; Glikson et al., 1976; Neumann et al., 2009; Rubenach et al., 2008; Scott et al., 2000; Withnall, 1985). Basaltic magmatism continued through to 1655 Ma in the east by which time the Leichhardt Superbasin and lower parts of the Calvert Superbasin had also been intruded farther west by 1680-1670 Ma A-type granites (Sybella Granite)(Neumann et al., 2009) and partially unroofed on top-to-the-northeast extensional shear zones (Gibson et al., 2008).

With the conclusion of bimodal magmatism at 1655 Ma, the tectonic setting of the Calvert Superbasin transitioned from backarc basin to passive rifted continental margin (Baker et al., 2010; Gibson et al., 2018; Gibson et al., 2012; Neumann et al., 2009) and began to cool and subside, precipitating a marine transgression during the course of which the North Australian Craton was buried beneath a post-rift sequence (Gun Supersequence; Fig. 3) of thin-bedded turbidites, carbonaceous shales, black dolomitic siltstones and carbonate rocks that extended westwards as far as the McArthur Basin (McArthur Group; Fig. 3) and Lawn Hill Platform (Betts et al., 2016; Betts et al., 2006; Gibson et al., 2012; Gibson et al., 2017; Southgate et al., 2013; Withnall and Hutton, 2013).

Passive margin conditions persisted until circa 1650 Ma by which time northern Australia was subjected to a further episode of basin inversion (Fig. 3) that lasted until at least 1640 Ma (Riversleigh Tectonic Event) and brought sedimentation in the Calvert Superbasin to a close (Gibson et al., 2018; Gibson et al., 2017;

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in the Mount Isa Province.

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I'm finding it hard to work out whether you think that there is a continuous depositional sequence here (as sort of implied here and in the Gibson et al 2016 column in Fig3) - or whether you think that there is a major hiatus between ca. 1690-1670 as suggested by the blue vertical lines in Fig 3 (I presume, although the blue lines have no explanation in the figure or caption). As a note, this time period is broadly consistent with the unconformity in the SE McArthur Basin of the NT that has the extensive Masterton sandstone overlying it (you can look at Kunzmann et al. 2020 here) - in the NW McArthur Basin this is represented by the Goyder Package rocks...

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Further west in the Batten Fault Zone, this is the depositional age of the Wollogorang shale and overlying Gold Creek Volcanics.. and younger volcanics overlie them... suggesting that this end of Leichhardt inversion is restricted to the east, in Queensland... with a diachronous unconformity reaching the Batten FZ region by ca. 1705 Ma - and at the Walker FZ there is a continuous sequence (Goyder Package) through to about 1670 Ma (Rawlings 1999).

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And further west (Batten FZ) still this is a time of exposure and erosion from ca. 1705/1700 Ma until ca. 1660 Ma

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This timing disagrees with Fig 3 - there the Gun supersuite is dated from ca. 1670-1655 Ma - not after 1655 Ma!

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The base of the McArthur Group is an extensive sandstone sequence (Masterton Sandstone) that then deepens up into shales and dolostones of the overlying McArthur Group formations - see Kunzmann et al. 2020

Kunzmann, M., Crombez, V., Catuneanu, O., Blaikie, T., Barth, G., Collins, A.S. 2020. High-resolution sequence stratigraphy of the ca. 1730 Ma Wollogorang Formation, McArthur Basin, Australia. *Marine and Petroleum Geology*, 116, 104297. HYPERLINK "https://doi-org.proxy.library.adelaide.edu.au/10.1016/j.marpetgeo.2020.104297"https://doi.org/10.1016/j.marpetgeo.2020.104297

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Again, interesting diffference with the McArthur Basin - here passive margin conditions (or shallow water carbonate dominated conditions at least..) continue until definitely younger than 1640 Ma (Barney Creek formation - with recently dated corollaries as far away as the Birindudu Basin on the NT/WA border - Munson et al. 2019) - But the first siliciclastic formation in the SE McArthur Basin is the Stretton Sandstone with an age of 1625 ± 2 Ma (from a tuff - Page et al. 2000) - suggesting that at least the sedimentological response to this inversion to the west occurred at about 1625 Ma.

T. J. Munson, S. W. Denyszyn, J. M. Simmons & M. Kunzmann (2020) A 1642 Ma age for the Fraynes Formation, Birrindudu Basin, confirms correlation with the economically significant Barney Creek Formation, McArthur Basin, Northern Territory, Australian Journal of Earth Sciences, 67:3, 321-330, DOI: 10.1080/08120099.2020.1669708

Number: 8 Author: a1130525 Subject: Highlight Date: 8/04/2020 9:51:11 AM
Interested at how this is constrained... as mentioned in the point above.. could this be bought forward until 1630-1625 Ma to better fit the McArthur Basin record? I note that there was one detrital zircon in Page et al 2000 that came out at 1623 ± 13 Ma, but was discounted...

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Hinman, 1995; Withnall and Hutton, 2013). Thereafter, the tectonic environment fundamentally changed and crustal extension resumed in a north-south direction (Fig. 3), giving rise to the 1640-1580 Ma Isa Superbasin (Fig. 2) and deposition of a further 6-8 km of sandstone, carbonaceous shales, and dolomitic siltstones (Riversleigh and Term Supersequences) in fault-bounded basins predominantly oriented ENE-WSW (Bradshaw et al., 2000; Bradshaw et al., 2018; Gibson et al., 2020; Gorton and Troup, 2018). Despite the resumption in crustal extension, basaltic rocks are absent and, save for a few tuff beds, there was no corresponding resurgence in felsic magmatism until after the Isa Orogeny had concluded at ca. 1590-1580 Ma, some 50-60 Ma later (Black and McCulloch, 1990; Gibson et al., 2018; Withnall and Hutton, 2013). The absence of any significant magmatism is in stark contrast to the two older superbasins, leading some researchers to conclude that the Isa Superbasin represents a sag basin, albeit one periodically punctuated by crustal extension (Betts et al., 2003; Betts et al., 2006), whereas others have argued for deposition in a foreland setting (McConachie and Dunster, 1996), pull-apart basin (Scott et al., 1998; Scott et al., 2000; Southgate et al., 2000a) or syn-orogenic basin in which extension was facilitated by orogen-parallel strike-slip faulting and lateral extrusion of continental crust (Gibson et al., 2020; Gibson et al., 2017). This episode of orogenesis concluded at ca. 1590 Ma (Gibson et al., 2020) or possibly as late as 1580 Ma (Pourteau et al., 2018) before being followed by further crustal extension and successive episodes of pluton-enhanced low pressure-high temperature metamorphism at 1560-1540 Ma and 1520-1490 Ma (Duncan et al., 2011; Foster and Rubenach, 2006; Rubenach et al., 2008). Granitic rocks associated with this late metamorphism have both A- and S-type compositions and are mainly to be found in the east where they are demonstrably of post-tectonic origin, truncating and cutting across folds and axial plane fabrics produced during the Isan Orogeny (Foster and Austin, 2008; Giles et al., 2006; Page and Sun, 1998; Pollard and McNaughton, 1997; Pollard et al., 1998; Withnall and Hutton, 2013).

With the conclusion of granitic magmatism at 1500 Ma, much of northern Australia was uplifted and eroded before being buried again beneath younger rocks of the 1490-1450 Ma South Nicholson Basin (Sweet, 2017). This Mesoproterozoic basin directly overlies the Isa Superbasin in areas to the west and north of the Lawn Hill Platform (Fig. 1a) and has recently been the subject of a deep seismic reflection study (Carr et al., 2019). Although the seismic data were primarily acquired with a view to better understanding the geometry, thickness and lateral dimensions of this younger basin (Fig. 4), they also serve as a window on the deeper subsurface geology all the way down to crystalline basement and beyond (Carr et al., 2019), thereby providing an opportunity to compare basin architecture in the older sequences below this basin with the results of previous seismic reflection surveys and across a greatly expanded geographical area (Bradshaw et al., 2018; Bradshaw and Scott, 1999; Gibson et al., 2016; McConachie et al., 1993; Scott et al., 1998). These previous seismic reflection surveys highlighted the asymmetric nature of faulting and basin development across the Lawn Hill Platform but differed in respect to basin history and evolution, and more particularly the record of basin inversion and its tectonic drivers (Scott et al., 1998; Gibson et al., 2016; see also Betts et al., 2004). By virtue of the increase in seismic coverage, these issues have become more amenable to investigation and it is to these aspects of basin history and evolution in northern Australia that we now turn.

Seismic record of basin formation and inversion in northern Australia

Survey lines for seismic reflection data acquired across the Lawn Hill Platform and already in the public domain are shown in Figure 5. Most of these are legacy lines dating back to the late 1980s and early 1990s (Burketown Survey, Comalco)(McConachie et al., 1993) and for which reprocessed data became available in 2014 (Armoury Energy). Other lines (Fig. 6a & 6b) were acquired by the minerals industry (Teck Resources, 2011) or minerals industry in collaboration with state and federal Governments (Zinifex, Geological Survey of Queensland and Geoscience Australia, 2006), interpretations of which can be found in several publications and Government records (Bradshaw et al., 2018; Bradshaw and Scott, 1999; Gibson

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I think that its 'Armour' not 'Armoury'

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et al., 2017; Gibson et al., 2016; Krassay et al., 2000b; Scott et al., 1998; Southgate et al., 2000b). Results and interpretations of the more recent 2017 South Nicholson Basin survey (Fig. 4) were published jointly by Geoscience Australia and the geological surveys of Queensland and the Northern Territory (Carr et al., 2019) although their interpretation of geology beneath the Carrara Sub-basin (Fig. 4) is not exactly the same as the one presented here, in part owing to uncertainties in extrapolating stratigraphy from existing seismic lines into areas of little or no outcrop or exploratory drilling. A few rare outcrops of basement schist and Carrara Range Group rocks intruded by 1725 Ma Top Rocky Rhyolite (Jackson et al., 2000; Rawlings et al., 2008) are known from the southern Carrara Range immediately north of seismic line 017GA-SN1 but otherwise older parts of the regional stratigraphy are not well exposed, including basaltic rocks (Mitchiebo Volcanics) long thought to be correlative of the Eastern Creek Volcanics in the Leichhardt Superbasin (Fig. 3). In a further departure from previously published interpretations of existing seismic data (Gibson et al., 2017), the Calvert and Isa superbasins are both thought here to comprise discrete syn- and post-inversion sedimentary fractions (Fig. 3). These broadly conform with the sedimentary units or supersequences previously identified at the top of each superbasin (Bradshaw et al., 2000; Bradshaw et al., 2018; Domagala et al., 2000; Krassay et al., 2000a; Krassay et al., 2000b; Southgate et al., 2000a) and have an important bearing on basin evolution, and more particularly on the timing and duration of the basin inversion events that brought successive basin cycles to a close. These and other differences with previously published interpretations can be illustrated with a few well-chosen survey lines and there is no need to include interpretations of the full seismic dataset. All lines chosen here are composite and make for two orthogonal but not completely continuous transects across the Lawn Hill Platform, Carrara Range and neighbouring Carrara Sub-basin (Fig. 5). For an alternative and slightly different interpretation of these and other lines in the dataset, the reader is referred to Bradshaw and Scott (2009). Bradshaw et[1] (2018) and Carr et[2] (2019).

North-south seismic transect across Lawn Hill Platform

This composite transect is made up of several segments (Figs. 6a & 6b) oriented at high angles to the dominant ENE trend of the Isa Superbasin (Fig. 5). Collectively, these segments image a variably inverted southward-thickening sedimentary wedge disrupted by faults and bounded at its top and bottom by major [3]nconformity surfaces. Limited outcrop across the Lawn Hill Platform and ties to cross lines for which oil well stratigraphic data are available (Fig. 5 & 7) would further suggest that the greater part of this wedge comprises rocks of the Calvert and Isa superbasins (Bradshaw et al., 2000; Bradshaw and Scott, 1999; Gorton and Troup, 2018; Scott et al., 1998; Southgate et al., 2000a) and that the Leichhardt Superbasin is either missing or reduced to a thin layer sandwiched between [4]asement and the overlying younger basins (Figs. [5]a & 6b). All five supersequences of the Isa Superbasin (Fig. 3) are represented in the seismic sections, with the base of the sequence reaching extending to depths of 5-6 km along Comalco line 91Bn33-91Bn28 (Fig. 6a). Basin architecture along this line was first described in detail by Bradshaw et al (2000) and their interpretation of inversion-related structures in the River and Term supersequences is not dissimilar to the one presented here. More specifically, as in Bradshaw et al (2000), several inverted normal faults are recognised along this line into which both the River and Term Supersequences manifestly thicken (Fig. 6a); they typically dip northward and even though some of these same faults disrupt and offset sedimentary units in the underlying Calvert Superbasin (Loretta and Prize supersequences, there is no evidence in the seismic section that these structures ever [6]erved as growth faults during deposition of the older sedimentary basin. Rather, these north-dipping faults cuts across and postdate stratigraphy in the Calvert Superbasin, and first became active [7]uring deposition of the younger Isa Superbasin. No less importantly, both the River and Term supersequences continue southward across the Bluewater Fault Zone into the hangingwall of the Tin Tank Fault where stratigraphy is even more spectacularly inverted (Fig. 6a) and has been deformed into an asymmetric, km-scale south-verging antiform (Punjaub Structure). The

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'.' after 'al'

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same here... 'et al.'

Number: 3 Author: a1130525 Subject: Highlight Date: 8/04/2020 10:46:22 AM
It looks as if there is a truncation surface (unc) between the Prize and the Loretta Fm on 91Bn28-Bn33?

Number: 4 Author: a1130525 Subject: Highlight Date: 8/04/2020 10:43:53 AM
??? You have an extensive Leichhardt Superbasin sequence in 06GA-M1???

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Note that you haven't labeled them a) and b)

Number: 6 Author: a1130525 Subject: Highlight Date: 8/04/2020 10:59:26 AM
Well, the 'Calvert Superbasin' packaged coloured in 2011 Bluebush01-02 certainly seems to change in thickness acoss the Tin Tank Fault Zone to a similar degree as the River and Term??? Also look at the thickness change across the Bluewater FZ??? These are surely growth features? even in 91Bn28-Bn33 the Prise distinctly thickeens into the most southern fault (marked "Normal faults (Isa SB)") on Fig 6a

Number: 7 Author: a1130525 Subject: Highlight Date: 8/04/2020 10:53:08 AM
I don't think that the 2011 Bluebush01-02 line supports this... Maybe I'm missing something, but the thickness changes across the major faults appear just as important during Calvert times as River times? In fact the Bluewater FZ seems to have been a growth structure during Prize to early River, and then inactive during Term....

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River and Term supersequences both attain maximum stratigraphic thickness between the Bluewater and Tin Tank fault zones and occupy much of the fold core (Fig. 6a).

Conversely, owing to the effects of erosion, the overlying Lawn and Wide supersequences are only partially preserved over the crest of the antiform. Even so, enough survives of both units beneath their Mesozoic cover rocks to show that these two units progressively thinned over the crest of this fold through a combination of 1nlap and truncation (Fig. 6a), indicating that the Punjaub Structure either already existed by the time these two units were being deposited or was actively growing during their deposition. In either event, and contrary to previous interpretations (Bradshaw et al., 2000), these two units cannot therefore form part of the syn-extensional growth package. Rather, extension in the Isa Superbasin had already come to a close before sedimentation ceased and these two units more rightly belong to the syn-inversion fraction of basin fill. This is the same conclusion reached by Gibson et al (2017) for the Lawn and Wide sequences exposed along seismic line 06GA-M2 in the Century region farther south (see below).

It is further evident from the abrupt truncation of older Calvert-age stratigraphy at the base of the River Supersequence 2n seismic section 91Bn33-91Bn28 (Fig. 6a) that rocks of the Lawn Hill platform were subjected to an earlier phase of basin inversion, uplift, and erosion before sedimentation in the Isa Superbasin had even started (Bradshaw et al., 2000; Bradshaw et al., 2018; Gibson et al., 2020; Gibson et al., 2017; Scott et al., 1998; Southgate et al., 2000b). As much as 1700m of sedimentary section is estimated to have been lost from the Calvert Superbasin during this inversion event (Bradshaw et al., 2000), a significant amount of which may have been redeposited farther south in the Leichhardt River Fault Trough (Fig. 1a) where there was a commensurate influx of quartz sand at or just before 1640 Ma (Southgate et al., 2000b) during the closing 3ages of the Calvert Superbasin (Gibson et al., 2017). Truncation of the Calvert Superbasin beneath the River Supersequence is also evident in the Century area (Gibson et al., 2017) and may be further inferred from onlap of the River Supersequence onto older folded rocks of the Calvert Superbasin at depth beneath 4ount Caroline (Fig. 6b). Folding of the same amplitude and intensity is not replicated in the overlying River Supersequence and younger sedimentary units, and appears to be confined to the Calvert-age rocks. As elsewhere in the region, the existence of these older structures has largely gone unrecognised owing to extensive overprinting or tightening during the 1620-1580 Ma Isa Orogeny and at least one younger shortening event that postdates the Isa Orogeny and folded all units up to and including the South Nicholson Basin (Fig. 6a). At least some of the folding observed in younger stratigraphic units around the Punjaub Structure may also date from this younger shortening event as is some of the deformation associated with the two northeast-trending periclinal folds (Ploughed Mountain and Mount Caroline) developed northeast of the Century Mine (Fig. 1b). Even more striking are the steep (Boga Fault) and low angle reverse faults that disrupt the core of the Punjaub Structure and cut up section all the way to the Wide Supersequence (Fig. 6a) and may themselves have been folded or reactivated during a younger deformational event.

West-east seismic transect through the Calvert and Isa superbasins

As in the first transect (Fig. 6), seismic sections oriented west-east reveal a wedge-like basin geometry except that units thicken westwards (Fig. 7a & 7b) rather than southward. This is particularly evident in the Isa Superbasin whose constituent lithologies likely occupy a large half-graben that diminishes in depth both laterally and at right angles to the normal faults bounding its southern margin (Fig. 5). As north-dipping structures, these faults are effectively rendered "invisable" in the seismic data. Conversely, growth faults of Calvert age in most seismic sections are well imaged and dip towards the east or northeast (Figs. 7a & 7b). They have effected varying amounts of differential thickening and in some instances cut up-section no farther than the Loretta Supersequence at the top of the basin as would be expected of growth faults of this age. A notable exception is the Riversleigh Fault into which stratigraphic units of both the Calvert and Isa

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certainly hard to see on these figures...

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again, it is a bit hard to see what you mean here? the 'truncation' indicated on the figure appears to be at the top of the Prize with the base Loretta truncating the Prize - but i admit, it is hard to see on the figure.

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note that this may also be the voluminous Masterton Sandstone seen throughout the McArthur Basin (Kunzmann et al. 2020)

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superbasins conspicuously thicken (Fig. 8a). This fault was evidently reactivated subsequent to formation of the Calvert Superbasin and continued to be active for a limited time up to and including deposition of the River and lowermost part of the Term supersequences. Thereafter, rocks of the Lawn Hill Platform were buried beneath a post-rift blanket of near constant thickness that comprises the rest of the Term Supersequence, along with an even thicker syntectonic sedimentary package made up of the Lawn, Wide and possibly Doom supersequences (Figs. 3 & 8a). Sedimentary sequences making up this syntectonic package were deposited contemporaneously with basin inversion and commonly thin over the crests of antiformal folds developed in the hangingwall of the Riversleigh Fault and related shortcut thrust fault developed in its footwall (Fig. 8a). Other thrusts, both synthetic and antithetic to the main fault and hangingwall structures, likely developed during the same deformational event, taken here to be the Isan Orogeny. The few large faults cutting upwards through these younger stratigraphic units from deeper levels in the Isa or Calvert superbasins have steeper attitudes and do not appear to be associated with differential thickening, indicating that they too may have formed during the Isa Orogeny or possibly an even younger unrelated tectonic event. In any event, this phase of basin inversion is clearly in addition to the one that predates deposition of the Isa Superbasin and whose main expression in the seismic data is a surface onlapping the older Calvert Superbasin and beneath which rocks of the latter are visibly truncated.

Continuation of west-east seismic transect beneath South Nicholson Basin

Seismic data for the South Nicholson Basin have already been interpreted and published in their entirety (Carr et al., 2019)and this paper is only concerned with parts of the seismic grid (Fig. 4) that connect with existing lines to the east (Fig. 5) and likely share a common basin architecture with the immediately adjacent Lawn Hill Platform. Particularly important in this context is the eastern end of seismic line 017GA-SN1 (Fig. 8b) which connects with the Century line (06GA-M2) and extends this west-east transect for some considerable distance westwards (Fig. 4). Older basinal sequences in this region lie buried beneath the South Nicholson Basin and younger cover rocks of Cambrian (Georgina Basin) and Mesozoic age (Carpentaria Basin) and their stratigraphy has largely been determined through the extrapolation of interpreted rock units (Gibson et al., 2017; Gibson et al., 2016) from the existing Century 06GA-M2 line (Fig. 8a). The Isa and Calvert superbasins are both exposed at the surface along line 06GA-M2 but even so interpretations of the subsurface geology along this line and 017GA-SN1 are not completely identical (cf Gibson et al., 2017 and Carr et al., 2019), especially in regard to depth to basement and stratigraphic affinity of the more deeply buried basinal sequences (see also FrogTech Geocience, 2018). Basement in this study is thought to extend upwards to much higher crustal levels along line 017GA-SN1 than in either Carr et al. (2019) or FrogTech Geoscience (2018) and to be directly overlain by a commensurately thinner Leichhardt Superbasin (Fig. 8b). Basin fill in the latter thins westward and, despite disruption by several low-angle faults, can nevertheless be traced for some considerable distance across the seismic section before it pinches out beneath rocks of the unconformably overlying Isa Superbasin and eventually terminates against a major east-dipping normal fault (Fig. 8b). Sedimentary units in the overlying Isa Superbasin have a wedge-like geometry and thicken into this same east-dipping structure which, like the similarly east-dipping Riversleigh Fault, was evidently active at the time this superbasin was deposited (Fig. 8b). Both the River and Term supersequences appear to be represented in this wedge as do correlatives of the Lawn, Wide and Doom supersequences (Fig. 8b). As with their counterparts farther east, the Wide and Doom both thin over the crest of an antiform developed in the hangingwall of the structure and likely constitute the syn-inversion fraction of basin fill. By way of contrast, the River and Term supersequences making up the syn-rift component of basin fill were deposited on an already inverted Leichhardt Superbasin as evidenced by the abrupt truncation of the latter against the base of the overlying River Supersequence (Fig. 8b). Truncation of the Leichhardt Superbasin beneath the Isa Superbasin is no less obvious in the hangingwalls of minor and less intensely inverted faults elsewhere along line 017GA-SN1, lending strong support to the suggestion

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made repeatedly in this paper that the two older basinal sequences had already undergone at least one phase of uplift and erosion before deposition of the 1640 Ma River Supersequence. Much less clear from line 017GA-SN1, owing to the amount of basin inversion involved, is whether the Calvert Superbasin was ever present and simply lost to erosion before sedimentation in the Isa Superbasin commenced. Many of the more important east-dipping faults cut up section all the way to the base of the Isa Superbasin but have only brought about a displacement of the older units and do not appear to be growth faults (Fig. 8b). These faults are either of Calvert or Isa Basin age and possibly predate the much shallower dipping inversion structures that offset all basinal units and continue all the way to the surface. These faults, and some of the steeper or near vertical structures, appear to have been active subsequent to deposition of the South Nicholson Basin, which is mildly inverted across them.

North-south seismic sections orthogonal to 017GA-SN1

As a further check on basin geometry and structural architecture to the west of the Lawn Platform, two sections (017GA-SN2 and 017GA-SN4) were selected for interpretation in a direction at a high angle or orthogonal to 017GA-SN1 (Figs. 9a & 9b). With its NW-SE orientation, seismic line 017GA-SN2 cuts across many of the same north or northwest-striking structures imaged in 017GA-SN1, most notably at least one crustal-scale east- or southeast-dipping fault that extends down to the MOHO (Fig. 9a) and is manifestly the same structure responsible for much of the basin inversion observed in the Isa Superbasin. The most obvious difference between the two lines is the thick wedge-like basinal sequence imaged in its hangingwall down to 7.0 seconds TWT. This sequence lies below the interpreted base of the Leichhardt Superbasin in line 017GA-SN1 (Fig. 8b) and either represents an entirely separate older sedimentary package or a continuation of the Leichhardt Superbasin downward to much deeper crustal levels than is immediately apparent in the west-east oriented seismic section. In the absence of independent information, it is not possible to discriminate between these two possibilities except to say that the same package is evidently present in line 017GA-SN1 and corresponds to a zone of non-reflective crust which at a depth of 10 kilometres or more seems much too deep for the Leichhardt Superbasin (Fig. 9a) and shares none of the higher amplitude reflectors common to other seismic lines through this basin elsewhere in the Mount Isa region (e.g. 06GA-M3; Gibson et al., 2016). Several low-angle faults on lines 017GA-SN1 and 017GA-SN2 also root downward into this zone (Figs. 8b & 9a) although neither they nor the surfaces bounding the older sedimentary package are particularly conspicuous or maintain their individual character at depth. Rather, all faults and surfaces appear to merge downward into one seismically bland and homogenised region of middle crust more in keeping with expectations for metamorphic basement than the Leichhardt Superbasin. Moreover, because line 017GA-SN1 is probably more closely aligned with lithological strike in the older sedimentary package and its bounding surfaces, their apparent dip in this particular seismic section is close to zero, resulting in surfaces whose traces are subhorizontal and parallel to each other. Only along line 017GA-SN2 is the northern dip of this older package discernible.

As with the other two lines across the South Nicholson Basin, 017GA-SN4 (Fig. 9b) encompasses a basement block bounded on its northern side by a near vertical fault. This structure shares the same steep dip as the fault developed along the northern flank of the Punjaub Structure (Fig. 6a) and is possibly the same structural feature. It too serves as the boundary to a wedge of southward-thickening sedimentary rocks whose seismic character (short, high amplitude reflectors) is reminiscent of the along-strike River and Term supersequences. These two sequences are consequently taken here to be part of the Isa Superbasin. They, in turn, are overlain by a sedimentary sequence that likely includes the rest of the Isa Superbasin as well as younger rocks of the South Nicholson and Georgina basins (Fig. 9b).

All older sequences are also recognised on the other side of the basement block (Fig. 9b) where they are similarly buried beneath a thin veneer of younger sediments belonging to the South Nicholson and Georgina

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It is hard to match this structure with the structures interpreted on SN4 line - is it supposed to be the along-strike equivalent of the Little Range Fault?

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how a metamorphic basement might be expected to look rather

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basins. Basement is pene-planated beneath the Georgina Basin (Fig. 9b) although this likely represents only the latest in a series of uplift and erosion events to have affected this older cratonic block and its overlying sedimentary sequences. Sedimentary sequences on the southern side of the basement block are consistently thinner than their counterparts on the northern side (Fig. 9b) indicating that this block was probably being actively uplifted and eroded before all of the Isa Superbasin had been deposited. Sediment shed from a rising basement block could easily explain the northward-thickening wedge of sediment making up the younger part of the Isa Superbasin identified at the northern end of the seismic section and is in keeping with suggestions made elsewhere that sedimentation and basin inversion in the Isa Superbasin were coeval. Significantly, as in lines 017GA-SN1 and 017GA-SN2, the Leichhardt Superbasin persists in highly attenuated and truncated form, perceptibly thinning up section beneath the overlying Isa Superbasin (Fig. 9b).

Discussion

Extensional basins and their structural architecture both before and after inversion are now reasonably well understood following numerous field studies combined with the results of numerical modelling and sandbox experiments (Cooper et al., 1989; Hayward and Graham, 1989; McClay et al., 2002; McClay and White, 1995; Turner and Williams, 2004). Emphasised in most of these studies is the strongly asymmetric nature of basin fill and the consequences of shortening a sedimentary sequence whose individual unit lengths are all different and increase upward from bottom to top of the section (Hayward and Graham, 1989; Lowell, 1995; Turner and Williams, 2004). The net result during shortening is development of an equally asymmetric fold in the hangingwall of the original normal fault which may or may not have been reactivated during the process. This hangingwall fold is one of the most distinctive features of basin inversion and may be regarded as a diagnostic feature, particularly in cases where folding is enhanced by the reactivation of coeval antithetic structures leading to the expulsion of basin fill in opposite directions. Further enhancements of the basic inverted structure may occur where the normal fault locks up early and strain is transferred to a footwall shortcut thrust or taken up by some other structure such as a strike-slip fault (Dooley and McClay, 1997; McClay, 1995; McClay et al., 2002). These and other variations on structural architecture developed during basin inversion (Martínez et al., 2012) are illustrated in Figure 10. All examples are from inverted basins of Mesozoic or younger age but are clearly no less relevant in the case of the older basins described here from northern Australia. Footwall shortcut thrusts have been captured in several of the seismic sections but are conspicuously well developed in the footwalls of the Century (06GA-M2) and Punjaub structures (Figs. 8a & 6b). However, by far the most common and widely imaged structure is the hangingwall antiform (Fig. 10). Moreover, this same structural feature is evident in all sections irrespective of whether they are oriented north-south or west-east, supporting suggestions made elsewhere that there has been more than one episode of basin inversion and that these were imposed on basins that were originally orthogonal to one another. As such, basin inversion affords clues to basin orientation before and after successive episodes of crustal shortening got underway and it is to this topic that we now turn.

The Isa Superbasin is best known from the Lawn Hill Platform (Fig. 5) and has been previously interpreted as a sag or foreland basin deformed during a subsequent north-south shortening event identified as the Isan Orogeny (Betts et al., 2003; McConachie et al., 1993; McConachie and Dunster, 1996). More recently, an extensional origin has been proposed for this same basin consistent with seismic data and general thickening of sedimentary units like the River and Term supersequences into normal faults oriented ENE-WSW (Bradshaw et al., 2018; Gorton and Troup, 2018). Antiformal closures developed in the Punjaub Structure and periclinal folds exposed just to its south share the same ENE-WSW trend (Fig. 1b) and likely represent basin inversion structures formed during the same north-south shortening event. However, as already pointed out, the Punjaub Structure is not a simple structure and likely underwent limited folding before or

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Number: 1 Author: a1130525 Subject: Pencil Date: 17/04/2020 4:36:07 PM subsequent to the start of deposition in the River and Term supersequences (Gibson et al., 2020). Along with rocks of Calvert age in the core of the Punjaub Structure, these two sequences were deformed during the 1650-1640 Ma Riversleigh Tectonic Event for which a NE-SW shortening direction has been proposed (Gibson et al., 2020; Gibson et al., 2017). As such, shortening during the earlier stages of basin inversion in the Punjaub Structure would have been approximately orthogonal to strike in the Calvert Superbasin and its NW-SE basin-bounding normal faults. Seismic sections oriented parallel to this shortening direction consistently show faults of Calvert age dipping eastwards (e.g. Riversleigh Fault) and several have antiformal structures developed in their hangingwalls (Figs. 8a & 8b) in line with expectations that basin geometry prior to inversion was highly asymmetric and had the form of a westward deepening half-graben. Westward deepening of Calvert-age extensional basins on the Lawn Hill Platform is contrary to the results of earlier geophysical modelling (Betts et al., 2004) indicating that half-graben of this age deepen southwards towards normal faults with NE orientations essentially orthogonal to what is proposed here. However, while faults with this orientation have been previously mapped (Hutton and Sweet, 1982) or have been known to exist in the subsurface for a long time (Krassay et al., 2000a; Scott et al., 1998), it is debatable that they are of Calvert age or exercised any significant control on depositional patterns during this phase of basin formation. They share the same NE to ENE strike as normal faults in the Isa Superbasin and likely belong to the same generation of structures that controlled deposition of the younger sedimentary basin. Importantly, faults of this age exhibit increased amounts of throw southwards which would have been accompanied by commensurate amounts of downward displacement in rocks of the underlying Calvert Superbasin, as captured in seismic images (Fig. 6a) along line 91Bn-28-91Bn33 and the northern flank of Punjaub Structure where the Loretta and Prize supersequences, along with older elements of the Isa Superbasin, have been faulted downward by several kilometres relative to their counterparts across the crest of the fold. This is the same stepped basin geometry picked up in the results of geophysical modelling for the Lawn Hill Platform (Betts et al., 2004) and which, during later crustal shortening, would have produced south-verging folds with the same NE axial direction orientation as periclinal folds now observed at Mount Caroline and Ploughed Mountain (Fig. 1b). It further follows that the NW-SE extensional direction previously proposed for the Calvert Superbasin more likely relates to the younger Isa Superbasin and only came about because erosion across the Lawn Hill Platform during or subsequent to the Isa Orogeny removed much of the younger basin infrastructure leaving behind only the inverted and once more deeply buried rocks of the older basin.

West of the Lawn Hill Platform, crystalline basement lies at much shallower crustal depths and may even have been exposed during deposition of the Georgina or South Nicholson basins, forming one or more structural highs over the top of which there is a conspicuous thinning or draping of the younger cover rocks (Fig. 9b). The older Paleoproterozoic-early Mesoproterozoic sequences are similarly notably thinner over basement in this region and the Calvert Superbasin may be entirely missing (Figs. 8b & 9b), either because it was never deposited or was removed by erosion during uplift accompanying the Riversleigh Tectonic Event. The River Supersequence consequently directly overlies on a truncated and westward thinning older sequence taken here to be the Leichhardt Superbasin based on continuity with line 06GA-M2 (Fig. 8a) for which a stratigraphic interpretation has already been published. As with line 06GA-M2 (Fig. 8a), an angular unconformity separates the two sequences (e.g. Fig. 8b), and the Leichhardt Superbasin had likely already been inverted before the River Supersequence was laid down. In keeping with this suggestion, the older sequence has locally been completely eroded away so that the River Supersequence rests directly on older crystalline basement (Fig. 8b). Moreover, even though a significant amount of this uplift and erosion may have been accommodated on reactivated older normal faults, the dominant structures in the seismic images are sub-vertical to steeply dipping and abruptly truncate stratigraphy not only in basement but thick basinal sequences developed in their footwalls. These footwall sequences encompass most if not all units of the Isa Superbasin (Figs. 8b & 9b), pointing to either a considerable amount of downward throw to the north on

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whether

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these structures or an equally significant amount of strike-slip displacement. The latter is thought more likely here consistent with the scale and abruptness of truncation and the observation that the faults overall have the character of flower-like structures (Fig. 9b). Either way, it is difficult to avoid the conclusion that basement uplift on these subvertical faults occurred late as these structures displace all units in the Isa Superbasin and cut up-section all the way to the base of the Cambrian. Faults with similarly steep attitudes and character are also evident in north-south oriented seismic sections (Fig. 6) for the northern Lawn Hill Platform (e.g. 91Bn-28; 91Bn-33) and likely belong to the same generation of strike-slip faults. Significantly, they share the same NE to ENE strike and were possibly initiated on older structures dating back to formation of the Isa Superbasin into which they root downward (Fig. 6a).

Basin inversion and implications for Pb-Zn mineralisation

As revealed in seismic sections oriented orthogonal to one another, basin inversion in the north Australian Paleoproterozoic-Mesoproterozoic sequences occurred on more than one occasion and gave rise to a structural architecture not unlike that recorded in basins of much younger age such as the Irish and North seas and North Atlantic petroleum province more generally. No less important in this context are the results of past and recent drilling confirming that northern Australia is prospective for oil and gas (Gorton and Troup, 2018; Jackson et al., 1986; McConachie et al., 1993) thereby amply justifying the case for such comparisons. Further warranting such comparisons is the work of Broadbent et [1] (1998) who reported that rocks hosting the Century Pb-Zn deposit (Wide Supersequence) are bituminous, since corroborated by more recent studies showing this and other parts of the Isa Superbasin to contain exceptionally high levels of total organic carbon (Gorton and Troup, 2018; Jarrett et al., 2018). Host rocks to the Century deposit include carbonaceous siltstones and dolostones whose carbon content is thought to have transformed these rocks into a suitable reductant during the passage of more oxidising metal-bearing fluids from below. On encountering this reducing environment, a number of catalysed redox reactions ensued during the course of which metal sulphides were precipitated (Broadbent et al., 1998; see also Huston et al., 2006). Other Pb-Zn deposits across the region, including Mount Isa, are thought to have formed through the same process although mineralisation is typically determined to have occurred during basin formation with the metal-bearing fluids transported upwards along normal faults active at the time of sedimentary deposition. Mineral exploration has accordingly often been directed towards the identification of structures and sedimentary sequences formed during the course of basin formation as opposed to those that may have formed during later basin inversion.

However, as is now evident from recent seismic interpretations of line 06GA-M2 (Gibson et al., 2017; Gibson et al., 2016), the carbonaceous rocks hosting Century belong to the syn-inversion fraction of basin fill and were deposited at a time of crustal shortening accompanying onset of the Isan Orogeny. There is no evidence that this shortening was accompanied by reactivation of the basin-bounding structure. Instead, as with many normal faults, the Riversleigh Fault dipped too steeply to be easily reactivated and strain was taken up on a footwall shortcut thrust; it rather than the Riversleigh Fault would have served as the better fluid conduit. Interestingly, the Termite Range Fault has some of the same attributes as a footwall shortcut thrust and is widely believed (Broadbent et al., 1998; Yang and Radulescu, 2006) to have been the main fluid conduit for the Century deposit which lies either above or in a minor offshoot immediately adjacent to the master structure. No less importantly, mineralisation is transgressive with respect to stratigraphy and occurred through replacement processes, consistent with the [2]575 Ma age reported for this deposit (Carr et al., 2004). This is long after the start of crustal shortening and probable concomitant expulsion of hydrocarbons to higher stratigraphic levels where they would have pooled or been trapped in structures formed during inversion. Alternatively, basin fill at these levels may already have been sufficiently enriched in carbon during the depositional stage. Irrespective of such uncertainties, the metal-bearing fluids migrated into the same structures where they were reduced and forced to give up their Pb and Zn. It seems further

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likely if the analogy with the petroleum system has any validity that a significant amount of this metal-bearing fluid found its way into the same type of hangingwall structures that are so prospective of oil and gas in the younger inverted basins of the North Atlantic petroleum province. If this is indeed the case, then exploration strategies for sediment-hosted Pb-Zn mineralisation may have to change with exploratory drilling redirected away from former normal faults towards potential structural traps in their hangingwalls.

Acknowledgements

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Figure Captions

Figure 1. (a) Simplified geological map for northern Australia showing principal tectono-morphological elements and Pb-Zn mineral deposits (after Jackson et al., 2000). (b) More detailed geological map of periclinal folds developed in inverted stratigraphy of the Isa Superbasin on the Lawn Hill Platform east of Century Mine and seismic reflection lines 06GA-M1 and 06GA-M2 along which these structures are imaged. Figure reproduced with permission under the Creative Commons Attribution 4.0 International Licence: http://creativecommons.org/licenses/by/4.0/legalcode. © Commonwealth of Australia (Geoscience Australia) 2020.

Figure 2. Map showing presently defined limits of outcropping Leichhardt, Calvert and Isa superbasins across the Mount Isa region. Seismic reflection data indicate that all three basins are variably preserved in the subsurface geology beneath the South Nicholson and Georgina basins and continue northwards into the McArthur Basin and Batten Trough (see Carr et al., 2019). Reproduced with permission: Licensed CC BY version 4.0 © State of Queensland, 2020.

Figure 3. Simplified stratigraphic column for Mount Isa region and neighbouring southern McArthur Basin showing three-fold subdivision into Leichhardt, Calvert and Isa superbasins but different interpretations of basin history and tectonic evolution (Betts et al., 2003; Betts and Lister, 2001; Gibson et al., 2016; Southgate et al., 2000a). The Carrara Range Group is shown as part of the lower Tawallah Group and a correlative of the Leichhardt Superbasin based on revised mapping (Rawlings et al., 2008) and recently published geochronological data (Kositcin and Carson, 2019) for the McArthur Basin.

Figure 4 Superposition of South Nicholson seismic grid over an anomalously deep gravity low bounded by the Carrara Range (gravity high) to the north of line 17GA-SN1 (after Carr et al., 2019) requiring the presence of less dense rocks at depth such as an unusually thick sedimentary basin and/or large felsic igneous body of batholithic proportions such as observed farther south in the Sybella Granite. Figure reproduced with permission under the Creative Commons Attribution 4.0 International Licence: http://creativecommons.org/licenses/by/4.0/legalcode. © Commonwealth of Australia (Geoscience Australia) 2020.

Figure 5. Basin and basement architecture for northern Lawn Hill Platform showing main depocentres and fault trends for Isa Superbasin (after Gorton and Troup, 2018). Also shown are various industry seismic survey lines from 1994 (Comalco) and 2011 (Teck Resources) across the Isa Superbasin and adjacent Punjuab Structure (P). Yellow lines are for composite image presented in Figures 6-7. Note compartmentalisation of depocentres brought about by interference between the ENE and NW-trending faults; latter are of Calvert age and include older normal faults (e.g. Riversleigh Fault) reactivated as strike-slip structures during crustal extension accompanying formation of the Isa Superbasin. Reproduced with permission: Licensed CC BY version 4.0 © State of Queensland, 2020.

Figure 6. North-south oriented transect across northern Lawn Hill Platform made up of selected industry and government seismic sections (Fig. 5) showing predominance of north-dipping normal faults on which there has been successive episodes of basin inversion, leaving behind a legacy of fault reactivation and periclinal folding in (a) Punjaub Structure and (b) Mount Caroline and Ploughed Mountain (after Gibson et al., 2017; 2020). Note thinning of River and Term supersequences northward through onlap in (a); the underlying Loretta Supersequence similarly thins northward but is bounded top and bottom by truncated surfaces thought to reflect considerable loss of stratigraphic section by uplift and erosion accompanying the 1650-1640 Ma Riversleigh Tectonic Event. Sedimentary patterns point to growth faulting on north-dipping structures during deposition of the Isa, but not underlying Calvert Superbasin whose sequences are merely offset. Bluewater, Boga and Tin Tank Fault names adopted from Bradshaw et al (2018) and industry

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(Pursuit Minerals, 2017). In (b) the older sequence had already been folded before the River Supersequence was deposited as evidenced by thinning of the latter over the crests of folds developed in the Calvert Superbasin at deeper levels beneath Mount Caroline. The Calvert Superbasin is in turn separated by an angular unconformity from an even older underlying sequence inferred (Gibson et al., 2017; Gibson et al., 2016) to be the Leichhardt Superbasin. Colour coding is same as Figure 3.

Figure 7. West-east oriented seismic transects through northern Lawn Hill Platform. Westward thickening of Calvert-age sedimentary units in both (a) and (b) is consistent with growth faulting on east-dipping normal faults which have since been variably reactivated (Isa Orogeny). Conversely, no such growth is evident in the overlying Isa Superbasin whose lithological strike and inversion structures are essentially parallel to the line of section. These units still thicken into the centre of the Isa Superbasin but in a direction orthogonal to normal faults active during its deposition. Such faults, if imaged, would be expected to be flat-lying or have very shallow dips parallel or subparallel to bedding in both sections rending their recognition very difficult. Some of the disruption to bedding in (b) along line 90Bn-10 may be due to such faults but overall the most obvious structural feature in the section is the broad arching and folding of stratigraphy in the middle of the section consistent with imaging of an inversion fold in longitudinal cross-section.

Figure 8. West-east oriented section through (a) Century Mine (06GA-M2) and (b) its western continuation (017GA-SN1) across the South Nicholson Basin and Carrara Sub-basin (Carr et al., 2019). The older basins of Paleo- Mesoproterozoic age are nowhere exposed along line 017GA-SN1 and the only constraint presently available on their stratigraphy and structural architecture west of the Lawn Hill Platform comes from contiguity with the Century line 06GA-M2 for which an interpretation has already been presented (Gibson et al., 2017; Gibson et al., 2016). Particularly noteworthy in line 017GA-SN1 is the westward thinning of the older sequence beneath the Isa Superbsin, and inversion of it and the Isa Superbasin above a major east-dipping structure that also brought basement to much shallower crustal levels. This older sequence is thought to be of Leichhardt age and has been visibly truncated around the crest of the inversion structure such that the overlying Isa supersequences comes to rest directly on crystalline basement. As in (a), most if not all units of the Isa Superbasin, including the syn-inversion fraction (Lawn, Wide and Doom supersequences), appear to be preserved on the western flank of this inversion structure. An uplifted basement horst block across which basin polarity changes is evident at the western end of the seismic section. The South Nicholson Basin is thinner and shown lying higher than in other recent interpretations (Carr et al., 2019; Geoscience, 2018).

Figure 9. North-south oriented seismic sections west of Lawn Hill Platform showing shallow crystalline basement and same basement-rooted inversion structure. Note major basement structure in (a) that cuts downward all the way to the MOHO is probably the same basement structure imaged in (b) and over which all older sedimentary basins have been eroded so that rocks of Cambrian age (Georgina Basin) directly overlie basement (017GA-SN4). Rocks of the South Nicholson have similarly been removed for the crest of this basement block in 017GA-SN4 and, together with rocks of the Isa Superbasin, increase in thickness northwards. The Isa Superbasin is abruptly truncated by the basement structures and other subvertical structures suggestive of a flower structure and late-stage onset of strike-slip faulting at or before deposition of Cambrian Georgina Basin.

Figure 10. Basin inversion and resulting styles of structural architecture to be anticipated during crustal shortening (after Martinez et al, 2012; McClay, 1995): (a) early normal fault; (b) harpoon structure from partially inverted normal fault; (c) buttressing; (d) hangingwall is faulted forming hangingwall shortcut; (e) footwall shortcut thrust; (f) folding and truncation of normal fault by younger thrust; (g) thrust ramp above normal fault.

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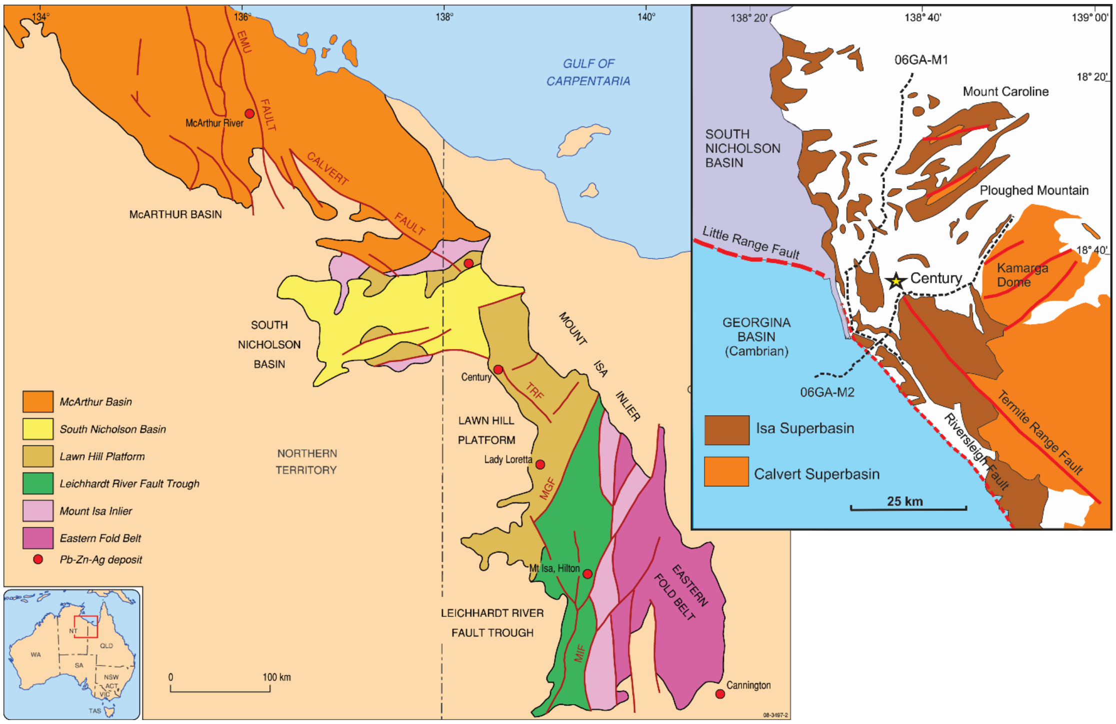

Figure 1

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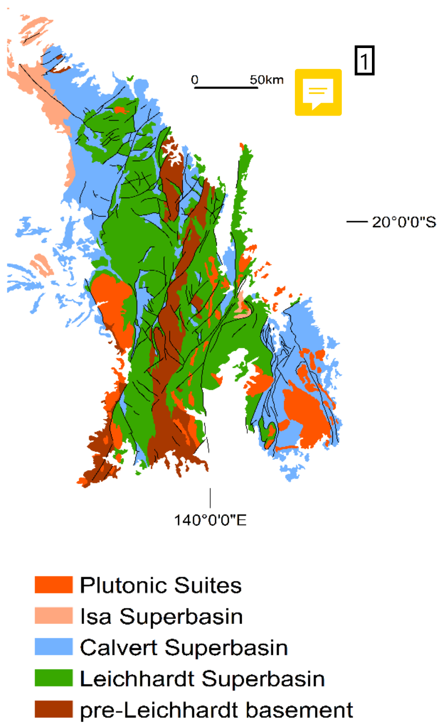

Figure 2

Number: 1 Author: a1130525 Subject: Sticky Note Date: 8/04/2020 10:23:55 AM

This map needs to be redrafted or at least put into a proper figure

https://doi.org/10.5194/se-2020-31
Preprint. Discussion started: 6 April 2020

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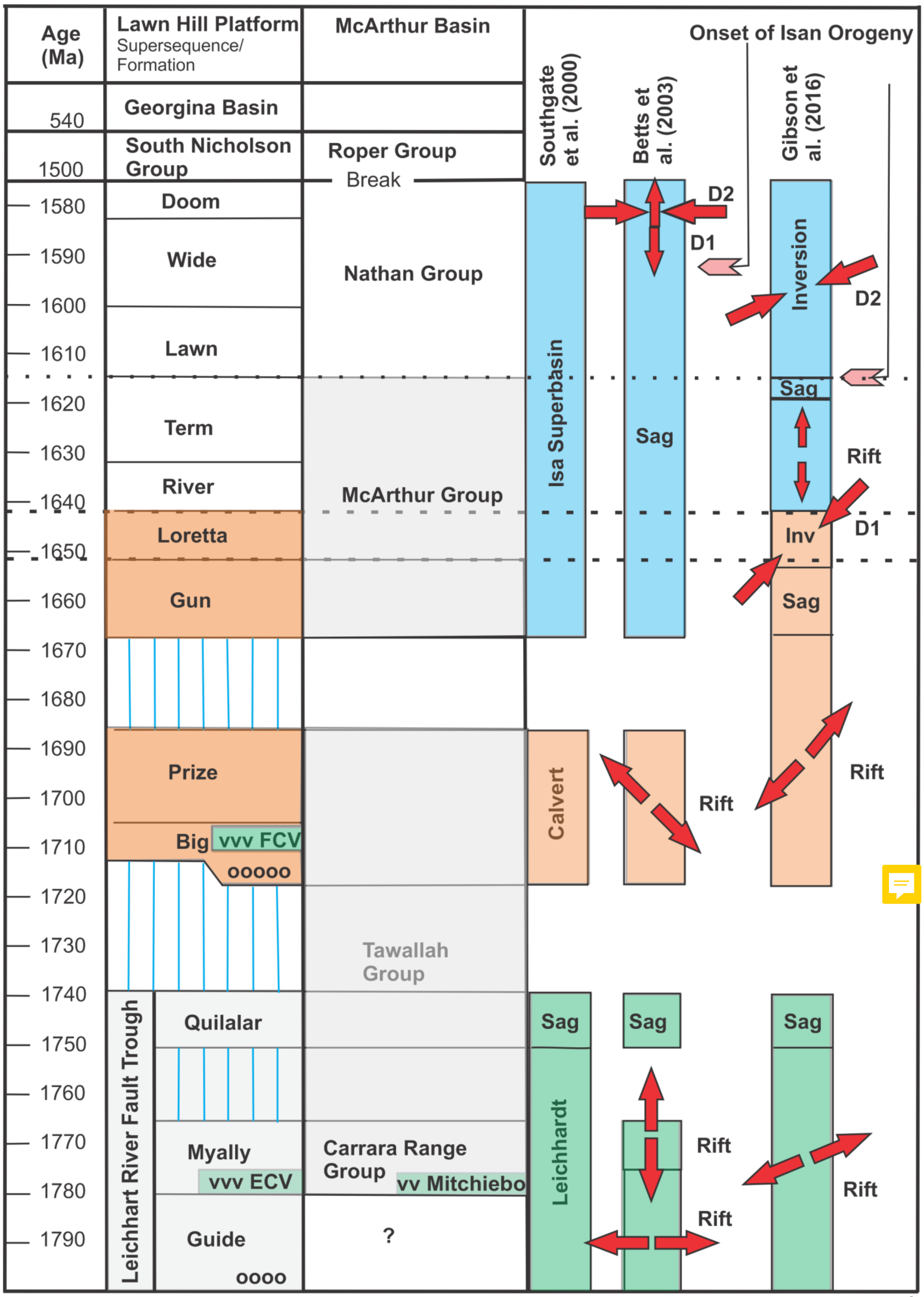

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Number: 1 Author: a1130525 Subject: Sticky Note Date: 8/04/2020 10:26:21 AM

The vertical blue lines need explanation as do the symbols 'ooo' 'vvv'. Why is the 'Tawallah Group' a light grey? Are the dashed lines that outline the Loretta Formation supposed to line up with the 'Inv' phase in the Gibson et al. 2016 column? if so, can this be drafted better

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Figure 3

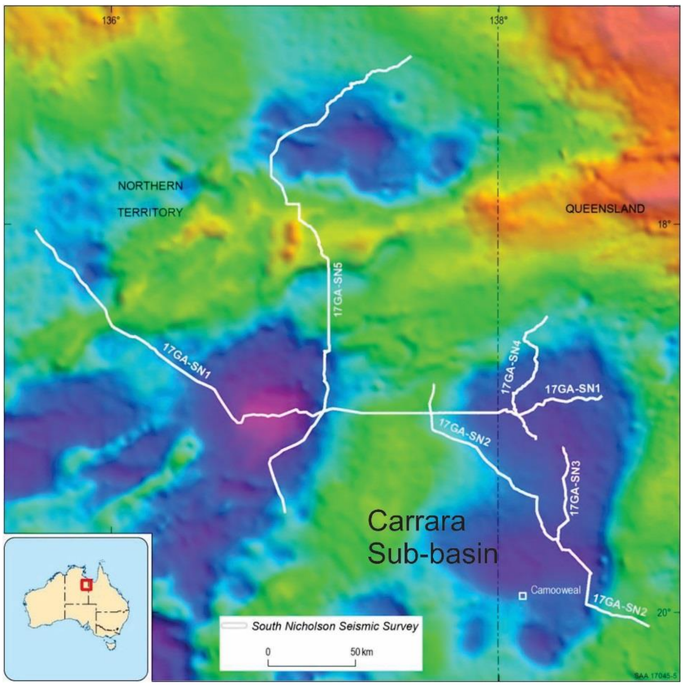

Figure 4

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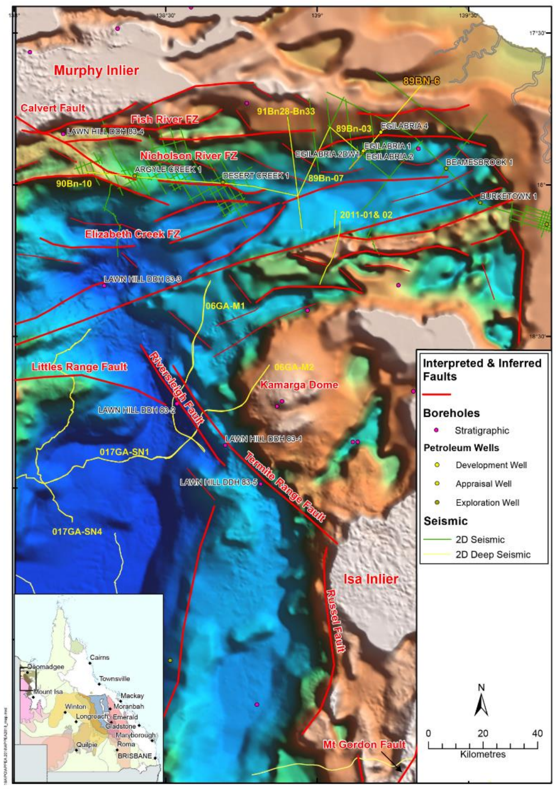

851

852 Figure 5

Page: 23

Number: 1 Author: a1130525 Subject: Sticky Note Date: 17/04/2020 4:50:20 PM

Likewsie - this figure is really not of a high enough quality as it is

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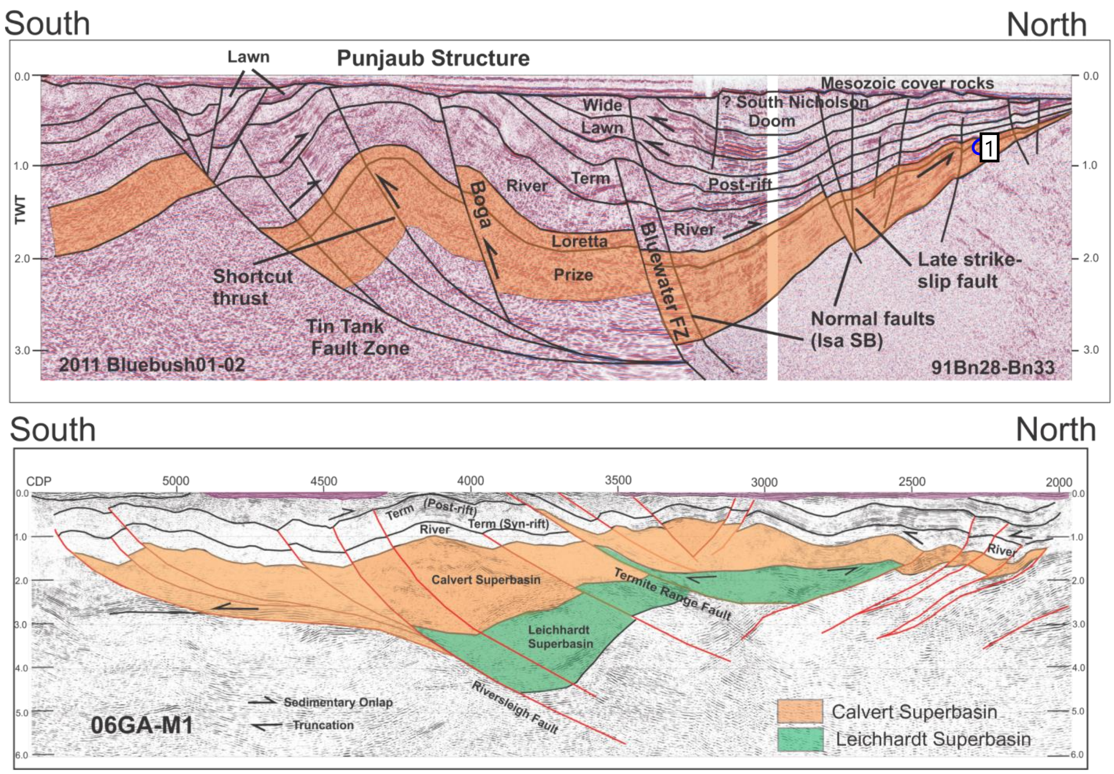
853 

854 Figure 6

Page: 24

Number: 1 Author: a1130525 Subject: Pencil Date: 8/04/2020 12:07:17 PM

This appears to show Prize reflectors being truncated by the Loretta... not the Loretta being truncated by the River??

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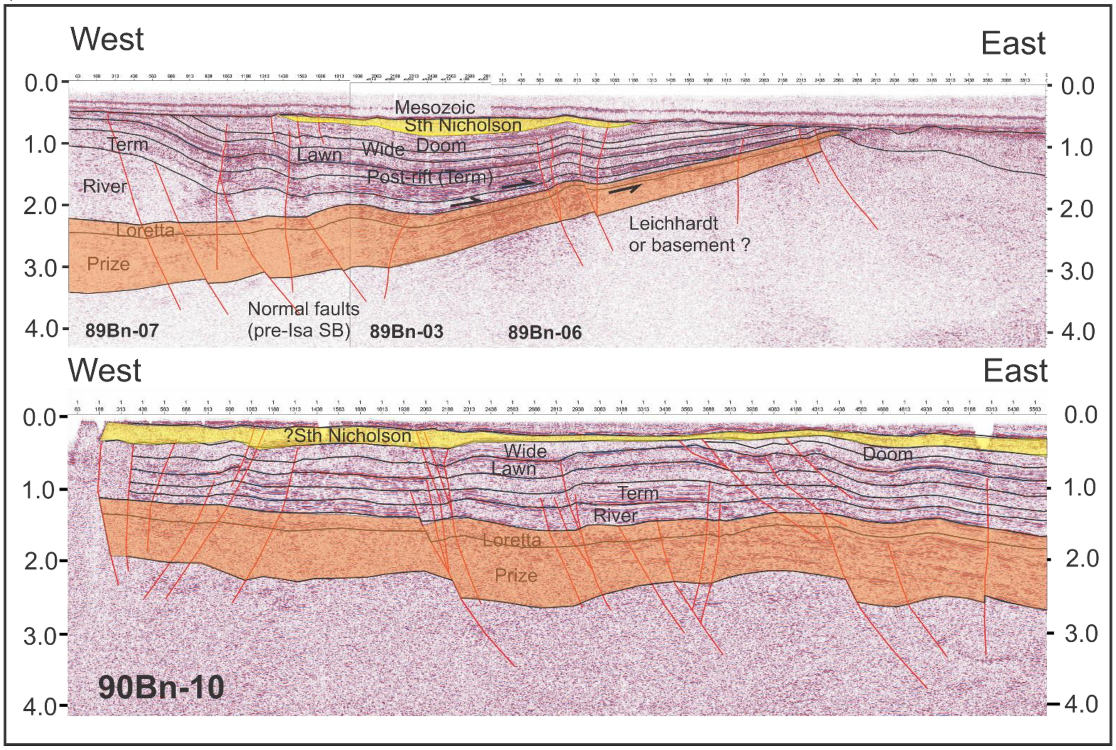

Figure 7

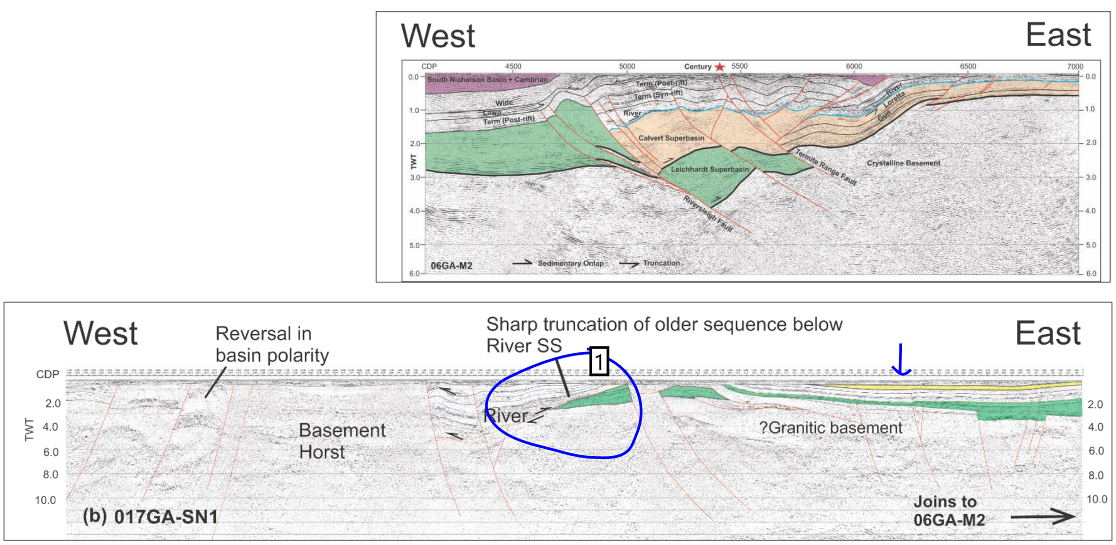

Figure 8

Page: 25

Number: 1 Author: a1130525 Subject: Pencil Date: 17/04/2020 4:26:25 PM

Really very difficult to see anything here at this resolution

Author: a1130525 Subject: Sticky Note Date: 17/04/2020 4:26:56 PM

Can't really see whether these faults cut the South Nicholson Basin as mentioned in the test - they don't seem to on the interpretation here??

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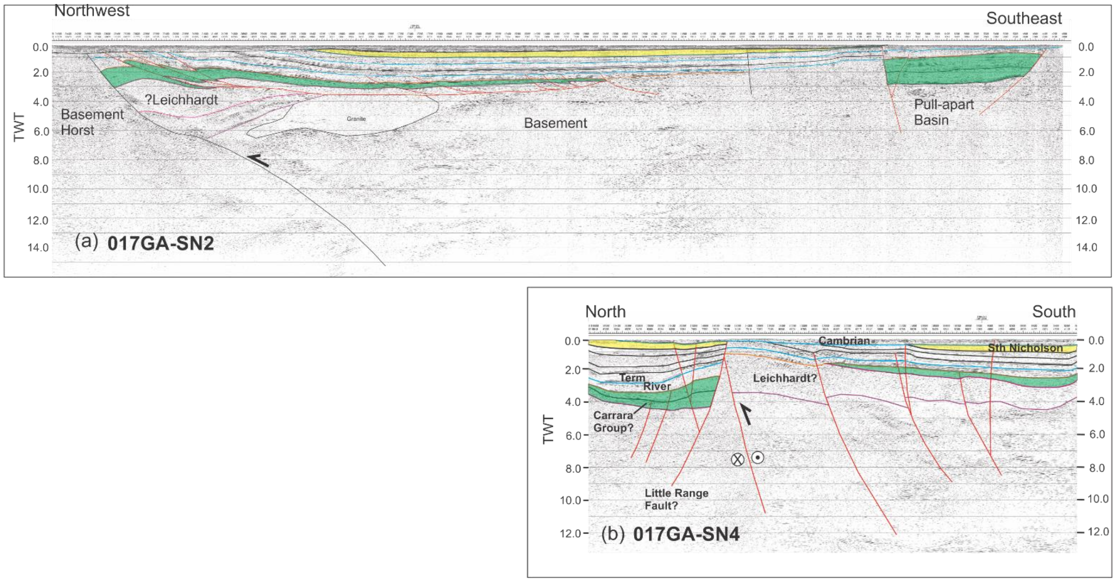

Figure 9

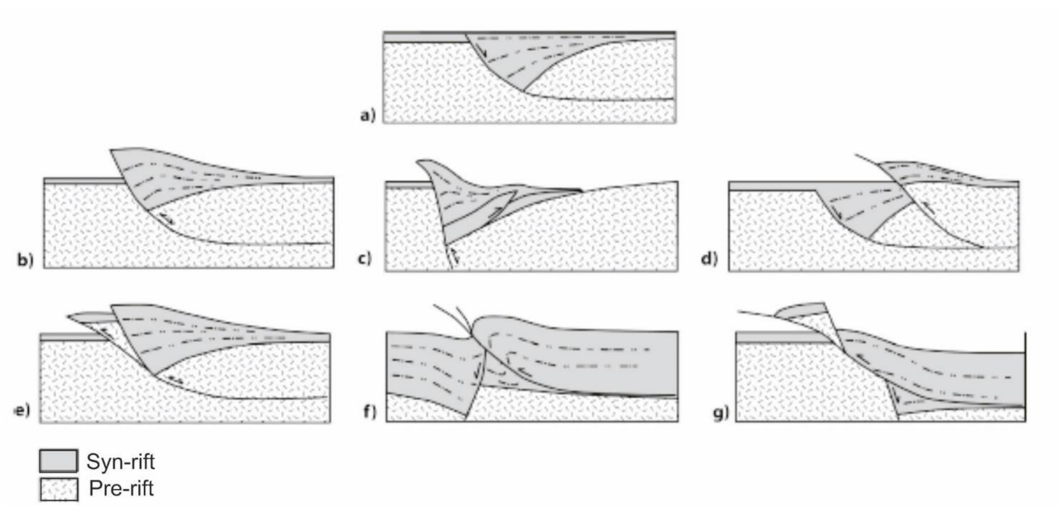

Figure 10

This page contains no comments