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Key Points:

- Basinal sequences in Paleoproterozoic eastern Australia and western Laurentia underwent orogenesis at similar times
- Development of single orogenic belt whose across-strike dimensions are comparable to the Tibetan-Himalaya orogenic system
- Shared crustal shortening at circa 1650 Ma under Barrovian-style conditions followed by late-orogenic pluton-enhanced low-pressure-high-temperature metamorphism from circa 1600 Ma

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Orogenesis in Paleo-Mesoproterozoic Eastern Australia: A response to Arc-Continent and Continent-Continent Collision During Assembly of the Nuna Supercontinent

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Abstract Northern and southern Australia preserve a common record of 1790–1655 Ma intracontinental rifting and backarc extension culminating in formation of a marginal sea that subsequently collapsed following a 1650–1640 Ma reversal in plate motion and onset of arc-continent collision. Arc-continent collision was accompanied by intermediate-pressure Barrovian-type metamorphism (6–8 kb) and widespread crustal thickening as reflected in a clockwise pressure-temperature-time path. Later metamorphism during the 1620–1580 Ma Isa and Olary orogenies occurred under intrusion-enhanced lower pressure conditions (4–6 kb) and followed a counterclockwise pressure-temperature-time path incompatible with either significant amounts of crustal thickening or tectonic models which have Australia and Laurentia commencing collision at this time. Continent-continent collision more likely followed on closely behind arc-continent collision (Riversleigh Tectonic Event), precipitating a switch in crustal shortening from northeast-southwest to west-east as the older rift template and underlying basement structures were reactivated in a transpressive or multicollisional tectonic regime not unlike that which produced the Himalayan-Tibet orogenic system. As in the latter, ongoing collision was accommodated by thrusting, extensional collapse and lateral extrusion of still thermally weak crust on orogen-parallel strike-slip faults, resulting in formation of the west-east-striking Isa Superbasin, isothermal decompression and granite intrusion from 1620 Ma. A comparable record of deformation, metamorphism, and magmatic intrusion from 1650 until 1600 Ma has been documented for northern and southern North America (Forward/Racklan and Mazatzal orogenies) indicating that Laurentia and Australia were likely proximal to each other throughout this period.

1. Introduction

Supercontinents have come and gone throughout Earth history, leaving behind a record of continental breakup and collision that transcends present-day ocean boundaries. Accordingly, much attention has been paid to the identification and matching of formerly contiguous passive margin sequences (Bradley, 2008), large igneous provinces (Ernst et al., 2008), or once continuous transcontinental orogenic belts (Betts et al., 2008; Burrett & Berry, 2000; Cawood & Buchan, 2007; Karlstrom et al., 2001) as a means of reconstructing these ancient continents. However, even where such constraints exist, consensus is far from guaranteed, particularly for reconstructions of the older Proterozoic Nuna and Rodinia supercontinents whose assumed building blocks have been repeatedly reworked during younger tectonic events and may not even be indigenous to the continent in which they are now embedded. Exemplifying this problem are the deformed late Paleo-Mesoproterozoic basinal sequences of western and southern Laurentia whose record of subduction rollback, backarc extension, and bimodal magmatism (Bickford et al., 2008; Whitmeyer & Karlstrom, 2007) is shared by basins of near-identical 1800–1580 Ma age in Proterozoic Australia, leading some researchers to conclude that they once lay along strike from each other (Figure 1a) and formed part of a single convergent plate margin (Betts et al., 2016; Giles et al., 2002; Karlstrom et al., 2001), whereas others have concluded that one or more of these same North American basinal sequences had their origins in the opposing Australian-Antarctic margin (Figure 1b) and are exotic to Laurentia (Furlanetto et al., 2016; Gibson et al., 2008; Gibson & Champion, 2019; Thorkelson & Laughton, 2016). In this alternative interpretation, the basinal sequences in question evolved independently of North America until brought together during a major

Figure 1. Alternative reconstructions for Australia and Laurentia in Nuna Supercontinent at 1720 Ma based on (a) single shared continuous convergent plate margin and common record of arc-backarc basin formation along strike (Betts et al., 2016; Karlstrom et al., 2001) and (b) no continuity along strike and Laurentia is separated from Paleoproterozoic eastern Australia by an intervening ocean basin or marginal sea (Pisarevsky et al., 2014); (c) closure of intervening ocean basin no later than 1650 Ma (Pisarevsky et al., 2014) leads to arc-continent collision, accretion of arc-backarc basin assemblages onto southern and western margins of Laurentia (Furlanetto et al., 2013; Gibson et al., 2017; Pisarevsky et al., 2014; Thorkelson & Laughton, 2016), and continent-continent collision, which continues through until circa 1600 Ma (this paper). NAC and SAC = North and South Australian cratons; MO, YAV and MAZ = Mojave, Yavapai and Mazatzal crustal provinces; BO = Bonnetia.

crustal thickening event at or before 1600–1580 Ma (Figure 1c) when they were thrust imbricated and emplaced over the Laurentian margin (Furlanetto et al., 2016; Gibson et al., 2017; Gibson & Champion, 2019; Thorkelson & Laughton, 2016). In a further variation on this theme, some researchers have suggested that late Paleoproterozoic basinal sequences making up much of the Georgetown Province in northern Australia may similarly be exotic with respect to their host continent but have North American affinities (Boger & Hansen, 2004; Nordsvan et al., 2018; Pourceau et al., 2018).

Regardless of differences in opinion about the provenance of any single basinal sequence, orogenesis during Nuna assembly was evidently more complex than existing tectonic models based on accretion along a single long-lived convergent plate margin would allow (Betts et al., 2016; Giles et al., 2002; Whitmeyer & Karlstrom, 2007) and new models are required that better reflect the role played by continental collision processes. Here, we present such a model and argue that orogenesis and crustal growth during formation of the Nuna Supercontinent likely occurred through processes not unlike those that produced the present-day

European Alps and Himalayan Mountain Belt (Aitchison et al., 2007; Ding et al., 2005; Searle et al., 1988; Stampfli & Hochard, 2009; Yin & Harrison, 2000), involving multiple ocean basin closures and accretionary events before culminating in crustal thickening, continent-continent collision and the redistribution of crustal blocks through lateral escape via regional-scale crustal extension, thrusting and strike-slip faulting. As in previously published tectonic interpretations (Betts et al., 2016; Whitmeyer & Karlstrom, 2007), subduction and convergent margin processes are retained as important drivers of orogenesis except that there is no common plate boundary or continuity of these processes along strike from one continent into the other. Instead, Laurentia and Australia-Antarctica are interpreted to have lain on different tectonic plates (Figures 2a and 2b) and remained separate from each other from 1800 Ma until at least 1650 Ma (Gibson et al., 2008; Gibson et al., 2018; Thorkelson & Laughton, 2016).

2. Paleoproterozoic Eastern Australia: Basin History and Tectonic Setting

Variably deformed basinal sequences of 1800–1600 Ma age and greenschist to granulite facies metamorphic grade extend for several thousand kilometers along the entire length of Proterozoic eastern Australia from McArthur River in the north through the Mount Isa and Georgetown Provinces into the Curnamona and Gawler cratons (Figure 2a). As the repository of several world class mineral deposits (e.g., Mount Isa, McArthur River, and Broken Hill), these sequences have attracted considerable geological interest and most researchers are now agreed that basin development occurred in three successive cycles (Gibson et al., 2016; Jackson et al., 2000; Southgate, Bradshaw, et al., 2000). The oldest cycle, represented by the 1790–1740 Ma Leichhardt Superbasin in northern Australia (Figure 3) and correlative Wallaroo and Hutchison groups farther south (Figure 4) in the Gawler craton (Cowley et al., 2003; Hand et al., 2007; Szpunar et al., 2011), marks the onset of lithospheric extension and comprises kilometer-thick piles of tholeiitic basalt and rhyolite interstratified with subordinate but still substantial volumes of cross- and trough-bedded quartzite and feldspathic sandstone deposited in a fluvial to shallow marine environment (Betts et al., 2006; Betts et al., 2016; Gibson et al., 2008; Gibson et al., 2018; Jackson et al., 2000; Withnall & Hutton, 2013). Basaltic rocks were erupted through an older ≥ 1840 Ma continental basement and in sufficiently large volumes across northern Australia to warrant the term large igneous province (Gibson et al., 2018; Scott et al., 2000). They have been compared to 180 Ma continental flood basalts in southern Africa (Karoo) and share many of the same compositional characteristics, including a subduction or arc-like geochemical signature thought to reflect decompressional melting of a metasomatically enriched or crustally contaminated lithospheric mantle (Gibson et al., 2018; Gregory et al., 2008; Scott et al., 2000). A backarc intracontinental rift setting for basaltic magmatism is widely accepted although no corresponding agreement has yet been reached on the position of the contemporary subduction zone and magmatic arc which have been variously located (Figures 1a and 2a) along the southern edge of the Arunta Block in central Australia (Betts et al., 2006; Betts et al., 2008; Giles et al., 2002; Karlstrom et al., 2001; Scott et al., 2000) or farther outboard along the eastern or western margins of conjoined Australian and Antarctic continents (Betts et al., 2016; Gibson et al., 2016; Gibson et al., 2018). A position along the eastern margin of the Australian-Antarctic plate is adopted here (Figure 2a) consistent with the observation that the Leichhardt Superbasin and its correlative sequences farther south share a common north-south trend and likely comprise different parts of a single basin system formed through west-east-directed crustal extension. Given the orientation of this system, it seems further likely that subduction dipped westward and retreated oceanward over time (along with the magmatic arc) so as to not only facilitate thinning of the lithosphere but generate ever increasing amounts of accommodation space in the overriding Australian plate. Accordingly, basin depocenters in northern and southern late Proterozoic Australia not only deepened over time but shifted eastward where basaltic rocks (Marraba Volcanics) are interstratified with stromatolite-bearing carbonate rocks in addition to shallow-marine quartzite and sandstone (Gibson et al., 2018; Withnall & Hutton, 2013).

Following a brief episode of uplift and erosion linked to late-stage basin inversion and/or block faulting toward the close of Leichhardt time, the next cycle (Figures 3 and 4) commenced with the 1730–1640 Ma Calvert Superbasin (Betts, 1999; Betts et al., 2006; Blaikie et al., 2017; Gibson et al., 2012; Gibson et al., 2018; Jackson et al., 2000; Withnall & Hutton, 2013). During this cycle, the area undergoing intracontinental rifting and backarc extension greatly expanded, precipitating further bimodal magmatism and sedimentation in fault-bounded basins as far afield as the Georgetown and Curnamona provinces (Betts et al., 2006; Gibson et al., 2018; Withnall & Hutton, 2013). Bimodal volcanism and sedimentation

Figure 2. (a) Distribution of dominant late Paleoproterozoic basinal sequences in eastern Australia versus western and southern Laurentia based on configuration from Figure 1b; (b) configuration subsequent to continent-continent collision as per Figure 1c. Cross sections for arc-continent and continent-continent collision are for northern Australia-northwest Canada (Gibson et al., 2017) but apply equally to southern Australia-Antarctica and southern Laurentia (Gibson & Champion, 2019).

in northern Australia initially occurred under subaerial conditions as evidenced by the deposition of coeval conglomerates, cross-bedded quartzite and redbeds (Betts et al., 1999; Blaikie et al., 2017; Gibson et al., 2008; Jackson et al., 2000), but, by 1690 Ma, the floor of the basin had begun to rapidly subside in the east and basaltic rocks were increasingly erupted and/or intruded into a deep marine environment dominated by turbidites while shallow marine sandstones and siltstones continued to accumulate in the west (Southgate et al., 2013; Withnall & Hutton, 2013). A similar change from shallow to deep water sedimentation is evident in the Georgetown region (Withnall & Hutton, 2013) and 1730–1670 Ma lower Willyama Supergroup (Figure 4) farther south in the Curnamona Province (Conor & Preiss, 2008; Willis et al., 1983). With ongoing rifting, basaltic compositions shifted toward more MORB (mid-ocean ridge basalt)-like compositions as the underlying lithospheric mantle was either replaced by less metasomatically enriched sources or became so vanishingly thin as to allow the asthenosphere to rise to much shallower crustal levels (Gibson et al., 2018; Rutherford et al., 2006; Withnall & Hutton, 2013). Basaltic magmatism and backarc extension concluded at circa 1655 Ma at which point the magmatic arc that had been developing off the eastern margin of Australia-Antarctica since 1790 Ma split off and severed all connection with the rest of the continent. Proterozoic eastern Australia-Antarctica then lay along the inboard side of a fully mature backarc basin or marginal sea not unlike those observed today in the western Pacific Ocean (Gibson et al., 2012; Gibson et al., 2018; Lambeck et al., 2012; Southgate et al., 2013; Withnall & Hutton, 2013).

In the absence of any further basaltic magmatism, the entire eastern seaboard of Paleoproterozoic Australia-Antarctica began to cool and thermally subside from 1655 Ma if not earlier. Passive margin conditions ensued and the newly formed rifted continental margin was buried beneath a postrift blanket of thin-bedded turbidites, black carbonaceous shales, dolomitic siltstones, and carbonate rocks (Gibson et al., 2012; Gibson et al., 2018; Southgate et al., 2013; Withnall & Hutton, 2013). Moreover, given that ≤ 1650 Ma thin-bedded sandstones and carbonaceous shales in the Georgetown region (Townley and Heliman Formations; Figure 4) would appear to be part of this same postrift sequence (Gibson et al., 2018) and similarly overlie an older turbidite sequence hosting ≥ 1655 Ma basaltic rocks (Neumann & Kositsin, 2011), it is debatable

Figure 3. Stratigraphic and magmatic map for Mount Isa region with superposed fault trends. Note that minor NW trending faults of mainly Calvert age are repeatedly offset and displaced by the more dominant NE trending basement structures of mainly strike-slip origin. Magmatic units of various ages displaced by these large strike-slip faults typically exhibit dextral offsets. Insets show areas for which detailed structure or seismic images are available (see below).

whether these rocks originated elsewhere and once formed part of western Laurentia (Nordsvan et al., 2018). Instead, these rocks and their underlying turbidite sequence were deposited further outboard from the continental margin and represent a more distal fraction of the Calvert Superbasin (Figure 2a). The abnormally high number of Archean ages reported from detrital zircons in older parts of the Georgetown sequence (Neumann & Kositsin, 2011) remains problematic but need not point to a North American provenance for these sediments (Nordsvan et al., 2018) so much as a change in local source area as the magmatic arc and its older ≥ 1840 Ma continental substrate were extensionally exhumed as they retreated eastward (Gibson & Champion, 2019).

Passive margin conditions persisted for only a few million years, and by 1650 Ma, if not earlier, the Calvert Superbasin was being inverted and intensely deformed in a tectonic event (Riversleigh Tectonic Event; Figure 4) thought to have been occasioned by a reversal in plate motion (Idnurm, 2000) and onset of north-south to northeast-southwest-directed crustal shortening (Abu Sharib, 2012; Gibson et al., 2012; Gibson et al., 2017; Rubenach et al., 2008; Sayab, 2005; Withnall & Hutton, 2013). A switch to west-east shortening followed shortly thereafter (Gibson et al., 2016; Gibson et al., 2017), during the course of which crustal extension resumed in a north-south direction (Bradshaw et al., 2000; Gorton & Troup, 2018), leading to formation of the 1640–1580 Ma Isa Superbasin and deposition of a further 4–6 km of deep marine carbonaceous shale, dolomitic siltstone and turbidites in fault-bounded basins mainly oriented west-east (Figures 3 and 5a). These basins and their sedimentary fill make up the third cycle of basin development (Figure 4) but unlike the previous two cycles, deposition of the Isa Superbasin was unaccompanied by basaltic magmatism and, save for the occasional thin horizon of intercalated tuff or 1620 Ma rhyolite, igneous activity was subdued or absent altogether (Gibson et al., 2018). Stratigraphically equivalent parts of the Willyama Supergroup (upper Paragon Group) are similarly lacking in synsedimentary magmatic rocks (Figure 4) and, like the Isa Superbasin, were previously interpreted to be entirely of postrift origin and represent the sag phase of basin development (Betts et al., 2003; Connor & Preiss, 2008;

Willis et al., 1983). However, as is clear from already published seismic reflection data for the Lawn Hill Platform (Figure 5b), normal faulting and crustal extension did not cease at 1640 Ma but continued through until at least 1620 Ma when the Isa Superbasin was itself subjected to crustal shortening and basin inversion following onset of the Isa Orogeny (Bradshaw et al., 2000; Gibson et al., 2016; Gibson et al., 2017; Krassay et al., 2000; Southgate, Scott, et al., 2000). It is equally clear from the abrupt change in magmatic style and extensional direction after 1640 Ma, that tectonic conditions fundamentally changed after the Riversleigh Tectonic Event with the Isa Superbasin representing an entirely separate phase of basin development (Figure 4). A prominent hairpin bend in the apparent polar wander path for northern Australia at this time supports the case for significant tectonic change at 1640 Ma (Idnurm, 2000; Southgate, Scott, et al., 2000), and further suggests that it was externally imposed, most likely in response to collapse of the backarc basin as first the magmatic arc and then the leading edge of the Australian-Antarctic continent (Figure 2) collided with Laurentia (Gibson et al., 2016, 2017). This compares with other models for orogenesis in Paleoproterozoic Australia where successive deformational events are attributed to the accretion of continental ribbons and/or magmatic arcs around the peripheries of the North and South Australian cratons (Betts et al., 2016; Giles et al., 2002; Giles et al., 2004; Scrimgeour et al., 2005).

3. 1650–1640 Ma Regional Deformation (D1): The Riversleigh Tectonic Event

Except for brief intervals of basin inversion at the end of both Leichhardt and Calvert time (Blaikie et al., 2017; Southgate, Scott, et al., 2000), the period from 1790 until 1650 Ma in northern Australia was dominated

Figure 4. Space-time plots matching supersequences of northern Australia against lithostratigraphy, orogenic events, and major phases of basin formation in crustal provinces making up Paleoproterozoic eastern Australia (modified from Gibson et al., 2008; Page et al., 2005; Southgate, Bradshaw, et al., 2000; Withnall & Hutton, 2013). Note that boundary between Calvert and Isa Superbasins is placed at 1640 Ma based on seismic, structural, and paleomagnetic evidence (Gibson et al., 2017; Idnurm, 2000) rather than at 1670 Ma as previously argued by Southgate, Bradshaw, et al. (2000). For comparison, a stratigraphic column for northern Canada (western Laurentia) is included (after Furlanetto et al., 2016).

by extensional rather than contractional processes, producing fault-bounded asymmetric basins or half-graben with mainly north-south or northwest-southeast orientations (Derrick, 1982; Gibson et al., 2008; Gibson et al., 2012; Lister et al., 1999; O'Dea et al., 1997; Withnall & Hutton, 2013). With onset of the Riversleigh Tectonic Event, tectonic conditions abruptly changed and basinal sequences in both northern and southern Australia were subjected to an episode of south or southwest directed crustal shortening, transforming basin fill into NNW-SSE trending anticlinoria with upright to moderately overturned limbs and shallow-plunging axes. Asymmetric folds of this age have historically been labeled D1 in northern Australia (Figure 6) and have been mapped across the entire region from Mount Isa in the west to

Figure 5. (a) Basin and basement architecture for northern Lawn Hill Platform showing main depocenters and fault trends for Isa Superbasin (Gorton & Troup, 2018; FrogTech Geoscience, 2018). Also shown are government (06GA-M2; Geoscience Australia) and industry seismic survey lines from 1994 (Comalco) and 2011 (Teck Resources) across the Isa Superbasin and adjacent Riversleigh Fault and Punjab Structure (P). Note compartmentalization of depocenters brought about by interference between the ENE and NW trending faults; the 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. (b) Interpreted seismic image across the Riversleigh Fault and part of Lawn Hill Platform hosting the Century Pb-Zn deposit (modified after Gibson et al., 2017). Image shows onlap of younger stratigraphic units (≤ 1595 Ma Lawn and Wide supersequences) onto anticlines developed in hanging walls of both the master structure and a subsidiary footwall shortcut thrust to the west. Note also onlap of older ≤ 1640 Ma River Supersequence onto sedimentary units making up the underlying Calvert Superbasin. Section is about 10 km deep or 4 s two-way-time (TWT); CDP = common depth point. Color coding as per Figures 3 and 4.

Georgetown in the east (Abu Sharib, 2012; Cihan et al., 2006; Withnall & Hutton, 2013). They deform all parts of the Calvert Superbasin up to and including the 1670–1650 Ma postrift fraction (Gun Supersequence; Figure 4), which, along with the immediately overlying ≤ 1650 Ma Loretta Supersequence (Figure 4), had already been truncated and deeply eroded before the Isa Superbasin had even been deposited (Gibson et al., 2017; Southgate, Scott, et al., 2000). As much as 1,700 m of stratigraphic section is estimated to have been lost from the Loretta and Gun supersequences on the northern Lawn Hill Platform (Bradshaw et al.,

Figure 6. (a) Principal tectonostratigraphic elements for McArthur River and Mount Isa regions. Note most are bounded by either NE or NW trending faults; insets show areas where basin architecture and regional structure are known in detail from either seismic imaging or mapping; (b) D1 and D2 fold trends in the Mitakoodi Anticlinorium (Culmination) and Snake Creek Anticline (after O'Dea et al., 2006; Sayab, 2005; Abu Sharib, 2012; Rubenach et al., 2008; Withnall & Hutton, 2013). Note that D1 structures are for the most part oriented west-east, whereas younger D2 structures like the Snake Creek Anticline strike north-south consistent with a change from northeast-southwest shortening during D1 (Riversleigh Event) to west-east shortening during D2 (Isa/Olary orogeny).

2000; Southgate, Scott, et al., 2000) where the two units conspicuously thin northward through a combination of erosion and onlap before pinching out completely south of the Murphy Inlier (Figure 6a). Seismic images (Figure 7) further indicate that this amount of erosional loss is not the result of fault-block rotation and

Figure 7. Uninterpreted and interpreted composite north-south seismic images for unexposed section through northern Lawn Hill Platform and Bluebush Pb-Zn Prospect showing large inversion structure or periclinal fold of probable Riversleigh age (ca. 1650 Ma) cored and partly dismembered by thrust faults (see Figure 5 for location of section). This fold (here named the Punjaub Structure) served as a structural high during deposition of the onlapping River and Term supersequences. It is uncertain from the image whether folding predates or formed synchronously with deposition of these two units although the northern flank of the fold is cut by normal faults into which both units thicken. Conversely, Calvert-age units (blue) in the core of the fold maintain uniform thickness throughout before thinning northward through onlap and truncation. Note particularly prominent truncation surfaces at top and base of Loretta Supersequence indicating significant erosion occurred immediately prior and subsequent to deposition of this unit.

consequent peneplanation of rift shoulders and other structural highs created during normal faulting. Rather, the evidence points to uplift and truncation during a deformational event of considerable regional significance, commencing at or before deposition of the Loretta Supersequence and continuing through until the last of this unit was deposited at 1640 Ma (Figure 4).

Lending further support to this interpretation is the unexposed but seismically imaged Punjaub Structure which deforms the aforementioned erosional surfaces and served as a structural high during deposition of both the River and Term supersequences (Figure 7). These two units not only lap onto the flanks of this large periclinal fold but would appear to become conspicuously thinner over the crest of the structure (Figure 7), indicating that the structural high either already existed or formed contemporaneously with sedimentation. Conversely, older units of Calvert age making up the core of the fold maintain uniform thickness throughout and more importantly do not appear to thicken into the low-angle fault developed at the base of the structure (Figure 7). Along with the periclinal fold developed in its hanging wall, this low-angle fault formed early, most likely during north-south shortening and is cut and displaced by younger north dipping structures into which both the River and Term supersequences appear to thicken (Figure 7). These relations are more in keeping with a first generation fold that predates deposition of the River and Term supersequences but underwent disruption once north-south extension commenced at circa 1640 Ma.

Much the same relationship has been reported (Gibson et al., 2016; Gibson et al., 2017) for the Century Mine region (Figure 6a) farther south where the River and Term supersequences similarly overlie an already folded and thrust-faulted sequence of Calvert age east of the Riversleigh Fault (Figure 5b). Along with the Punjaub Structure, earlier-formed folds and thrusts in this region belong to the same generation of early D1 structures developed more widely across the Mount Isa and Georgetown regions and which share a common west-east orientation. These folds typically have a slaty cleavage or schistosity (S1) as the main axial plane fabric and demonstrably predate the main phase of deformation and

Figure 8. Pressure-temperature-time paths for metamorphism and successive tectonothermal events in the eastern Mount Isa, Georgetown, and Curnamona (Broken Hill) regions based on information compiled from literature (Abu Sharib, 2012; Boger & Hansen, 2004; Cihan et al., 2006; Forbes et al., 2005; McFarlane & Frost, 2009; Pourteau et al., 2018; Rubenach et al., 2008; Sayab, 2006). Note clockwise or looping path for Willyama Supergroup and Snake Creek Anticline in Mount region consistent with an initial phase of crustal thickening or higher-pressure metamorphism before isothermal decompression and later episode of low-pressure-high-temperature metamorphism. Curnamona and Gawler cratons are shown in their original and present-day positions.

folding accompanying the Isan Orogeny (D2) whose axial plane fabric is more typically a north-south striking crenulation cleavage (Stewart, 1992; Winsor, 1985; Withnall & Hutton, 2013).

Well-documented examples of second generation structures overprinting an older set of upright west-east trending D1 folds (Figure 6b) include the Mitakoodi Anticlinorium (O'Dea et al., 2006; Potma & Betts, 2006) and Snake Creek Anticline east of the Leichhardt-Kalkadoon block (Abu Sharib, 2012; Rubenach et al., 2008; Sayab, 2005). Folds of D1 age overprinted by the Snake Creek Anticline (Figure 6b) invariably deform an even earlier pre-D1 fabric, producing a west-east trending crenulation cleavage (Abu Sharib, 2012), which has led some researchers (Giles et al., 2006) to conclude that these folds are no different in age to the Snake Creek Anticline (Figure 6b) for which an Isan or D2 age is more generally accepted (Abu Sharib, 2012; Foster & Rubenach, 2006; Rubenach et al., 2008). The alternative interpretation is that this pre-D1 fabric is of extensional origin (Abu Sharib, 2012; Rubenach et al., 2008) and predates the Riversleigh Tectonic Event. Significantly, this pre-D1 fabric is overprinted by kyanite-staurolite-garnet-bearing mineral assemblages for which monazite ages dating back to 1650 Ma have been reported (Abu Sharib, 2012; Rubenach et al., 2008). Conversely, the north-south trending D2 fabric is associated with andalusite-sillimanite-bearing mineral assemblages which typically yield ages as young as 1580 Ma (Abu Sharib, 2012; Giles & Nutman, 2002; Rubenach et al., 2008). These two deformational events are separated by as much as 60 Myr during the course of which the thermal regime fundamentally changed because, by 1580 Ma, kyanite was no longer the stable aluminosilicate polymorph and metamorphism was taking place under low-pressure as opposed to intermediate-pressure conditions (Rubenach et al., 2008; Sayab, 2006). Moreover, this same change in metamorphic conditions from one deformational event to the next is not confined to the Soldiers Cap Group but appears to have been replicated across formerly contiguous parts of Paleo-Mesoproterozoic eastern

Australia, including the Georgetown and Curnamona Provinces (Abu Sharib, 2012; Cihan et al., 2006; Gibson et al., 2004; Rubenach et al., 2008; Sayab, 2005; Sayab, 2006).

4. Post-1650 Ma Metamorphism in Proterozoic Eastern Australia

As in Soldiers Cap Group, low-pressure-high-temperature andalusite-sillimanite-grade mineral assemblages yielding 1600–1580 Ma monazite or zircon ages are pervasively developed throughout both the Curnamona (Willyama Supergroup) and Georgetown Provinces (Einsleigh Metamorphics) (Forbes et al., 2005; Giles et al., 2002; McFarlane & Frost, 2009; Page et al., 2005; Rubenach et al., 2008; Sayab, 2006). Notwithstanding the intensity of metamorphism at this time, vestiges of an older 1650 Ma intermediate- to higher-pressure tectonothermal event of equivalent age to the Riversleigh Tectonic Event are widely preserved and, in the Georgetown region, include Barrovian-style staurolite-garnet-bearing mineral assemblages for which metamorphic pressures of 6–7 kb (Figure 8) have been reported (Boger & Hansen, 2004; Cihan et al., 2006). These assemblages are a product of the same event that gave rise to kyanite grade metamorphism in the Snake Creek Anticline and derive from parts of the sequence that had already been recumbently folded and thickened (D1) before the main phase of west-east directed crustal shortening and orogenesis (D2) began at 1620–1580 Ma (Boger & Hansen, 2004; Withnall & Hutton, 2013). They are consequently likely to be a product of D1 crustal thickening consistent with the observation (Cihan et al., 2006) that metamorphism followed a clockwise pressure-temperature-time path (Figure 8). Crustal thickening was driven by north-south shortening and produced recumbent folds with mainly west-east orientations (Boger & Hansen, 2004; Withnall & Hutton, 2013). By way of contrast, andalusite-sillimanite-grade metamorphism subsequent to north-south shortening followed an anticlockwise and probable looping pressure-temperature-time path (Figure 8) in which metamorphic pressures barely exceeded 4 kb (Pourteau et al., 2018).

Barrovian-style metamorphic mineral assemblages have not been identified in the Willyama Supergroup (Figure 4) although by 1650 Ma parts of the sequence had already been buried to crustal depths consistent with the formation of 6–8 kb garnet granulite assemblages from which most of the older monazite ages derive (McFarlane & Frost, 2009). It is further evident from the ≤ 10 km stratigraphic thickness of the Willyama Supersequence (Willis et al., 1983) that these pressures were attained subsequent to rifting and represent an entirely separate tectonothermal event. As in Soldiers Cap Group and the rocks of Georgetown, the most likely cause of this higher-pressure metamorphism is early recumbent folding and shortening leading to crustal thickening. Recumbent to isoclinal folding is developed at all scales across the Willyama Supergroup, and depending on the significance and level of recognition afforded to an earlier-formed, layer-parallel schistosity (S1) has been variously labeled D1 or D2 (Forbes et al., 2005; Gibson et al., 2004; Hobbs et al., 1984; Marjoribanks et al., 1980). An extensional origin for this earlier fabric is now generally accepted (Forbes et al., 2005, 2007; Gibson et al., 2004) in which case previous suggestions (Hobbs et al., 1984; Marjoribanks et al., 1980) that it formed axial planar to an even earlier cryptic but poorly preserved phase of isoclinal folding (D1) are unlikely to be correct.

Instead, only one phase of recumbent to isoclinal folding ever occurred and it concluded before all of the Willyama Supergroup had been deposited because, by 1640 Ma, the Curnamona Province was again undergoing extension along with the rest of Proterozoic eastern Australia as the upper Paragon Group was being laid down (Gibson et al., 2016; Gibson et al., 2017). As in northern Australia, crustal extension ceased at 1620 Ma, and all parts of the Willyama Supergroup underwent renewed but limited amounts of crustal thickening accompanying northwest directed folding and thrusting during the Olary Orogeny (Forbes et al., 2005; Gibson et al., 2004; Hobbs et al., 1984; Marjoribanks et al., 1980). Metamorphism during this deformational event peaked at 4–6 kb (Phillips, 1981; Powell & Downes, 1990; Wilson & Powell, 2001) and exhibits an anticlockwise pressure-temperature-time path (Figure 8) consistent with an initial episode of crustal thickening followed by extensional unroofing and isobaric cooling during the later stages of deformation (Gibson et al., 2004; Hobbs et al., 1984). Post-D1 metamorphism in the Willyama Supergroup, Mount Isa, and Georgetown Provinces thus share broadly similar anticlockwise pressure-temperature-time paths although peak pressures in all three regions were well below those obtaining during crustal shortening at 1650 Ma (6–8 kb; Figure 8), reinforcing the

observation made here that the crust appreciably thinned subsequent to 1640 Ma and before the onset of west-east shortening accompanying the Isa and Olary orogenies at circa 1600 Ma (see also Forbes et al., 2005). Moreover, not all of this metamorphism is down to crustal extension because in some parts of the Isa Superbasin, basin formation was accompanied by transpression and uplift along strike-slip faults active at the time of sedimentation (Hinman, 1995; Ireland et al., 2004; Southgate, Scott, et al., 2000).

5. Post-1640 Ma Strike-Slip Faulting in the Isa Superbasin

Strike-slip faulting coupled to right-lateral transtension followed by basin inversion and transpressive deformation along the eastern margin of the Batten Fault Zone in the McArthur Basin (Figure 6a) has long been recognized as key to understanding the controls on sedimentation during the initial stages of basin formation in the Isa Superbasin west of the Lawn Hill Platform (Davidson & Dashloot, 1993; Hinman, 1995). Bounding this trough on its eastern side is the regionally significant Emu Fault (Figure 6a). In seismic images, this structure has the characteristics of a positive flower structure (Rawlings et al., 2004) whose eastern flank served as a structural high and sediment source during deposition of the 1640 Ma Barney Creek Formation (Figure 4), shedding coarse sediment and conglomeratic debris flows westward into a rapidly subsiding deep marine basin that was already undergoing shortening before the last of this formation had been laid down (Hinman, 1995; Ireland, Bull, & Large, 2004). The Barney Creek Formation thus incorporates an uppermost less deformed condensed section that onlaps and unconformably overlies a much more steeply dipping, folded and reverse-faulted lower section (Hinman, 1995). Transpression evidently commenced before the last of the unit had been deposited, mirroring the situation farther east on the Lawn Hill Platform (Figure 6a) where the temporally equivalent River Supersequence was similarly deposited during or subsequent to a period of folding and thrusting (Figure 7; Gibson et al., 2016). Geochronological data would further suggest that equivalents of this and other sedimentary units making up this part of the Isa Superbasin extend northwards from the southern McArthur Basin into the correlative fault-bounded Walker Trough to the north (Figure 9a) (Munson, 2019).

Farther east on the Lawn Hill Platform (Figure 6a), the Punjaub Structure (Figure 7) similarly served as a structural high during deposition of the temporally equivalent River Supersequence (Figure 4) and may be an expression of the same tectonic event. A transpressive as opposed to purely compressive tectonic environment for formation of the Punjaub Structure cannot therefore be entirely discounted, consistent with the observation that this part of northern Australia had already undergone a significant amount of deformation at or before 1640 Ma and may have continued to be uplifted and eroded before sedimentation in this unit concluded. Interestingly, sedimentary rocks in the upper part of the Willyma Supergroup are reported to have undergone an abrupt change in sedimentary provenance about this same time (Barovich & Hand, 2008) and may be recording the same tectonic event with material eroded from northern Australia being shed southward into the then formerly contiguous Curnamona Province. This observation aside, tectonic conditions elsewhere on the Lawn Hill Platform were very different with both the River and Term supersequences being deposited in a rapidly deepening basin (Figure 5a) controlled by north-south directed extension and strike-slip reactivation of older Calvert-age normal faults (Bradshaw et al., 2000; Gorton & Troup, 2018; Scott et al., 1998; Southgate, Scott, et al., 2000). The latter were reactivated in a right-lateral sense, commonly offsetting the younger extensional structures and effecting a compartmentalization of the Isa Superbasin into several subbasins bounded by two mutually crosscutting and nearly orthogonal fault sets (Figure 5a). The older reactivated structures strike NNW and include the Riversleigh Fault into which both the River and Term supersequences conspicuously thicken (Gibson et al., 2016; Gibson et al., 2017). However, as other seismic sections for the Lawn Hill Platform make clear, this thickening was subordinate to that associated with the more dominant ENE trending extensional faults of Isan age (Bradshaw et al., 2018; Gorton & Troup, 2018). Accordingly, while strike-slip faulting was an important part of the basin-forming process, it was secondary to north-south extension and probably only came about because the older Calvert-age structures lay oblique to the principal extensional direction and were thus suitably oriented for reactivation during formation of the Isa Superbasin. An element of transtension or transpression is implied although, contrary to some earlier interpretations (Southgate, Scott, et al., 2000), deposition of the River and Term supersequences was not limited to narrow fault-bounded pull-apart basins but occurred over a much wider area (Figure 5a) before

terminating in an episode of postextensional thermal subsidence immediately prior to onset of the Isa orogeny at 1620–1615 Ma (Figure 4).

6. 1620–1580 Ma: Basin Closure and Inversion

Beginning around 1615 Ma or slightly earlier, rocks in the Isa Superbasin and Willyama Supergroup were subjected to west-east crustal shortening and began to invert, heralding onset of the Isa and Olary orogenies (Figure 4). Sedimentation nevertheless continued uninterrupted on the Lawn Hill Platform, producing the ≤ 1615 Ma Lawn and ≤ 1595 Ma Wide supersequences (Figure 4), both of which thin through onlap over the crests of actively growing anticlines developed in the hangingwalls (Figure 5b) of reactivated NNW trending normal faults (Gibson et al., 2017). A syn-tectonic depositional origin for these two supersequences is implied consistent with more recently acquired seismic data (Carr et al., 2019) indicating that any thinning and loss of accommodation space over the crests of these folds was more than matched by an increase in sedimentation in the footwalls of these same inverted normal faults (Figure 5b). Footwall basins not only contain a substantially greater volume of these two units but have a synclinal geometry (Figure 5b) not unlike that expected in response to loading of the crust during contemporaneous thrust faulting. The Doom Supersequence (Figure 4) followed on from both these units and may also form part of the footwall sequence but is not preserved in any hangingwall structure imaged to date, either because it was lost to erosion or never deposited in the Lawn Hill area. A syn-tectonic origin for this unit is nevertheless inferred because, like the other two units, it too thins onto the northern flank of the Punjaub Structure (Figure 7). Alternatively, the Punjaub Structure already existed and the thinning is simply due to post-inversion filling of the last remaining accommodation space over the crest and flanks of the fold. Either way, by the time sedimentation in the Isa Superbasin came to a close circa 1580 Ma (Southgate, Bradshaw, et al., 2000), a significant volume of sediment had been shed westward into a basin that has all the hallmarks of a foreland basin, whereas farther east in northern and southern Australia, rocks that had originally been buried to lower crustal depths during recumbent folding were being partially unroofed and subjected to further metamorphism under low-pressure-high-temperature conditions. These temporally equivalent events are separated by hundreds of kilometers and make for a long-lived, variably complex orogenic system that is continental in scale and on par with the collisional belts of the Himalaya and European Alps (Figure 9a).

7. Discussion

Despite a wealth of geochronological data that Proterozoic eastern Australia underwent major deformation and metamorphism as early as 1650–1640 Ma, it is often assumed that orogenesis, and more particularly the Isa and Olary orogenies, did not commence until all sedimentation in the Isa Superbasin and Willyama Supergroup had been completed (e.g., Southgate, Bradshaw, et al., 2000; Conr & Preiss, 2008). In this view, there is a causal relationship between basin closure and the onset of orogenesis. Conversely, no such relationship is recognized here and crustal shortening in the Isa Superbasin is thought to have been already well advanced on the Lawn Hill Platform before the last of the sedimentary units had been deposited. Abrupt changes in sedimentary provenance and Sm-Nd isotopic signatures at or around 1640 Ma (Barovich & Hand, 2008; Lambeck et al., 2012) point to an even earlier start to uplift and erosion, requiring a significant change in the tectonic landscape and distribution of sedimentary sources from this time forward. Formation of the Punjaub Structure (Figure 7) and ongoing transpression and uplift along the Emu Fault and related structures during deposition of the Barney Creek Formation (Hinman, 1995) would further indicate that crustal shortening continued after 1640 Ma and became ever more widely distributed, accommodated by lateral escape of previously overthickened crust in the more proximal McArthur and Mount Isa regions and related basin inversion further afield in central Australia (1640–1635 Ma Leibig and 1610–1600 Ma Chewings events). Lateral escape was facilitated by a combination of strike-slip faulting and north to NNE directed extensional collapse, which not only served to thin the crust and produce low as opposed to intermediate- or higher-pressure Barrovian metamorphic conditions but led to deposition of the River and Term supersequences in west-east oriented half-graben on the Lawn Hill Platform (Figure 5a). Strike-slip faulting occurred mainly on older, regional-scale NE trending basement structures (Figure 3), which were reactivated in a dextral sense during the process (Figure 9a). The Mount Isa region is host to many such structures (e.g., Mount Gordon, Pilgrim and Fountain Range fault zones), some of which have effected off-sets of 20 km or more (Figure 3) and were evidently active both during and after onset of the Isa Orogeny

Figure 9. Comparative maps of (a) late Paleoproterozoic eastern Australia and western Laurentia versus the (b) Himalaya-Tibetan orogenic system (after Yin & Harrison, 2000; Tapponier, 1982) showing distribution of regionally significant normal faults and coeval strike-slip faults and their relationship to the inferred direction of plate convergence and lateral escape as crustal shortening and continent-continent collision progress. For Paleoproterozoic Australia crustal extension and shortening overlapped both spatially and temporally from 1650 Ma (Riversleigh Event) until the conclusion of the Isa/Olary orogeny at 1595 Ma.

because basin and normal fault polarity in the Leichhardt and Calvert superbasins change across them (e.g., Mount Gordon Fault Zone; Gibson et al., 2012), while granites of the 1760–1740 Ma Wonga Suite or younger 1550–1500 Ma Williams Batholith are either cut or offset by these same structures (Figure 3). Total cumulative dextral displacement on these reactivated strike-slip faults is difficult to estimate but likely involves several hundred kilometers, which, in combination with crustal extension, promoted isothermal decompression, crustal melting and granite intrusion, and also possibly the flare-up in silicic volcanism represented elsewhere in Australia by the 1594 Ma Gawler Range Volcanics (Hand et al., 2007).

Granites of 1590–1580 Ma age (Mundi Mundi Suite; Figure 4) occur widely throughout the Willyama Supergroup (Page et al., 2005) and were emplaced around the same time as low-pressure-high-temperature metamorphism peaked in the Mount Isa and Georgetown regions (Cihan et al., 2006; Rubenach et al., 2008; Withnall & Hutton, 2013). Metamorphism during the Isa and Olary orogenies evidently occurred under greatly reduced pressures compared to the earlier event at 1650 Ma and was largely driven by magmatic intrusion. Thermal gradients during these two events are estimated to have been as high as 40–60°/km (Foster & Rubenach, 2006; Powell & Downes, 1990) with metamorphism in both cases predictably following a looping or anticlockwise pressure-temperature-time paths in which peak pressures barely or just exceeded the aluminosilicate triple junction at 4 kb (Figure 8). Either crustal thickening associated with the Isa and Olary orogenies had already concluded before the bulk of metamorphism and magmatic intrusion took place or the widely observed D2 folding and thrusting of 1620–1580 age failed to appreciably thicken the crust owing to ongoing uplift and erosion during basin inversion as revealed in seismic reflection data for the Lawn Hill Platform (Gibson et al., 2017). In either case, recent suggestions that deformation accompanying the Isa and Olary orogenies marks the onset of supercontinent assembly and collision between Australia and Laurentia at around 1600 Ma (Betts et al., 2016; Pourteau et al., 2018) may have to be reassessed. Instead, supercontinent assembly commenced significantly earlier during the 1650–1640 Ma Riversleigh Tectonic Event and continued through until at least 1600 Ma. Given the amount of strike-slip faulting and basin segmentation incurred during continental collision, it seems further likely that neither extensional collapse nor basin inversion were mutually exclusive processes or occurred at different times across the Isa Superbasin. Rather, new extensional depocenters were continually being generated even while others were being inverted. Previous suggestions (Betts et al., 2003; Betts et al., 2016) that the Isa Superbasin represents a sag basin punctuated by periods of basin extension and inversion are not entirely dissimilar to this interpretation but differ in several important respects, not least of which is a much more dynamically active depositional environment where thermal subsidence has yet to commence and the crust continues to thin through extensional processes. Crustal thinning rather than thermal subsidence likely drove the increase in accommodation space during formation of the Isa Superbasin.

Conversely, crustal thickening is unlikely to have followed or outlasted low-pressure-high-temperature metamorphism in the Snake Creek Anticline and other well-studied structures of Isan age across the Mount Isa region (Figure 6b). Their axial plane fabrics are consistently overprinted by andalusite- and sillimanite-bearing assemblages from which 1600–1580 Ma metamorphic monazite ages have been reported (Abu Sharib, 2012; Rubenach et al., 2008). These fabrics and mineral assemblages are no different in age to those described from the Georgetown Province (Pourteau et al., 2018) and similarly contain relicts of an earlier higher-pressure (6–7 kb) mineral assemblage made up of kyanite, staurolite, and garnet (Boger & Hansen, 2004; Cihan et al., 2006). Tellingly, in the case of the Snake Creek Anticline, this older mineral assemblage is entirely preserved within the interior of andalusite and sillimanite porphyroblasts and is unequivocally older, predating both the D2 folds and their axial plane crenulation cleavage in the core of the structure (Abu Sharib, 2012; Rubenach et al., 2008; Sayab, 2006). Monazite dates of 1650 Ma obtained from this assemblage (Abu Sharib, 2012) support an older age for this higher-pressure event. The fact that kyanite may itself occasionally overprint an even older crenulation fabric and low-pressure cordierite-producing metamorphic event in the Snake Creek Anticline does not invalidate this interpretation because the latter is almost certainly of extensional origin (Abu Sharib, 2012; Rubenach et al., 2008). Similar relations have been observed in the Willyama Supergroup where a higher-pressure garnet-bearing assemblage (McFarlane & Frost, 2009) overprints an earlier-formed layer-parallel extensional fabric (Forbes et al., 2005; Gibson et al., 2004) and is itself overprinted by low-pressure-high-temperature andalusite-sillimanite-bearing assemblages formed at circa 1600 Ma (Figure 8). Significantly, this higher-pressure garnet granulite assemblage formed at 1650 Ma (McFarlane & Frost, 2009) and thus at the same time as the

Figure 10. Comparative time-space plots for major orogenic events in late Paleoproterozoic eastern Australia versus southern and western Laurentia (modified after Gibson et al., 2012).

kyanite-bearing assemblages in Snake Creek Anticline (Abu Sharib, 2012). This would suggest that the higher-pressure assemblages observed in all regions are manifestations of one and the same tectonic event and formed in response to crustal thickening accompanying the Riversleigh Tectonic Event. Accordingly, the Isa and Olary orogenies occurred long after the peak in crustal thickening and were imposed on a metamorphic pile that had either already undergone significant thinning immediately following the Riversleigh Event or continued to extend even as it was being shortened (Figure 9a).

This is not unlike the situation in mountain belts like the Himalayas and adjoining Tibetan Plateau (Figure 9b) where crustal extension and shortening are not mutually exclusive processes but coexist in crust that has been thickened by more than 50% (Liu & Yang, 2003). At this stage in any mountain belt, it becomes more energy efficient for further shortening to be accommodated not by increased thickening and higher topographic relief but lateral escape of material away from the point of convergence (Figure 9b), typically through a combination of orogen-parallel strike slip faulting and extension (Hintersberger et al., 2010; Rutte et al., 2017; Tapponnier et al., 1982; Taylor et al., 2003; Yin & Harrison, 2000). Very similar conditions may have been met in Proterozoic eastern Australia during or immediately subsequent to the Riversleigh Tectonic Event where a passive margin sequence originally no more than 13–15 km thick (Gibson et al., 2012; Gibson et al., 2018; Withnall & Hutton, 2013) was recumbently folded, thickened, and buried to depths of ~20–24 km (6–8 kb; Figure 8) before undergoing extensional collapse, dismemberment, and northward displacement on orogen-parallel NE trending strike-slip faults (Figure 9a). Farther south in the western Gawler Craton (Figure 9a), east directed thrust faulting occurred in tandem with dextral transpressive motion on the Karari Fault Zone at circa 1660 Ma (Direen et al., 2005; Fraser et al., 2012; Stewart & Betts, 2010), whereas in central Australia, the Warumpi terrane was thrust northward over the North Australian craton during the 1640–1635 Ma Leibig event (Scrimgeour et al., 2005). Even farther afield, in parts of western and southern Laurentia (e.g., Cheyenne Belt) thought to have once lain opposite Proterozoic eastern Australia or even formed part of the latter (Burrett & Berry, 2000; Furlanetto et al., 2016; Gibson et al., 2012; Gibson & Champion, 2019; Thorkelson & Laughton, 2016), major faults (Figure 9a) preserve evidence for transpression in the opposite sense (Cavoise & Selverstone, 2003), inviting speculation that they may be conjugate to structures of the same age in proto-Australia. If this is indeed the case, then supercontinent assembly and convergence between the Australian and Laurentian plates, beginning with arc-continent collision and closure of the intervening backarc basin, may have commenced as early as 1650 Ma and been

largely complete by 1640 Ma. Thereafter, the plates continued to converge and interact but much of the shortening strain was taken up by distributed strike-slip faulting as is currently occurring in the present-day Himalaya (cf. Verbaas et al., 2018).

7.1. Himalayas as Analogue for Orogenesis in Paleoproterozoic Eastern Australia

As with the Himalayas and Tibetan Plateau, crustal thickening in the Paleoproterozoic basinal sequences of eastern Australia was ultimately linked to plate margin processes and more particularly arc-continent and then continent-continent collision as successive elements of the more outboard parts of the Australian plate, including one or more interpreted arc and backarc basin assemblages (Figure 2), were thrust-imbricated, recumbently folded, and emplaced over the opposing Laurentian margin where they have remained ever since (Bickford & Hill, 2007; Duebendorfer, 2015; Furlanetto et al., 2013; Holland et al., 2018; Jones et al., 2009; Thorkelson & Laughton, 2016; Whitmeyer & Karlstrom, 2007). Recumbent folds throughout the Willyama Supergroup and eastern part of the Mount Isa region mainly verge east or northeast (Gibson et al., 2004; O'Dea et al., 1997; Rubenach et al., 2008; Winsor, 1985; Withnall & Hutton, 2013) toward the likely direction of the incoming Laurentian plate as do thrust faults in the western Gawler Craton (Stewart & Betts, 2010). Together, these structures make for a nappe pile analogous to that which forms the present-day Himalayan mountain belt (Searle & Treloar, 2019). Crustal thickening and intermediate-pressure metamorphism followed (Figures 8 and 10), producing kyanite-garnet-bearing assemblages at midcrustal depths throughout the eastern Mount Isa region and granulite grade mineral assemblages at deeper levels in the Curnamona and Georgetown provinces. Laurentia, on the other hand, occupied a position analogous to India and was thrust beneath the leading edge of the Australian plate (Figure 9a); its passive margin sequences were never as deeply buried as their more fully overridden Australian counterparts and metamorphism barely exceeded middle to upper amphibolite facies conditions (Figure 10). Kyanite-bearing mineral assemblages are consequently no less common (Grambling et al., 1989; Pedrick et al., 1998) than in Proterozoic eastern Australia and seemingly formed under comparable, if not slightly higher, pressures around the same time (Williams & Karlstrom, 1996). Moreover, as in Australia (Abu Sharib, 2012; Rubenach et al., 2008; Sayab, 2005), these assemblages were subsequently overprinted by a lower pressure metamorphic event (Figure 10), which in combination with the earlier higher-pressure metamorphism gives rise to an overall clockwise or looping pressure-temperature-time path in which the anticlockwise component is invariably late and as such postdates both crustal thickening and the higher-pressure metamorphism that accompanied it. The Himalayan-Tibetan orogenic system shares this same pattern with intermediate-pressure mineral assemblages overprinted by a later low-pressure-high-temperature event (Searle & Treloar, 2019). It seems further likely from the steep section of the pressure-temperature-time paths for the Willyama Supergroup and Robertson River Group (Figure 8) that low pressure-high temperature in these two regions was immediately preceded by an episode of isothermal decompression marking the time of extensional exhumation of these rocks. If so, this would confirm the conclusion made elsewhere in this paper that extensional collapse occurred before 1580 Ma and thus before sedimentation in the Isa Superbasin had come to a close. Rather, sedimentation, basin formation, and normal faulting in the Isa Superbasin (Figures 4 and 5a) may all be manifestations of the same tectonic process and been similarly driven by extensional collapse of an overthickened nappe pile brought about by the collision of proto-Australia with Laurentia. Moreover, as with the Himalaya, extensional collapse was likely facilitated by lateral extrusion of material in a direction broadly orthogonal to crustal shortening and plate convergence between the two continents—viz., north-south as was the case during formation of the Isa Superbasin and related extensional structures. Significantly, these events also precipitated one of the most intense periods of sediment-hosted mineralization in Australia's geological history with no less than 17% (182 Mt Zn + Pb) of known global Zn-Pb resources formed at this time. They include four of the ten largest Zn-Pb deposits in the world (Broken Hill, McArthur River (HYC), Hilton-George Fisher and Mount Isa) as well as a number of small, but still world-class, deposits, all of which formed during or shortly after sedimentation and have clear links to continental margin tectonic processes (Huston et al., 2016; Ireland et al., 2004; King & Thomson, 1953; Williams, 1978).

An extensional as opposed to compressional tectonic setting has been invoked to explain the anticlockwise or looping clockwise pressure-temperature time paths for southern Laurentia (Grambling et al., 1989; Pedrick et al., 1998). Such similarities with Proterozoic eastern Australia are unlikely to be coincidental,

pointing instead to a shared thermal history and common origin in the events accompanying or immediately following continent-continent collision (Figure 10). The 1650–1600 Ma Mazatzal (Amato et al., 2008; Whitmeyer & Karlstrom, 2007) and correlative ≤ 1663 –1600 Ma Forward/Racklan orogenies in northwest Canada (Cook & MacLean, 1995; Furlanetto et al., 2013) are a good temporal match for late Paleoproterozoic orogenesis in eastern Australia (Figure 10) and likely mark the final stages of terrane assembly in western and southern Laurentia (Whitmeyer & Karlstrom, 2007). With a combined strike-length of several thousand kilometers, they made for an orogenic belt on the scale of the Himalayan fold mountain chain (cf. Figures 9a and 9b) that would appear to have stretched all the way from eastern Australia through Laurentia into Baltica (Furlanetto et al., 2013).

Importantly, the effects of continent-continent collision were not confined to the eastern periphery of the Australian Craton but extended for hundreds of kilometers inland away from the main areas of crustal thickening and higher-pressure metamorphism. Compressional events at 1680–1650 and 1610–1600 Ma are known from the Arunta Block (Figure 2a) along the southern margin of the North Australian Craton (Giles et al., 2002; Scott et al., 2000), whereas sedimentary rocks deposited in the same region between 1660 and 1640 Ma (Warumpi Terrane) were buried and metamorphosed up to pressures of 10 kb before undergoing exhumation and near isothermal decompression a few million years later during the 1640–1635 Ma Leibig Event (Scrimgeour et al., 2005). Northward thrusting and emplacement of the Warumpi Terrane over the edge of the North Australian Craton has been invoked as the most likely cause of decompression (Scrimgeour et al., 2005) although it is interesting to note that the proposed timeframe for deep burial, metamorphism, and exhumation is remarkably short and affords little or no time gap between the conclusion of sedimentation and the onset of north-south crustal shortening. This is not unlike the situation at the top of the Calvert Superbasin in the Mount Isa region where the 1650–1640 Ma unconformity-bounded Loretta Supersequence was deposited syntectonically in a rapidly evolving and increasingly unstable tectonic environment during the Riversleigh Tectonic Event (Figure 4). The Leibig and Riversleigh events are about the same age and both were associated with north-south or northeast-southwest crustal shortening, indicating that they are likely to be expressions of one and the same orogenic event. The Punjaub Structure and other folds of D1 age date from this same event although it is difficult to be certain from seismic images as to whether all shortening associated with the former predates deposition of the ≤ 1640 Ma River and Term supersequences or was in part synchronous with deposition of these two sedimentary units. In central Australia, the Leibig Event continued through to 1635 Ma (Scrimgeour et al., 2005), raising the possibility that north-south crustal shortening and thickening may indeed have occurred continuously from late Calvert time all the way through to deposition of the ≤ 1635 Ma Term Supersequence. Yet, along with the River Supersequence, this unit is for the most part unequivocally extensional in origin and, on the Lawn Hill Platform, conspicuously thickens into ENE striking normal faults (Figure 6). Thus, as already proposed elsewhere in this paper, crustal shortening and extension in northern Australia are unlikely to have operated independently of each other but occurred in different segments of a rapidly evolving Himalaya-Tibetan orogenic system (Figure 9a) where strain was continually being partitioned and redistributed between these two deformational end-members as the orogen evolved. Moreover, as with the Himalaya-Tibetan orogenic system (Figure 9b), strain partitioning was likely facilitated by strike-slip displacement on large regionally significant structures such as the transpressive Emu Fault (Hinman, 1995).

The Emu Fault strikes north-south (Figure 6a) and was demonstrably active during formation of the Batten Fault Zone, serving as both basin edge and a region of higher elevation from which conglomerates and other coarse sediments were sourced during deposition of the Barney Creek Formation (Hinman, 1995), a time equivalent of the 1640 Ma River Supersequence (Figure 4) in the Mount Isa region (Southgate, Bradshaw, et al., 2000). Displacement on this and other similarly oriented faults in the Isa and McArthur basins is mainly dextral (Figure 9a) and consistently in a direction that is conjugate to normal faults formed during the same north-south extensional event that produced the sedimentary basins (Figure 5a). On the Lawn Hill Platform (Figures 3 and 6a), normal faults mostly trend ENE and both cut across and are truncated by these strike-slip faults (Figure 5a), further supporting the idea that both sets of structures were active during formation of the Isa Superbasin and that not all movement on these structures occurred during later deformational events. Rather, strike-slip faulting exercised significant control over the distribution and localization of extensional strain with adjacent sedimentary subbasins compartmentalized and separated from each other by a network of interlinking normal and transcurrent faults as is the case across the

Himalayas-Tibetan orogenic system (Figure 9b). Previous suggestions (Scott et al., 1998; Scott et al., 2000; Southgate, Scott, et al., 2000) that the Isa Superbasin was laid down in a series of pull-apart basins are only partly correct insofar as the effects of strike-slip faulting were distributed over a wide region and not confined to narrow corridors (Figure 5a). Moreover, as in the Himalayas-Tibetan orogenic system (Figure 9b), there is some suggestion that parts of the basin network, including the Batten Trough and northern Lawn Hill Platform (Figure 6a), may have formed in a transpressive rather than transtensional environment where crustal shortening did not conclude with the Riversleigh Event but was ongoing into River and Term time (Punjab Structure). Accordingly, parts of the fault and basin network may not have remained in their original orientation for the duration of basin formation but were progressively rotated into a more northeasterly trend as crustal shortening and collision continued. Inspection of Figures 3 and 9a would further suggest that the degree of rotation increases from north to south with the Pilgrim Fault, for example, hewing to a more northeasterly strike than its northern counterparts (e.g. Emu and Mount Gordon fault zones). In the Himalayas-Tibetan fold mountain belt, this change in orientation was linked to tectonic escape and lateral extrusion of thermally weakened crust away from the point of collision (Butler, 2019) and is most conspicuously developed in the twin syntaxes on either side of the Indian subcontinent (Figure 9b). In these two regions, rocks of the Himalayan fold belt are exceptionally strongly strained and underwent 300° of rotation and bending consistent with lateral flow around the edges of the orogenic arc (Butler, 2019) and corresponding corners of the incoming continental indenter (Burg & Podladchikov, 2000). An equally conspicuous bend is evident in the 1650–1600 Ma orogens of northern (Forward/Racklan) and southern Laurentia (Mazatzal) which abruptly change orientation from north-south to NE-SW in the vicinity of the Mojave Province (Figure 9a), raising the possibility that collision between Proterozoic eastern Australia and Laurentia may have been accompanied by comparable levels of crustal flow, strike-slip faulting and lateral escape, if not formation of at least one syntaxis. Such speculations aside, it may be reasonably concluded that the Isa Superbasin is neither a sag (Betts et al., 2003) nor pull-apart basin (Southgate, Scott, et al., 2000) but was deposited at a time of considerable tectonic instability, warranting a revised tectonic model for both its formation and accompanying deformation.

7.2. Concluding Remarks and a Revised Model for Orogenesis in Late Proterozoic Eastern Australia

Comparisons drawn here with the Himalaya-Tibetan orogenic system (Figure 9b) presuppose that deformation in Proterozoic eastern Australia from 1650–1600 Ma was ultimately driven by collision with Laurentia and collapse of an intervening arc and backarc basin assemblage, relicts of which are now preserved in western and southern North America (Figures 2b and 9a). The 1710 Ma Bonnetia terrane of northwest Canada (Figure 2a) has long been suspected to have Australian affinities (Furlanetto et al., 2013; Thorkelson & Laughton, 2016; Verbaas et al., 2018) and more recently the same claim has been made for the 1790–1600 Ma Mojave, Yavapai, and Mazatzal provinces farther south in the United States (Gibson & Champion, 2019). All these terranes share a remarkably similar orogenic and magmatic record with northern and southern Australia, and all were accreted to the Laurentian margin about the same time that crustal shortening and orogenesis got underway in the formerly opposing Australian continental margin sequences (Figure 10). A collisional event common to both continents therefore seems likely, although contrary to some earlier interpretations (Betts & Giles, 2006; Karlstrom et al., 2001), this need not imply continuity along strike or that the two continents originally lay on the same plate (Figure 1a). Instead, Laurentia lay on the downgoing plate and was thrust beneath eastern Australia in much the same fashion as India was emplaced beneath Eurasia (Figure 9a). It represents the indenter and was subjected to successive phases of amphibolite to granulite facies metamorphism as the overriding plate with its arc and backarc basin assemblage was dismembered and thrust piece-meal over the Laurentian margin. This, in turn, would have precipitated crustal thickening, uplift and erosion, and the shedding of sedimentary detritus into a foreland basin formed ahead of the advancing thrust front though tectonic loading of the downgoing plate. Significantly, no such late Paleoproterozoic basin has yet been identified in North America and possible contenders of appropriate age like the ≤1640 Ma Wernecke Basin in northwest Canada (Figures 4 and 9a) have been interpreted as part of a rift or passive margin sequence (Furlanetto et al., 2016). It is nevertheless interesting to note that sedimentary rocks making up the Wernecke Supergroup have a major and trace element geochemistry consistent with development in an active continental margin setting (Furlanetto et al., 2016). Detrital zircon ages from these sediments, and more particularly those ≤1750 Ma, are also a good match for the late

Paleoproterozoic basal sequences of eastern Australia. No less importantly, there is an abrupt switch to ages <1670 Ma between the lower and upper part of the Wernecke Supergroup thought to reflect a change in provenance brought about by the ≤ 1663 Ma Forward Orogeny (Furlanetto et al., 2016) whose age and timing closely match the proposed onset of crustal shortening and orogenesis in eastern Australia (Figure 10). The Wernecke Breccia also contains large slabs of dismembered basalt and other volcanic arc rocks (Thorkelson et al., 2001; Verbaas et al., 2018) not usually found in such a setting but which occur more widely in tectonically unstable environments prone to avalanching like foreland basins. An obvious source for this volcanic material lies in the overriding Bonnetia terrane (Thorkelson & Laughton, 2016; Verbaas et al., 2018) and the tectonically unstable conditions created during its accretion to the North American margin.

Conversely, other than a few ash fall tuffs, no such breccia or significant volume of volcanic arc material has ever been recognized in the temporally equivalent Isa Superbasin and upper Willyama Supergroup. These two basal sequences were deposited well inboard of the convergent margin in a position distal to the site of initial arc-continent collision and more akin to that of the Tibetan Plateau (Figure 9b). Post-Riversleigh folds and thrusts in these sequences typically verge toward the continental interior or the rocks have been transported toward the north and northeast through a combination of distributed strike-slip faulting and crustal extension at high angles to the inferred direction of plate convergence. As already forementioned, and by analogy with the Tibetan Plateau (Figure 9b), crustal shortening and extension in some parts of northern Australia may have overlapped both spatially and temporally so that no one explanation for basin formation during Isa time exists. Instead, further crustal shortening was accommodated by lateral escape of material facilitated by ongoing crustal extension and strike-slip faulting (Figure 9a) until after the conclusion of plate convergence and collision at circa 1595 Ma when both the Isa and Olary orogenies came to a close. At this point, the still overthickened crust continued to extend, leading to orogenic collapse, isothermal decompression and widespread granite intrusion, beginning ca. 1590–1580 Ma and continuing through to emplacement of the post-tectonic 1560–1550 Ma Forsyth Batholith in the Georgetown region and 1520–1500 Ma Williams Suite farther west in the Mount Isa terrane. Along with other granites of similar age in northern and eastern Australia, these intrusive suites not only served as a heat source for further low pressure-high temperature metamorphism (Foster & Rubenach, 2006; Rubenach et al., 2008) but, on subsequent uplift and erosion, provided a supply of sedimentary detritus for younger extensional sedimentary basins developing in still contiguous parts of western Laurentia (Medig et al., 2016). Australia and Laurentia then remained adjacent to each other for the next 50–100 Myr or even longer as evidenced by a common record of intracontinental A-type magmatism and low pressure-high temperature metamorphism from 1500 Ma until 1450 Ma (Morrissy et al., 2019; Whitmeyer & Karlstrom, 2007). Significantly, these events are almost completely confined to the southern regions of both continents (Granite-Rhyolite Province) and likely point to a resumption in rifting and backarc extension following the re-establishment of subduction in a more southerly position outboard of now conjoined Laurentian and Australian-Antarctic plates. This configuration heralded onset of the next supercontinent cycle and persisted up to and including formation of the 1300–1100 Ma Grenville Orogeny, by which time the Rodinia supercontinent had assembled (Dalziel, 1991; Li et al., 2008; Whitmeyer & Karlstrom, 2007). Rodinia continued to host both continental blocks until it too began to break up in the Neoproterozoic with Australia-Antarctica separating from Laurentia at ca. 780–800 Ma (Li et al., 2008).

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References

- Abu Sharib, A. S. A. (2012). Foliation intersection axes (FIAs) preserved within porphyroblasts: Resolving plan view orthogonal refolding, Eastern Fold Belt, Mt Isa Inlier. *Australian Journal of Earth Sciences*, 59(4), 571–598.
- Aitchison, J. C., Ali, J. R., & Davis, A. M. (2007). When and where did India and Asia collide? *Journal of Geophysical Research: Solid Earth*, 112(B5).
- Amato, J. M., Bouillion, A. O., Serna, A. M., Sanders, A. E., Farmer, G. L., Gehrels, G. E., & Wooden, J. L. (2008). Evolution of the Mazatzal province and the timing of the Mazatzal orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico. *GSA Bulletin*, 120(3–4), 328–346. <https://doi.org/10.1130/B26200.1>
- Barovich, K., & Hand, M. (2008). Tectonic setting and provenance of the Paleoproterozoic Willyama Supergroup, Curnamona Province, Australia: Geochemical and Nd isotopic constraints on contrasting source terrain components. *Precambrian Research*, 166(1–4), 318–337. <https://doi.org/10.1016/j.precamres.2007.06.024>
- Betts, P. G. (1999). Palaeoproterozoic mid-basin inversion in the northern Mt Isa terrane, Queensland. *Australian Journal of Earth Sciences*, 46(5), 735–748. <https://doi.org/10.1046/j.1440-0952.1999.00741.x>
- Betts, P. G., Armit, R. J., Stewart, J., Aitken, A. R. A., Ailleres, L., Donchak, P., et al. (2016). Australia and Nuna. *Geological Society, London. Special Publications*, 424(1), 47–81. <https://doi.org/10.1144/SP424.2>

- Betts, P. G., & Giles, D. (2006). The 1800–1100 Ma tectonic evolution of Australia. *Precambrian Research*, 144(1–2), 92–125.
- Betts, P. G., Giles, D., & Lister, G. S. (2003). Tectonic environment of shale-hosted massive sulphide Pb–Zn–Ag deposits of Proterozoic northeastern Australia. *Economic Geology*, 98(3), 557–576. <https://doi.org/10.2113/gsecongeo.98.3.557>
- Betts, P. G., Giles, D., Mark, G., Lister, G. S., Goleby, B. R., & Aillères, L. (2006). Synthesis of the Proterozoic evolution of the Mount Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 187–211. <https://doi.org/10.1080/08120090500434625>
- Betts, P. G., Giles, D., & Schaefer, B. F. (2008). Comparing 1800–1600 Ma accretionary and basin processes in Australia and Laurentia: Possible geographic connections in Columbia. *Precambrian Research*, 166(1–4), 81–92. <https://doi.org/10.1016/j.precamres.2007.03.007>
- Betts, P. G., Lister, G. S., & Pound, K. S. (1999). Architecture of a Palaeoproterozoic rift system: Evidence from the Fiery Creek Dome region. *Mt Isa terrane, Australian Journal of Earth Sciences*, 46(4), 533–554. <https://doi.org/10.1046/j.1440-0952.1999.00721.x>
- Bickford, M. E., & Hill, B. M. (2007). Does the arc accretion model adequately explain the Paleoproterozoic evolution of southern Laurentia?: An expanded interpretation. *Geology*, 35(2), 167–170. <https://doi.org/10.1130/G23174A.1>
- Bickford, M. E., et al. (2008). Crustal evolution of southern Laurentia during the Paleoproterozoic: Insights from zircon Hf isotopic studies of ca. 1.75 Ga rocks in central Colorado. *Geology*, 36(7), 555–558.
- Blaikie, T. N., Betts, P. G., Armit, R. J., & Aillères, L. (2017). The ca. 1740–1710 Ma Leichhardt Event: Inversion of a continental rift and revision of the tectonic evolution of the North Australian Craton. *Precambrian Research*, 292, 75–92. <https://doi.org/10.1016/j.precamres.2017.02.003>
- Boger, S. D., & Hansen, D. (2004). Metamorphic evolution of the Georgetown Inlier, northeast Queensland, Australia; evidence for an accreted Palaeoproterozoic terrane? *Journal of Metamorphic Geology*, 22(6), 511–527.
- Bradley, D. C. (2008). Passive margins through earth history. *Earth-Science Reviews*, 91(1–4), 1–26.
- Bradshaw, B. E., Lindsay, J. F., Krassay, A. A., & Wells, A. T. (2000). Attenuated basin-margin sequence stratigraphy of the Palaeoproterozoic Calvert and Isa Superbasins: The Fickling Group, southern Murphy Inlier, Queensland. *Australian Journal of Earth Sciences*, 47(3), 599–623. <https://doi.org/10.1046/j.1440-0952.2000.00794.x>
- Burg, J.-P., & Podladchikov, Y. (2000). From buckling to asymmetric folding of the continental lithosphere: numerical modelling and application to the Himalayan syntaxes. *Geological Society, London, Special Publications*, 170(1), 219–236.
- Bradshaw, B. E., Orr, M. L., Bailey, A. H. E., Palu, T. J., & Hall, L. S. (2018). Northern Lawn Hill Platform Depth Structure and Isochore Mapping Update. *Geoscience Australia Record 2018/47*, 75 pp., Canberra.
- Burrett, C., & Berry, R. (2000). Proterozoic Australia–Western United States (AUSWUS) fit between Laurentia and Australia. *Geology*, 28(2), 103–106. [https://doi.org/10.1130/0091-7613\(2000\)28<103:PAUSAF>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<103:PAUSAF>2.0.CO;2)
- Butler, R. W. H. (2019). Tectonic evolution of the Himalayan syntaxes: the view from Nanga Parbat. *Geological Society, London, Special Publications*, 483(1), 215–254.
- Carr, L., et al. (2019). Exploring for the future: South Nicholson Basin region project outcomes and sequence stratigraphy, paper presented at AGES 2019 Proceedings, NT Geological Survey
- Cavosie, A., & Selverstone, J. (2003). Early Proterozoic oceanic crust in the northern Colorado Front Range: Implications for crustal growth and initiation of basement faults. *Tectonics*, 22(2).
- Cawood, P. A., & Buchan, C. (2007). Linking accretionary orogenesis with supercontinent assembly. *Earth-Science Reviews*, 82(3–4), 217–256.
- Cihan, M., Evins, P., Lisowiec, N., & Blake, K. (2006). Time constraints on deformation and metamorphism from EPMA dating of monazite in the Proterozoic Robertson River Metamorphics, NE Australia. *Precambrian Research*, 145(1–2), 1–23. <https://doi.org/10.1016/j.precamres.2005.11.009>
- Conor, C. H. H., & Preiss, W. V. (2008). Understanding the 1720–1640 Ma Palaeoproterozoic Willyama Supergroup, Curnamona Province, Southeastern Australia: Implications for tectonics, basin evolution and ore genesis. *Precambrian Research*, 166(1–4), 297–317.
- Cook, D. G., & MacLean, B. C. (1995). The intracratonic Paleoproterozoic Forward orogeny, and implications for regional correlations, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*, 32(11), 1991–2008.
- Cowley, W., et al. (2003). New and revised Proterozoic stratigraphic units on northern Yorke Peninsula. *MESA Journal*, 29, 46–58.
- Dalziel, I. W. D. (1991). Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair; evidence and implications for an Eocambrian supercontinent. *Geology*, 19(6), 598–601.
- Davidson, G. J., & Dashloot, S. A. (1993). The Glyde Sub-basin: A volcanoclastic-bearing pull-apart basin coeval with the McArthur River base-metal deposit, Northern Territory. *Australian Journal of Earth Sciences*, 40(6), 527–543.
- Derrick, G. M. (1982). A Proterozoic rift zone at Mount Isa, Queensland, and implications for mineralisation. *BMR Journal of Australian Geology and Geophysics*, 7, 81–92.
- Ding, L., Kapp, P., & Wan, X. (2005). Paleocene–Eocene record of ophiolite obduction and initial India–Asia collision, south central Tibet. *Tectonics*, 24(3), n/a. <https://doi.org/10.1029/2004TC001729>
- Direen, N. G., et al. (2005). Architecture of Proterozoic shear zones in the Christie Domain, western Gawler Craton, Australia: Geophysical appraisal of a poorly exposed orogenic terrane. *Precambrian Research*, 142(1–2), 28–44. <https://doi.org/10.1016/j.precamres.2005.09.007>
- Duebendorfer, E. M. (2015). Refining the early history of the Mojave–Yavapai Boundary Zone: Rifting versus Arc Accretion as Mechanisms for Paleoproterozoic Crustal Growth in Southwestern Laurentia. *The Journal of Geology*, 123(1), 21–37. <https://doi.org/10.1086/678950>
- Ernst, R. E., Wingate, M. T. D., Buchan, K. L., & Li, Z. X. (2008). Global record of 1600–700 Ma Large Igneous Provinces (LIPs): Implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. *Precambrian Research*, 160(1–2), 159–178. <https://doi.org/10.1016/j.precamres.2007.04.019>
- Forbes, C. J., et al. (2005). A structural metamorphic study of the Broken Hill Block, NSW, Australia. *Journal of Metamorphic Geology*, 23(8), 745–770. <https://doi.org/10.1111/j.1525-1314.2005.00608.x>
- Forbes, C. J., et al. (2007). A structural metamorphic study of the Broken Hill Block, NSW, Australia: Reply. *Journal of Metamorphic Geology*, 25(6), 719–723. <https://doi.org/10.1111/j.1525-1314.2007.00719.x>
- Foster, D. R. W., & Rubenach, M. (2006). Isograd patterns and regional low-pressure–high-temperature metamorphism of pelitic, mafic and calc-silicate rocks along an east-west section through the Mount Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 167–186. <https://doi.org/10.1080/08120090500434617>
- Fraser, G., Reid, A., & Stern, R. (2012). Timing of deformation and exhumation across the Karari Shear Zone, north-western Gawler Craton, South Australia. *Australian Journal of Earth Sciences*, 59(4), 547–570. <https://doi.org/10.1080/08120099.2012.678586>
- Furlanetto, F., Thorkelson, D. J., Daniel Gibson, H., Marshall, D. D., Rainbird, R. H., Davis, W. J., et al. (2013). Late Paleoproterozoic terrane accretion in northwestern Canada and the case for circum-Columbian orogenesis. *Precambrian Research*, 224, 512–528. <https://doi.org/10.1016/j.precamres.2012.10.010>

- Furlanetto, F., Thorkelson, D. J., Rainbird, R. H., Davis, W. J., Gibson, H. D., & Marshall, D. D. (2016). The Paleoproterozoic Wernecke Supergroup of Yukon, Canada: Relationships to orogeny in northwestern Laurentia and basins in North America, East Australia, and China. *Gondwana Research*, 39, 14–40. <https://doi.org/10.1016/j.gr.2016.06.007>
- Gibson, G. M., & Champion, D. C. (2019). Antipodean fugitive terranes in southern Laurentia: How Proterozoic Australia built the American West. *Lithosphere*, 11(4), 551–559. <https://doi.org/10.1130/L1072.1>
- Gibson, G. M., Champion, D. C., Withnall, I. W., Neumann, N. L., & Hutton, L. J. (2018). Assembly and breakup of the Nuna supercontinent: Geodynamic constraints from 1800 to 1600 Ma sedimentary basins and basaltic magmatism in northern Australia. *Precambrian Research*, 313, 148–169. <https://doi.org/10.1016/j.precamres.2018.05.013>
- Gibson, G. M., Henson, P. A., Neumann, N. L., Southgate, P. N., & Hutton, L. J. (2012). Paleoproterozoic-earliest Mesoproterozoic basin evolution in the Mount Isa region, northern Australia and implications for reconstructions of the Nuna and Rodinia supercontinents. *Episodes*, 35(1), 131–141. <https://doi.org/10.18814/epiugs/2012/v35i1/012>
- Gibson, G. M., Hutton, L. J., & Holzschuh, J. (2017). Basin inversion and supercontinent assembly as drivers of sediment-hosted Pb–Zn mineralization in the Mount Isa region, northern Australia. *Journal of the Geological Society*, 174(4), 773–786. <https://doi.org/10.1144/jgs2016-105>
- Gibson, G. M., Meixner, A. J., Withnall, I. W., Korsch, R. J., Hutton, L. J., Jones, L. E. A., et al. (2016). Basin architecture and evolution in the Mount Isa mineral province, northern Australia: Constraints from deep seismic reflection profiling and implications for ore genesis. *Ore Geology Reviews*, 76, 414–441. <https://doi.org/10.1016/j.oregeorev.2015.07.013>
- Gibson, G. M., Rubenach, M. J., Neumann, N. L., Southgate, P. N., & Hutton, L. J. (2008). Syn- and post-extensional tectonic activity in the Palaeoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia. *Precambrian Research*, 166(1–4), 350–369. <https://doi.org/10.1016/j.precamres.2007.05.005>
- Gibson, G. M., et al. (2004). Evidence and timing of crustal extension versus shortening in the early tectonothermal evolution of a Proterozoic continental rift sequence at Broken Hill, Australia. *Tectonics*, 23(5), n/a–n/a.
- Giles, D., Betts, P., & Lister, G. (2002). Far-field continental back-arc setting for the 1.8–1.67 Ma basins of north-east Australia. *Geology*, 30(9), 823–826. [https://doi.org/10.1130/0091-7613\(2002\)030<0823:FFCBSF>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0823:FFCBSF>2.0.CO;2)
- Giles, D., Betts, P. G., Aillères, L., Hulscher, B., Hough, M., & Lister, G. S. (2006). Evolution of the Isan Orogeny at the southeastern margin of the Mt Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 91–108. <https://doi.org/10.1080/08120090500432470>
- Giles, D., & Nutman, A. P. (2002). SHRIMP U–Pb monazite dating of 1600–1580 Ma amphibolite facies metamorphism in the southeastern Mt Isa Block, Australia. *Australian Journal of Earth Sciences*, 49(3), 455–465. <https://doi.org/10.1046/j.1440-0952.2002.00931.x>
- Gorton, J., & Troup, A. (2018). Petroleum systems of the Proterozoic in northwest Queensland and a description of various play types. *The APPEA Journal*, 58(1), 311–320. <https://doi.org/10.1071/AJ17115>
- Grambling, J. A., et al. (1989). The role of crustal extension in the metamorphism of Proterozoic rocks in northern New Mexico. In J. A. Grambling, & B. J. Tewksbury (Eds.), *Proterozoic Geology of the Southern Rocky Mountains* (pp. 87–110). Boulder, CO: Geological Society of America.
- Gregory, M. J., et al. (2008). Magmatic history of the Eastern Creek Volcanics, Mt Isa, Australia: iInsights from trace-element and platinum-group-element geochemistry. *Australian Journal of Earth Sciences*, 55, 1153–1173.
- Hand, M., et al. (2007). Tectonic framework and evolution of the Gawler Craton, Southern Australia. *Economic Geology*, 102(8), 1377–1395.
- Hinman, M. (1995). Base metal mineralisation at McArthur River: sStructure and kinematics of the HYC–Cooley Zone. *Australian Geological Survey Organisation Record*, 1995/5, 41.
- Hintersberger, E., Thiede, R. C., Strecker, M. R., & Hacker, B. R. (2010). East-west extension in the NW Indian Himalaya. *GSA Bulletin*, 122(9–10), 1499–1515. <https://doi.org/10.1130/B26589.1>
- Hobbs, B. E., et al. (1984). Tectonic history of the Broken Hill Block, Australia. In A. Kroner, & R. Greiling (Eds.), *Precambrian Tectonics Illustrated*, (pp. 353–368). Stuttgart, Germany: Schweizerbart.
- Holland, M. E., Karlstrom, K. E., Gehrels, G., Shufeldt, O. P., Begg, G., Griffin, W., & Belousova, E. (2018). The Paleoproterozoic Vishnu basin in southwestern Laurentia: Implications for supercontinent reconstructions, crustal growth, and the origin of the Mojave crustal province. *Precambrian Research*, 308, 1–17. <https://doi.org/10.1016/j.precamres.2018.02.001>
- Huston, D. L., et al. (2016). Tectono-metallogenic systems—The place of mineral systems within tectonic evolution, with an emphasis on Australian examples. *Ore Geology Reviews*, 76, 168–210.
- Idnurm, M. (2000). Towards a high resolution Late Palaeoproterozoic—Earliest Mesoproterozoic apparent polar wander path for northern Australia. *Australian Journal of Earth Sciences*, 47(3), 405–429. <https://doi.org/10.1046/j.1440-0952.2000.00788.x>
- Ireland, T., Bull, S. W., & Large, R. R. (2004). Mass flow sedimentology within the HYC Zn–Pb–Ag deposit, Northern Territory, Australia: Evidence for syn-sedimentary ore genesis. *Miner Deposita*, 39(2), 143–158. <https://doi.org/10.1007/s00126-003-0382-z>
- Ireland, T., Large, R. R., McGoldrick, P., & Blake, M. (2004). Spatial distribution patterns of sulfur isotopes, nodular carbonate, and ore textures in the McArthur River (HYC) Zn–Pb–Ag deposit, Northern Territory, Australia. *Economic Geology*, 99(8), 1687–1709. <https://doi.org/10.2113/gsecongeo.99.8.1687>
- Jackson, M. J., Scott, D. L., & Rawlings, D. J. (2000). Stratigraphic framework for the Leichhardt and Calvert Superbasins: Review and correlations of the pre-1700 Ma successions between Mt Isa and McArthur River. *Australian Journal of Earth Sciences*, 47(3), 381–403. <https://doi.org/10.1046/j.1440-0952.2000.00789.x>
- Jones, I. J. V., et al. (2009). Age, provenance, and tectonic setting of Paleoproterozoic quartzite successions in the southwestern United States. *GSA Bulletin*, 121(1–2), 247–264.
- Karlstrom, K. E., Åhäll, K. I., Harlan, S. S., Williams, M. L., McLelland, J., & Geissman, J. W. (2001). Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Research*, 111(1–4), 5–30. [https://doi.org/10.1016/S0301-9268\(01\)00154-1](https://doi.org/10.1016/S0301-9268(01)00154-1)
- King, H. F., and B. P. Thomson (Eds.) (1953), The geology of the Broken Hill district.
- Krassay, A. A., Bradshaw, B. E., Domagala, J., & Jackson, M. J. (2000). Siliciclastic shoreline to growth-faulted, turbiditic sub-basins: The Proterozoic River Supersequence of the upper McNamara Group on the Lawn Hill Platform, northern Australia. *Australian Journal of Earth Sciences*, 47(3), 533–562. <https://doi.org/10.1046/j.1440-0952.2000.00790.x>
- Lambeck, A., et al. (2012). An abrupt change in Nd isotopic composition in Australian basins at 1655 Ma: Implications for the tectonic evolution of Australia and its place in NUNA. *Precambrian Research*, 208–211, 213–221.
- Li, Z. X., Bogdanova, S. V., Collins, A. S., Davidson, A., De Waele, B., Ernst, R. E., et al. (2008). Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precambrian Research*, 160(1–2), 179–210.

- Lister, G. S., O'Dea, M. G., & Somaia, I. (1999). A tale of two synclines: Rifting, inversion and transpressional popouts at Lake Julius, northwestern Mt Isa terrane, Queensland. *Australian Journal of Earth Sciences*, 46(2), 233–250. <https://doi.org/10.1046/j.1440-0952.1999.00690.x>
- Liu, M., & Yang, Y. (2003). Extensional collapse of the Tibetan Plateau: Results of three-dimensional finite element modeling. *Journal of Geophysical Research: Solid Earth*, 108(B8), 2361. <https://doi.org/10.1029/2002JB002248>
- Marjoribanks, R. W., Rutland, R. W. R., Glen, R. A., & Laing, W. P. (1980). The structure and tectonic evolution of the Broken Hill region, Australia. *Precambrian Research*, 13(2-3), 209–240. [https://doi.org/10.1016/0301-9268\(80\)90005-4](https://doi.org/10.1016/0301-9268(80)90005-4)
- McFarlane, C. R. M., & Frost, B. R. (2009). Constraints on the early metamorphic evolution of Broken Hill, Australia, from in situ U-Pb dating and REE geochemistry of monazite. *Journal of Metamorphic Geology*, 27(1), 3–17.
- Medig, K. P. R., Turner, E. C., Thorkelson, D. J., & Rainbird, R. H. (2016). Rifting of Columbia to form a deep-water siliciclastic to carbonate succession: The Mesoproterozoic Pinguicula Group of northern Yukon. *Canada, Precambrian Research*, 278, 179–206. <https://doi.org/10.1016/j.precamres.2016.03.021>
- Morrissey, L. J., Barovich, K. M., Hand, M., Howard, K. E., & Payne, J. L. (2019). Magmatism and metamorphism at ca. 1.45 Ga in the northern Gawler Craton: The Australian record of rifting within Nuna (Columbia). *Geoscience Frontiers*, 10(1), 175–194.
- Munson, T. J. (2019). *Detrital zircon geochronological investigations of the Glyde and Favenc packages: implications for the geological framework of the greater McArthur Basin*. Northern Territory, Northern Territory Geological Survey, Alice Springs.
- Neumann, N. L., & Kositsin, N. (2011). New SHRIMP U-Pb zircon ages from north Queensland, 2007–2010 Geoscience Australia, Record, 2011/38, pp. 82.
- Nordsvan, A. R., Collins, W. J., Li, Z. X., Spencer, C. J., Pourteau, A., Withnall, I. W., et al. (2018). Laurentian crust in northeast Australia: Implications for the assembly of the supercontinent Nuna. *Geology*, 46(3), 251–254. <https://doi.org/10.1130/G39980.1>
- O'Dea, M. G., et al. (1997). Geodynamic evolution of the Proterozoic Mount Isa terrain. *Geological Society, London. Special Publications*, 121(1), 99–122. <https://doi.org/10.1144/GSL.SP.1997.121.01.05>
- O'Dea, M. G., et al. (2006). Sequential development of a mid-crustal fold-thrust complex: Evidence from the Mitakoodi Culmination in the eastern Mt Isa Inlier. *Australia, Australian Journal of Earth Sciences*, 53(1), 69–90. <https://doi.org/10.1080/08120090500432447>
- Page, R. W., et al. (2005). Geochronology of the Sequence Hosting the Broken Hill Pb-Zn-Ag Orebody, Australia. *Economic Geology*, 100(4), 633–661.
- Pedrick, J. N., et al. (1998). Reconciliation of conflicting tectonic models for Proterozoic rocks of northern New Mexico. *Journal of Metamorphic Geology*, 16(5), 687–707. <https://doi.org/10.1111/j.1525-1314.1998.00165.x>
- Phillips, G. N. (1981). Water activity changes across an amphibolite-granulite facies transition, Broken Hill, Australia. *Contrib Mineral Petrol*, 75(4), 377–386.
- Pisarevsky, S. A., Elming, S. Å., Pesonen, L. J., & Li, Z. X. (2014). Mesoproterozoic paleogeography: Supercontinent and beyond. *Precambrian Research*, 244(0), 207–225. <https://doi.org/10.1016/j.precamres.2013.05.014>
- Potma, W. A., & Betts, P. G. (2006). Extension-related structures in the Mitakoodi Culmination: Implications for the nature and timing of extension, and effect on later shortening in the eastern Mt Isa Inlier. *Australian Journal of Earth Sciences*, 53(1), 55–67. <https://doi.org/10.1080/08120090500432421>
- Pourteau, A., et al. (2018). 1.6 Ga crustal thickening along the final Nuna suture. *Geology*, 46(11), 959–962.
- Powell, R., & Downes, J. (1990). Garnet porphyroblast-bearing leucosomes in metapelites: Mechanisms, phase diagrams, and an example from Broken Hill, Australia. In J. R. Ashworth, & M. Brown (Eds.), *High-temperature Metamorphism and Crustal Anatexis* (pp. 105–123). Dordrecht: Springer Netherlands.
- Rawlings, D. J., et al. (2004). The 2002 Southern McArthur Basin Seismic Reflection Survey, Geoscience Australia Record 2004/17, 78 pp., Canberra.
- Rubenach, M. J., et al. (2008). Age constraints on the tectonothermal evolution of the Selwyn Zone, Eastern Fold Belt, Mount Isa Inlier. *Precambrian Research*, 163(1-2), 81–107. <https://doi.org/10.1016/j.precamres.2007.08.014>
- Rutherford, L., Barovich, K., Hand, M., & Foden, J. (2006). Continental ca 1.7–1.69 Ga Fe-rich metatholeiites in the Curnamona Province, Australia: A record of melting of a heterogeneous, subduction-modified lithospheric mantle. *Australian Journal of Earth Sciences*, 53(3), 501–519. <https://doi.org/10.1080/08120090600632466>
- Rutte, D., et al. (2017). Building the Pamir-Tibet Plateau—Crustal stacking, extensional collapse, and lateral extrusion in the Central Pamir: 1. *Geometry and kinematics, Tectonics*, n/a–n/a.
- Sayab, M. (2005). Microstructural evidence for N–S shortening in the Mount Isa Inlier (NW Queensland, Australia): The preservation of early W–E-trending foliations in porphyroblasts revealed by independent 3D measurement techniques. *Journal of Structural Geology*, 27(8), 1445–1468. <https://doi.org/10.1016/j.jsg.2005.01.013>
- Sayab, M. (2006). Decompression through clockwise P–T path: Implications for early N–S shortening orogenesis in the Mesoproterozoic Mt Isa Inlier (NE Australia). *Journal of Metamorphic Geology*, 24(2), 89–105. <https://doi.org/10.1111/j.1525-1314.2005.00626.x>
- Scott, D. L., Bradshaw, B. E., & Tarlowski, C. Z. (1998). The tectonostratigraphic history of the Proterozoic Northern Lawn Hill Platform, Australia: An integrated intracontinental basin analysis. *Tectonophysics*, 300(1-4), 329–358. [https://doi.org/10.1016/S0040-1951\(98\)00253-4](https://doi.org/10.1016/S0040-1951(98)00253-4)
- Scott, D. L., Rawlings, D. J., Page, R. W., Tarlowski, C. Z., Idnurm, M., Jackson, M. J., & Southgate, P. N. (2000). Basement framework and geodynamic evolution of the Palaeoproterozoic superbasins of north-central Australia: An integrated review of geochemical, geochronological and geophysical data. *Australian Journal of Earth Sciences*, 47(3), 341–380. <https://doi.org/10.1046/j.1440-0952.2000.00793.x>
- Scrimgeour, I., et al. (2005). High-T granulites and polymetamorphism in the southern Arunta region, central Australia: Evidence for a 1.64 Ga accretional event. *Precambrian Research*, 142(1-2), 1–27. <https://doi.org/10.1016/j.precamres.2005.08.005>
- Searle, M. P., Cooper, D. J. W., Rex, A. J., Herren, E., Rex, A. J., & Colchen, M. (1988). Collision tectonics of the Ladakh-Zaskar Himalaya. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 326(1589), 117–150. <https://doi.org/10.1098/rsta.1988.0082>
- Searle, M. P., & Treloar, P. J. (2019). Introduction to Himalayan tectonics: A modern synthesis. *Geological Society, London, Special Publications*, 483(1), 1–17.
- Southgate, P. N., Bradshaw, B. E., Domagala, J., Jackson, M. J., Idnurm, M., Krassay, A. A., et al. (2000). Chronostratigraphic basin framework for Palaeoproterozoic rocks (1730–1575 Ma) in northern Australia and implications for base-metal mineralisation. *Australian Journal of Earth Sciences*, 47(3), 461–483. <https://doi.org/10.1046/j.1440-0952.2000.00787.x>
- Southgate, P. N., Neumann, N. L., & Gibson, G. M. (2013). Depositional systems in the Mt Isa Inlier from 1800 Ma to 1640 Ma: Implications for Zn–Pb–Ag mineralisation. *Australian Journal of Earth Sciences*, 60(2), 157–173. <https://doi.org/10.1080/08120099.2013.758176>

- Southgate, P. N., Scott, D. L., Sami, T. T., Domagala, J., Jackson, M. J., James, N. P., & Kyser, T. K. (2000). Basin shape and sediment architecture in the Gun Supersequence: A strike-slip model for Pb-Zn-Ag ore genesis at Mt Isa. *Australian Journal of Earth Sciences*, 47(3), 509–531. <https://doi.org/10.1046/j.1440-0952.2000.00792.x>
- Stampfli, G. M., & Hochard, C. (2009). Plate tectonics of the Alpine realm. *Geological Society, London, Special Publications*, 327(1), 89–111. <https://doi.org/10.1144/SP327.6>
- Stewart, A. J. (1992). The role of thrusting in the structural development of the Mount Isa Mine and its relevance to exploration in the surrounding region; discussion. *Economic Geology*, 87(6), 1659–1664. <https://doi.org/10.2113/gsecongeo.87.6.1659>
- Stewart, J. R., & Betts, P. G. (2010). Implications for Proterozoic plate margin evolution from geophysical analysis and crustal-scale modeling within the western Gawler Craton, Australia. *Tectonophysics*, 483(1–2), 151–177. <https://doi.org/10.1016/j.tecto.2009.11.016>
- Szpunar, M., Hand, M., Barovich, K., Jagodzinski, E., & Belousova, E. (2011). Isotopic and geochemical constraints on the Paleoproterozoic Hutchison Group, southern Australia: Implications for Paleoproterozoic continental reconstructions. *Precambrian Research*, 187(1–2), 99–126. <https://doi.org/10.1016/j.precamres.2011.02.006>
- Tapponnier, P., Peltzer, G., Le Dain, A. Y., Armijo, R., & Cobbold, P. (1982). Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. *Geology*, 10(12), 611–616. [https://doi.org/10.1130/0091-7613\(1982\)10<611:PETIAN>2.0.CO;2](https://doi.org/10.1130/0091-7613(1982)10<611:PETIAN>2.0.CO;2)
- Taylor, M., et al. (2003). Conjugate strike-slip faulting along the Bangong-Nujiang suture zone accommodates coeval east-west extension and north-south shortening in the interior of the Tibetan Plateau. *Tectonics*, 22(4).
- Thorkelson, D. J., & Laughton, J. R. (2016). Paleoproterozoic closure of an Australia–Laurentia seaway revealed by megacrysts of an obducted volcanic arc in Yukon, Canada. *Gondwana Research*, 33, 115–133. <https://doi.org/10.1016/j.gr.2015.01.004>
- Thorkelson, D. J., Mortensen, J. K., Davidson, G. J., Creaser, R. A., Perez, W. A., & Abbott, J. G. (2001). Early Mesoproterozoic intrusive breccias in Yukon, Canada: The role of hydrothermal systems in reconstructions of North America and Australia. *Precambrian Research*, 111(1–4), 31–55. [https://doi.org/10.1016/S0301-9268\(01\)00155-3](https://doi.org/10.1016/S0301-9268(01)00155-3)
- Verbaas, J., Thorkelson, D. J., Crowley, J., Davis, W. J., Foster, D. A., Gibson, H. D., et al. (2018). A sedimentary overlap assemblage links Australia to northwestern Laurentia at 1.6 Ga. *Precambrian Research*, 305, 19–39. <https://doi.org/10.1016/j.precamres.2017.10.001>
- Whitmeyer, S. J., & Karlstrom, K. E. (2007). Tectonic model for the Proterozoic growth of North America. *Geosphere*, 3(4), 220–259. <https://doi.org/10.1130/GES00055.1>
- Williams, M. L., & Karlstrom, K. E. (1996). Looping P-T paths and high-T, low-P middle crustal metamorphism: Proterozoic evolution of the southwestern United States. *Geology*, 24(12), 1119–1122. [https://doi.org/10.1130/0091-7613\(1996\)024<1119:LPTPAH>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<1119:LPTPAH>2.3.CO;2)
- Williams, N. (1978). Studies of base metal sulfide deposits at McArthur River, Northern Territory, Australia: I. *The Cooley and Ridge deposits*, *Economic Geology*, 73, 1005–1035.
- Willis, I. L., Brown, R. E., Stroud, W. J., & Stevens, B. P. J. (1983). The early Proterozoic Willyama supergroup: Stratigraphic subdivision and interpretation of high to low-grade metamorphic rocks in the Broken Hill Block, New South Wales. *Journal of the Geological Society of Australia*, 30(1–2), 195–224. <https://doi.org/10.1080/00167618308729249>
- Wilson, C. J. L., & Powell, R. (2001). Strain localisation and high-grade metamorphism at Broken Hill, Australia: A view from the Southern Cross area. *Tectonophysics*, 335(1–2), 193–210. [https://doi.org/10.1016/S0040-1951\(01\)00050-6](https://doi.org/10.1016/S0040-1951(01)00050-6)
- Winsor, C. N. (1985). Interpretation of a set of faults across the hinge and a limb of a large-scale flexure in the Mount Isa district, Queensland, Australia, in terms of fractures related to the folding process. *Journal of Structural Geology*, 7(6), 719–725. [https://doi.org/10.1016/0191-8141\(85\)90147-6](https://doi.org/10.1016/0191-8141(85)90147-6)
- Withnall, I. W., & Hutton, L. J. (2013). Chapter 2: North Australian Craton. In P. A. Jell (Ed.), *Geology of Queensland* (pp. 23–112). Brisbane: Geological Survey of Queensland.
- Yin, A., & Harrison, T. M. (2000). Geologic Evolution of the Himalayan-Tibetan Orogen. *Annual Review of Earth and Planetary Sciences*, 28(1), 211–280. <https://doi.org/10.1146/annurev.earth.28.1.211>