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Early Palaeozoic continental growth in the Tasmanides of northeast Gondwana and its implications for Rodinia assembly and rifting

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Abstract

Gondwana formed in the Neoproterozoic to Cambrian mainly from collision along the East African and Kuunga orogens at about the same time that the Gondwana palaeo-Pacific facing margin became a long-lived active margin and formed the Terra Australis Orogen. This orogen, and in particular the Tasman Orogenic Belt (the Tasmanides) sector of eastern Australia, is distinguished by widespread shortening of quartz turbidite successions and underlying oceanic basement, with less abundant island arc assemblages. Early Palaeozoic accretionary development of the Tasmanides followed Rodinia breakup at 800-750 Ma to form the palaeo-Pacific Ocean. In eastern Australia, a second rifting episode at 600-580 Ma is more widely developed with siliciclastic sedimentation and rift-related igneous activity. In parts of the Delamerian Orogen of South Australia and northwestern New South Wales and in the exposed northern Thomson Orogen of north and central Queensland, the rift-related sedimentary successions have a dominant 1.3 to 1 Ga detrital zircon age signature implying local sources. They are considered to be derived from an eastward continuation of the 1.3-1 Ga Musgrave Province in central Australia, which marks a major Late Mesoproterozoic suture between the North Australian and South Australian/West Australian cratons and now buried within continental crust of the Thomson Orogen. Palaeomagnetic data suggest that an intraplate 40° anticlockwise rotation occurred between the North Australian Craton and an amalgam of the West and South Australian cratons during the transpressional Petermann Orogeny in central Australia at 650 to 550 Ma and overlapped the 600-580 Ma rifting event. The zone of rotational intraplate shearing is considered to have remobilised the preceding Late Mesoproterozoic suture and provides a marker in Rodinia that supports the AUSMEX reconstruction. Detrital zircon of 650-500 Ma, known as the Pacific-Gondwana association, is very widely represented in Phanerozoic sediment of eastern Australia. It may be that an upper crustal igneous assemblage, now removed by erosion, developed in the Petermann Orogeny contributed to part of this age association. However, a primary Antarctic far-field source is favoured. Given that prior to 650 Ma, the unravelled intraplate rotation shows substantial overlap of the Thomson Orogen and the South Australian Craton, much of the former must have developed by continental growth largely after 550 Ma. The Diamantina Structure, which truncates the Mount Isa Province and forms the northwestern margin of the Thomson Orogen, marks the eastern line of intraplate rotation. This zone of crustal weakness continues into the northern Thomson Orogen where it was remobilised in the mid-Palaeozoic to offset the Mossman Orogen and to later facilitate the Late Mesozoic-Cenozoic Townsville Trough and basin, a major feature of the continental margin. Basement cores and bedrock geology of the Thomson Orogen indicate deposition of widespread quartzose turbidites dominated by Pacific-Gondwana detrital zircon ages (650-500 Ma) that were affected by inferred Middle to Late Cambrian deformation and metamorphism (Delamerian Orogeny). The widespread Delamerian event was succeeded by Late Cambrian-Early Ordovician backarc extension and dominantly silicic igneous activity with granites, volcanic and volcaniclastic successions in the northern Thomson Orogen. Ordovician quartz turbidite deposition followed by compressional deformation in the Late Ordovician-Early Silurian Benambran Orogeny and scattered syn- and post-orogenic granitic plutonism is characteristic of northeast Gondwana and dominates rock assemblages of the Lachlan Orogen.

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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Early Paleozoic continental growth in the Tasmanides of northeast Gondwana and its implications for Rodinia assembly and rifting

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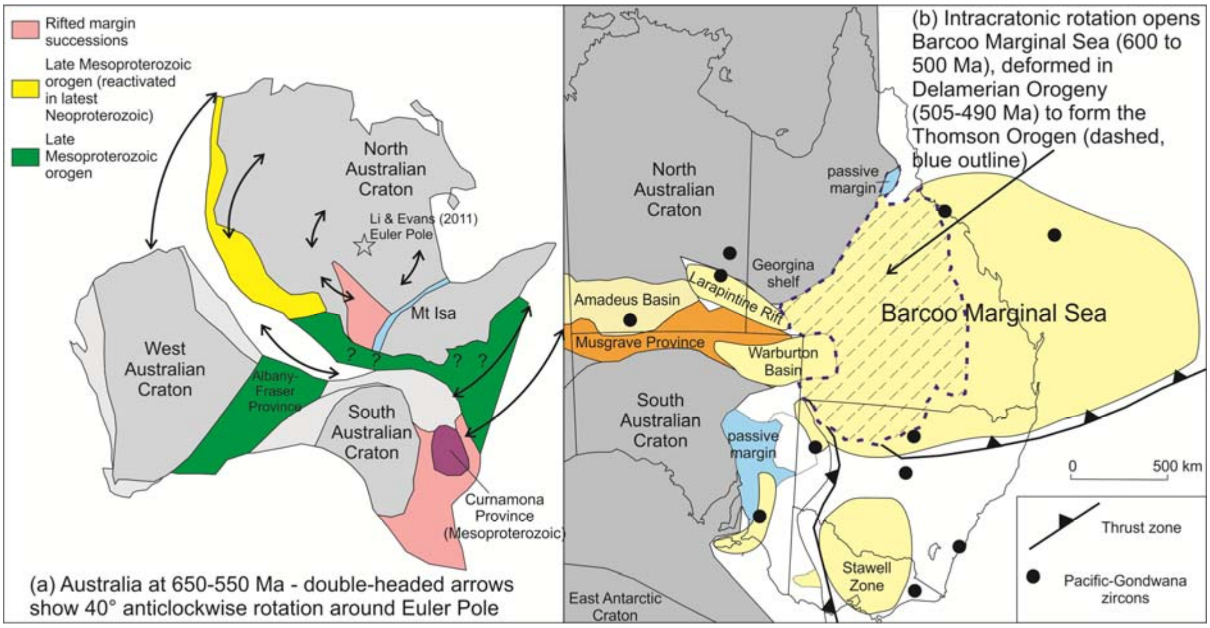
3 dot points

- Intracratonic rotation within Australia created accommodation space for the Thomson Orogen
- Older Thomson sediments were derived from continuation of the Musgrave Province into east Australia
- Thomson Orogen accretion resulted from Delamerian orogenesis and was followed by backarc extension

Graphical abstract



ABSTRACT

Gondwana formed in the Neoproterozoic to Cambrian mainly from collision along the East African and Kuunga orogens at about the same time that the Gondwana paleo-Pacific facing margin became a long-lived active margin and formed the Terra Australis Orogen. This orogen, and in particular the Tasman Orogenic Belt (the Tasmanides) sector of eastern Australia, is distinguished by widespread shortening of quartz turbidite successions and underlying oceanic basement , with less abundant island arc assemblages. Early Paleozoic accretionary development of the Tasmanides followed Rodinia breakup at 800–750 Ma to form the paleo-Pacific Ocean. In eastern Australia, a second rifting episode at 600–580 Ma is more widely developed with siliciclastic sedimentation and rift-related igneous activity. In parts of the Delamerian Orogen of South Australia and northwestern New South Wales and in the exposed northern Thomson Orogen of north and central Queensland, the rift-related sedimentary successions have a dominant 1.3 to 1 Ga detrital zircon age signature implying local sources. They are considered to be derived from an eastward continuation of the 1.3–1 Ga Musgrave Province in central Australia, which marks a major late Mesoproterozoic suture between the North Australian and South Australian/West Australian cratons and now buried within continental crust of the Thomson Orogen. Paleomagnetic data suggest that an intraplate 40° anticlockwise rotation occurred between the North Australian Craton and an amalgam of the West and South Australian cratons during the transpressional Petermann Orogeny in central Australia at 650 to 550 Ma and overlapped the 600–580 Ma rifting event. The zone of rotational intraplate shearing is considered to have remobilised the preceding late Mesoproterozoic suture and provides a marker in Rodinia that supports the AUSMEX reconstruction. Detrital zircon of 650–500 Ma, known as the Pacific–Gondwana association, is very widely represented in Phanerozoic sediment of eastern Australia. It may be that an upper crustal igneous assemblage, now removed by erosion, developed in the Petermann

Orogeny contributed to part of this age association. However, a primary Antarctic far-field source is favoured. Given that prior to 650 Ma, the unravelled intraplate rotation shows substantial overlap of the Thomson Orogen and the South Australian Craton, much of the former must have developed by continental growth largely after 550 Ma. The Diamantina Structure, which truncates the Mount Isa Province and forms the northwestern margin of the Thomson Orogen, marks the eastern line of intraplate rotation. This zone of crustal weakness continues into the northern Thomson Orogen where it was remobilised in the mid-Paleozoic to offset the Mossman Orogen and to later facilitate the Late Mesozoic – Cenozoic Townsville Trough and basin, a major feature of the continental margin. Basement cores and bedrock geology of the Thomson Orogen indicate deposition of widespread quartzose turbidites dominated by Pacific–Gondwana detrital zircon ages (650–500 Ma) that were affected by inferred Middle to Late Cambrian deformation and metamorphism (Delamerian Orogeny). The widespread Delamerian event was succeeded by Late Cambrian – Early Ordovician backarc extension and dominantly silicic igneous activity with granites, volcanic and volcaniclastic successions in the northern Thomson Orogen. Ordovician quartz turbidite deposition followed by compressional deformation in the Late Ordovician – Early Silurian Benambran Orogeny and scattered syn- and post-orogenic granitic plutonism is characteristic of northeast Gondwana and dominates rock assemblages of the Lachlan Orogen.

Keywords:

Australia

convergent margin

Rodinia

Terra Australis Orogen

Thomson Orogen

1. Introduction

Growth of continental crust is a much debated issue with recognition that accretionary orogens related to active continental margins, that formed without continental collision, are a significant driver of crustal formation (Cawood et al., 2009; Yamamoto et al., 2009; Isozaki et al., 2010; Xiao et al., 2010). Contrasts between diverse processes of continental growth are well illustrated by Gondwana (Fig. 1) which consists of many Precambrian cratons welded together by Pan-African orogenic belts, especially in West Gondwana but also extending into East Gondwana along the Kuunga and East African orogens (Meert, 2003; Boger and Miller, 2004; Veevers, 2004). Thus Gondwana has mainly formed by processes of continental collision at least in the interval following fragmentation of Rodinia up until final assembly by 530 Ma. In contrast the active Pacific-facing margin of Gondwana developed as an orogenic belt, the Terra Australis Orogen including the Tasmanides of eastern Australia and the Ross Orogen of Antarctica, and has been unaffected by major continental collisions (Cawood, 2005).

Development of Panthalassa, or the paleo-Pacific Ocean, followed breakup of Rodinia when Laurentia rifted away from an amalgam of Australia and much of East Antarctica within East Gondwana (Moores, 1991; Li et al., 2008). The South China Block may have separated Laurentia and East Gondwana in the Rodinia reconstruction (Li et al., 2008). Timing of this breakup has been the subject of debate with some authors favouring around 700 Ma based on the stratigraphic succession of the Adelaide Rift Complex preserved in the Delamerian Orogen of South Australia (Powell et al., 1994; Preiss, 2000). Others have argued, based on the presence of tholeiitic and alkaline mafic volcanic rocks in various parts of the Tasmanides, that rifting and separation of at least small continental fragments occurred at around 580 Ma (Direen and Crawford 2003a, b; Fergusson et al., 2009; Greenfield et al., 2011). Alternatively, breakup at around 560 Ma was favoured by Veevers et al. (1997) based on an inferred 400 Ma duration of a Pangean supercycle and further emphasised by Veevers (2000, 2004). Rifting at around 750 Ma with development of a wide ocean between Australia – East Antarctica and the South China Block by 720 Ma was argued by Li et al. (2003, 2008) based mainly on the ages of rift successions outside of Australia.

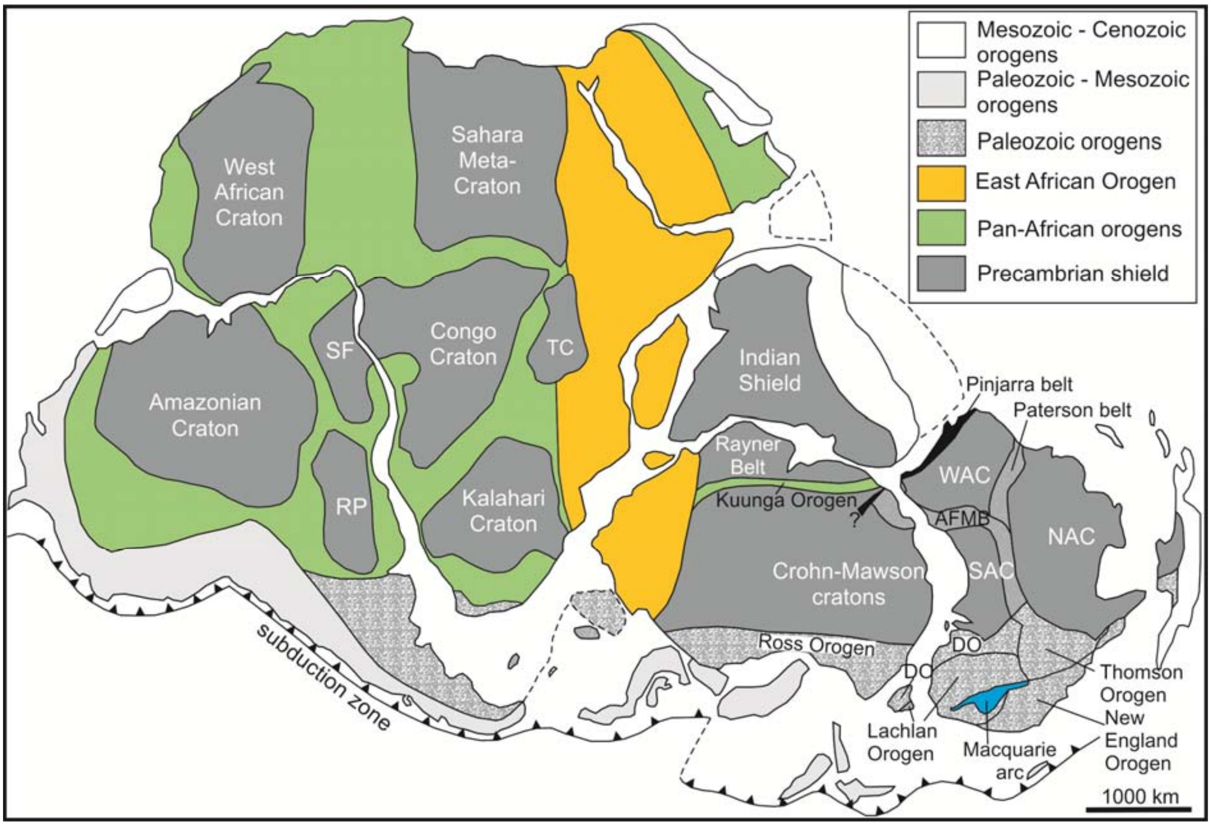


Fig. 1. Gondwana at the close of the Paleozoic following the reconstruction de Wit et al. (1988) with modifications after Myers et al. (1996), Gray et al. (2008), and Boger (2011). Cratons in Australia and Antarctica are from Myers et al. (1996) and Boger (2011) respectively. Abbreviations: AFMB—Albany–Fraser–Musgrave belt, DO—Delamerian Orogen, NAC—North Australian Craton, RP—Río de la Plata Craton, SAC—South Australian Craton, SF—São Francisco Craton, TC—Tanzania Craton, WAC—West Australian Craton.

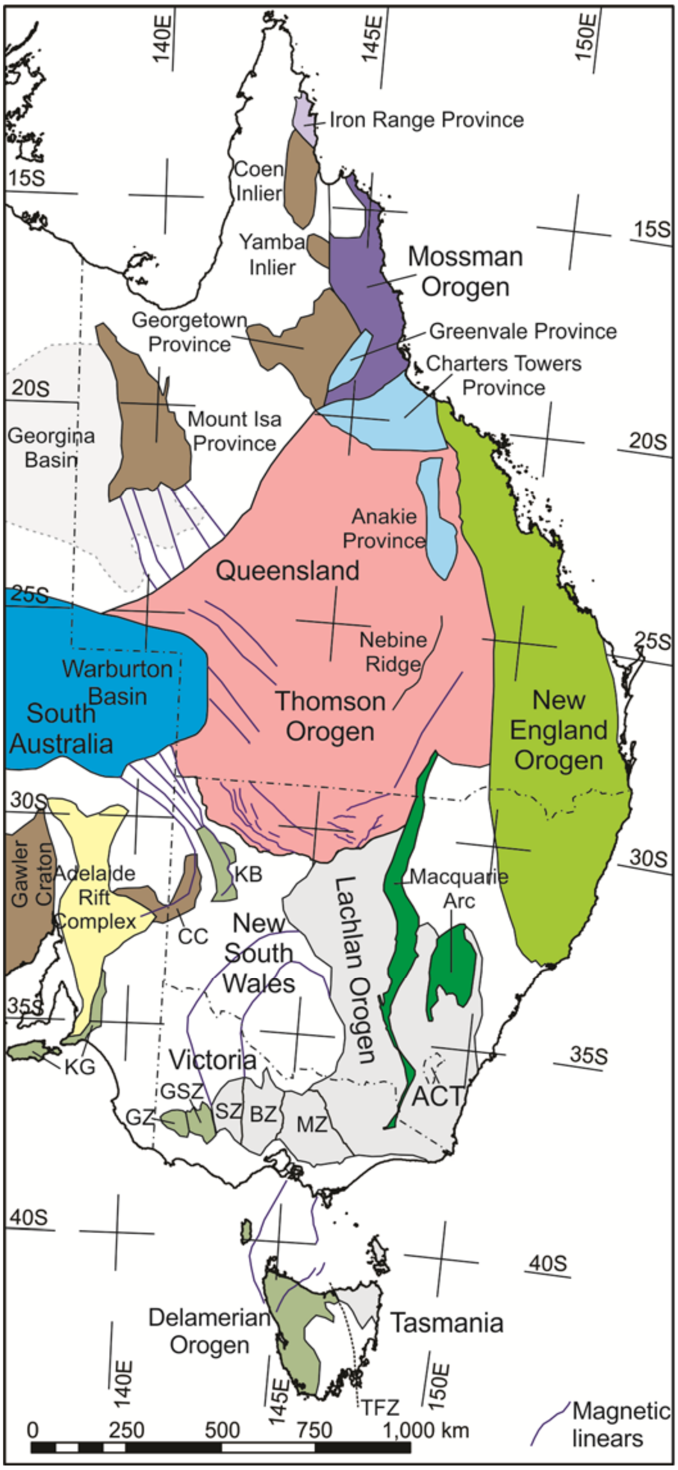


Fig. 2. Map of the Tasmanides of eastern Australia showing the main orogenic belts and other elements. Abbreviations: ACT—Australian Capital Territory, Delamerian Orogen (GSZ—Grampians–Stavely Zone, GZ—Glenelg Zone, KG—Kanmantoo Group, KB—Koonenberry Belt), Lachlan Orogen (BZ—Bendigo Zone, MZ—Melbourne Zone, SZ—Stawell Zone), Precambrian cratons (CC—Curnamona Craton).

By the early Paleozoic the paleo-Pacific Ocean was large enough for the Tasmanides (Fig. 2) to have formed in a continental margin setting involving backarc generation and accretion during several short-lived orogenic episodes (Foster and Gray, 2000; Glen, 2005; Foster and Goscombe, 2013). Ordovician quartz turbidites and an island arc assemblage (Macquarie Arc) are widely exposed in the Lachlan Orogen of southeastern Australia and are considered to have been deformed in the Late Ordovician to Early Silurian Benambran Orogeny, although plate tectonic arrangements associated with this episode of continental growth have long been disputed (Gray and Foster, 2004; Glen et al., 2009; Aitchison and Buckman, 2012; Glen, 2013; Fergusson, 2014; Quinn et al., 2014). Quartzose turbidites and island arc assemblages have also been accreted to the East Gondwana margin during the Middle to Late Cambrian Delamerian Orogeny in the Delamerian Orogen of southeastern South Australia, western Victoria, Tasmania and northwestern New South Wales (Preiss, 2000; Cayley, 2011; Gibson et al., 2011; Greenfield et al., 2011; Moore et al., 2013). It is now recognised that the Thomson Orogen of Queensland and northwestern New South Wales is probably largely related to this early phase of continental growth in the Delamerian Orogeny (Withnall et al., 1996; Fergusson and Henderson, 2013; Glen et al., 2013) rather than being a continuation of the Lachlan Orogen as argued previously (Murray and Kirkegaard, 1978; Powell, 1984a; Murray, 1986).

Tectonic development of the Tasmanides of East Gondwana is mostly considered in the context of plate tectonic interactions along the active paleo-Pacific margin of Gondwana without reference to tectonics of the adjoining Gondwana craton (Crawford et al., 2003; Glen et al., 2009). Exceptions to this approach include linking intraplate deformation in central Australia in the late Paleozoic Alice Springs Orogeny to megakinking in the Lachlan Orogen (Powell, 1984b) and tectonic extrusion in eastern Australia linked to Australian–Asian collision (Klootwijk, 2013). Paleomagnetic data suggest that there has been a 40°

anticlockwise rotation between the North Australian Craton and an amalgam of the West and South Australian cratons along the southern margin of the Musgrave Block in central Australia in the interval 650 to 550 Ma (Li and Evans, 2011). A rotation of this order and location had a significant effect on the shape of the East Gondwana continental margin in Neoproterozoic–Cambrian time and its reversal eliminates the present re-entrant in the margin occupied by the Thomson Orogen (Fig. 3). This rotation also has implications for proposed connections between the Australian cratons and in particular a connection between the Mt Isa Province and the Curnamona Craton (Betts and Giles, 2006; Cawood and Korsch, 2008; Foster and Austin, 2008; Hensen et al., 2011; Williams et al., 2012). Detrital zircon ages from the inferred oldest units mapped in the northeast Thomson Orogen suggest provenance from an eastern and northeastern continuation of the Musgrave Province into Queensland (Fergusson et al., 2007a) in support of earlier ideas that the North and South Australian cratons were merged in continental collisions at 1.2–1 Ga (Myers et al., 1996) during amalgamation of Rodinia.

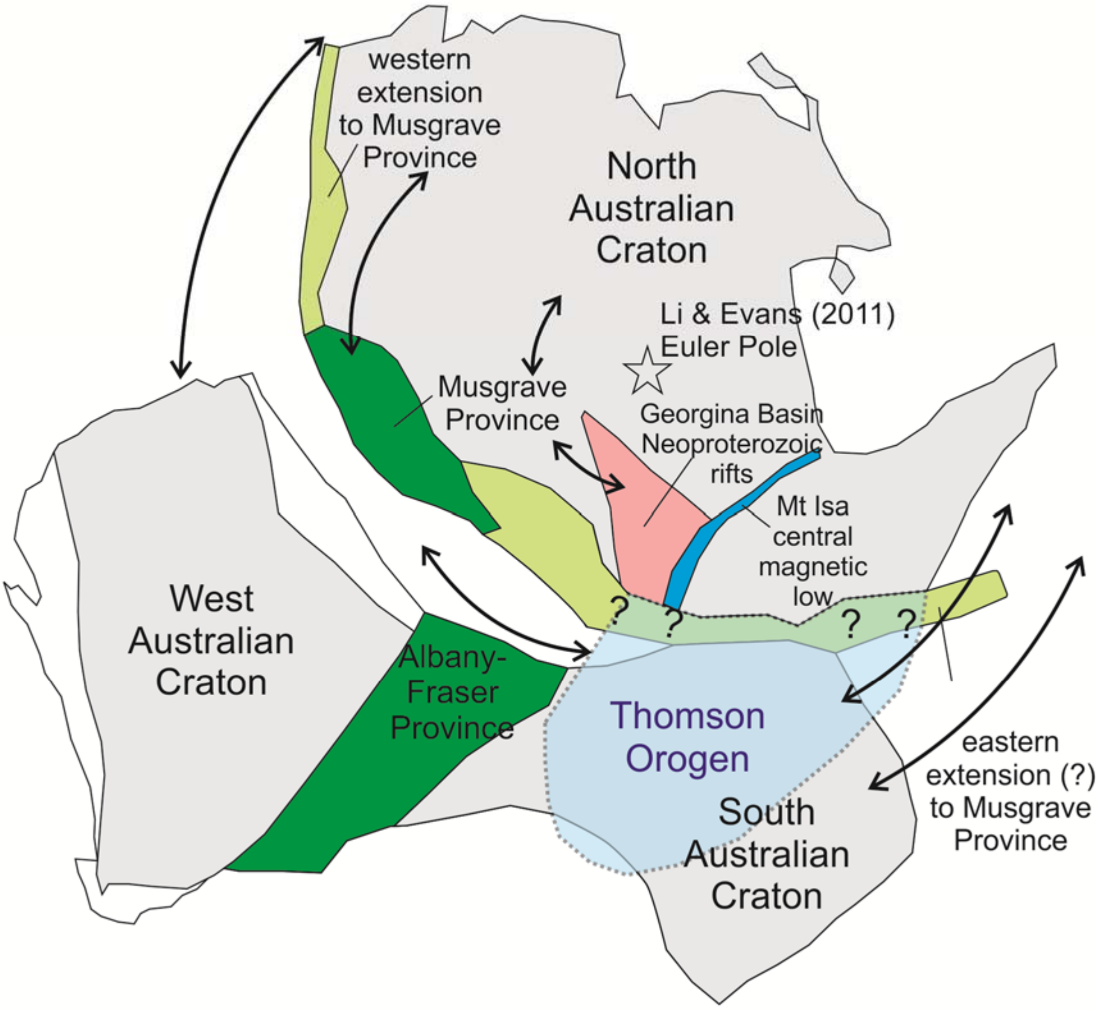


Fig. 3. Reconstruction of the Australian cratons following late Mesoproterozoic (1.3–1 Ga) amalgamation of the North, West and South Australian cratons (Myers et al., 1996) and predates intracratonic anticlockwise 40° rotation along the southern margin of the North Australian Craton at 650–550 Ma suggested by Li and Evans (2011) and adapted from the GPlates reconstruction given in Williams et al. (2012). Overlap between the Thomson Orogen (light blue) and South Australian Craton is shown. Suture zones shown in green. Euler pole of Li and Evans (2011) shown by star. Double-headed arrows show directions of 40° anticlockwise rotation.

As reviewed by Glen (2005) the southern sector of the Neoproterozoic – early Paleozoic Tasmanides consists of two successive orogenic systems (Fig. 2) for which architecture, ages of component rock systems and accretionary history are well documented. The older Delamerian Orogen developed on a rifted passive margin of East Gondwana in the Neoproterozoic and Cambrian. Its outboard part, best known from the Kanmantoo Group in the southeastern Delamerian Orogen of South Australia (Fig. 2), consists of tectonised, Cambrian, mainly deep-marine sedimentary rocks (Haines et al., 2001). Its inboard part, most extensively represented by a thick succession of shallow marine and terrestrial strata accumulated in the Adelaide Rift Complex (Fig. 2; Preiss, 2000). Crustal shortening accompanied by granitoid emplacement occurred in the Delamerian Orogeny at 514–490 Ma (Haines and Flöttmann, 1998) with a much earlier start to compressional deformation at 545 Ma proposed by Turner et al. (2009) on the basis of radiometric dating of cleavage and mylonite fabrics. Docking of an oceanic island arc, represented by Cambrian igneous rocks in western Victoria and Tasmania, has been attributed to this accretionary episode (Foster et al., 2005) but this interpretation remains contested (Foden et al., 2006; Moore et al. 2014). With the exception of the Koonenberry Belt and Tasmania (Fig. 2), the orogen was unaffected by post-Cambrian shortening episodes as widely developed elsewhere in the Tasmanides. The Lachlan Orogen has been studied more extensively than other parts of the Tasmanides, and recently completed deep seismic profiling has revealed its crustal-scale construction (Cayley et al., 2011). The nature of rock systems in the Lachlan Orogen, their ages and structures are now well established although the detailed dynamics of its evolution remain much debated (Aitchison and Buckman, 2012; Glen, 2013; Fergusson, 2014; Moresi et al., 2014; Quinn et al., 2014). The orogen has a substrate of diverse oceanic crust developed in the paleo-Pacific Ocean adjoining East Gondwana and considered to have been largely formed by supra-subduction zone magmatism and backarc extension during the Cambrian. It is overlain by a thick and once very extensive Ordovician deep-marine sedimentary suite consisting mainly of turbidites and derived largely from erosion of neighbouring East Gondwana (Fergusson et al., 2013). Major shortening and thickening of the crust occurred during the Benambran Orogeny at 450–425 Ma, with voluminous granitoid emplacement in its eastern part. Unlike the Delamerian Orogen, the Lachlan Orogen experienced a complex history post-dating the

Benambran Orogeny with periods of extension and successor basin development separated by episodes of compression mainly during Tabberabberan (~390–370 Ma) and Kanimblan (~340 Ma) orogenesis (Glen, 2005; Fergusson, 2010).

In contrast the Thomson Orogen, which forms most of the northern Tasmanides, has been not been studied in detail. However, new information has become available in the last decade enabling a wider appreciation of its tectonic significance for the development of the East Gondwana active margin (Withnall and Henderson, 2012; Fergusson and Henderson, 2013; Glen et al., 2013). The Thomson Orogen, although largely concealed by younger sedimentary basins, has a westward connection to sedimentary basins in central Australia via the Warburton Basin (Fig. 2; Draper, 2006, 2013a). Connections between central Australian basins, Precambrian belts and the Tasmanides are best examined in this region but have been largely overlooked in the literature even though much information is now known about the subsurface Cambrian–Ordovician Warburton Basin (PIRSA, 2007; Radke, 2009) and covered Thomson Orogen (Brown et al., 2012). Thus this account aims to review of the tectonic development of the Thomson Orogen with a reassessment of its implications for the assembly and breakup of Rodinia, development of the paleo-Pacific margin of East Gondwana, and connections to central Australian orogenic and sedimentary systems.

2. Geology and regional setting of the Thomson Orogen

The Thomson Orogen (Fig. 4) is very extensively obscured by Mesozoic cover of the Eromanga Basin but is distinguishable by its geophysical characteristics (Figs. 5 and 6). It was originally considered to be separate from the Lachlan Orogen to the south, mainly from the distinctive northeast structural trends inferred from gravity anomaly patterns (Figs. 4 and 6) in contrast to the more northerly structural trends mapped for the latter, and to facilitate a more objective study of the northern part of the Tasmanides (Kirkegaard, 1974, p. 48). Basement cores collected during petroleum exploration provided the main source of information on much of the Thomson Orogen and are dominated by steeply dipping quartzose metasedimentary rocks of inferred early Paleozoic age (Murray, 1994; Brown et al., 2012). It had been considered that these rocks were a northern continuation of the widespread Ordovician quartz turbidites of the Lachlan Orogen to the south (Murray and Kirkegaard, 1978; Murray, 1986; Burton, 2010). However, mapping of surface exposures of metamorphic basement in the northeastern Thomson Orogen in the Greenvale Province, Charters Towers Province and Anakie Province in central and north Queensland, has shown that the Thomson Orogen is the result of deformation and metamorphism of Late Neoproterozoic and Cambrian units in the Middle to Late Cambrian (Fig. 7; Withnall et al., 1996; Fergusson and Henderson, 2013). It is therefore equivalent to units of the eastern Delamerian Orogen including the Kanmantoo Group and western-most part of the Lachlan Orogen in the Stawell Zone of western Victoria, and the Koonenberry Belt of northwestern New South Wales (Preiss, 2000; Greenfield et al., 2010, 2011; Cayley, 2011).

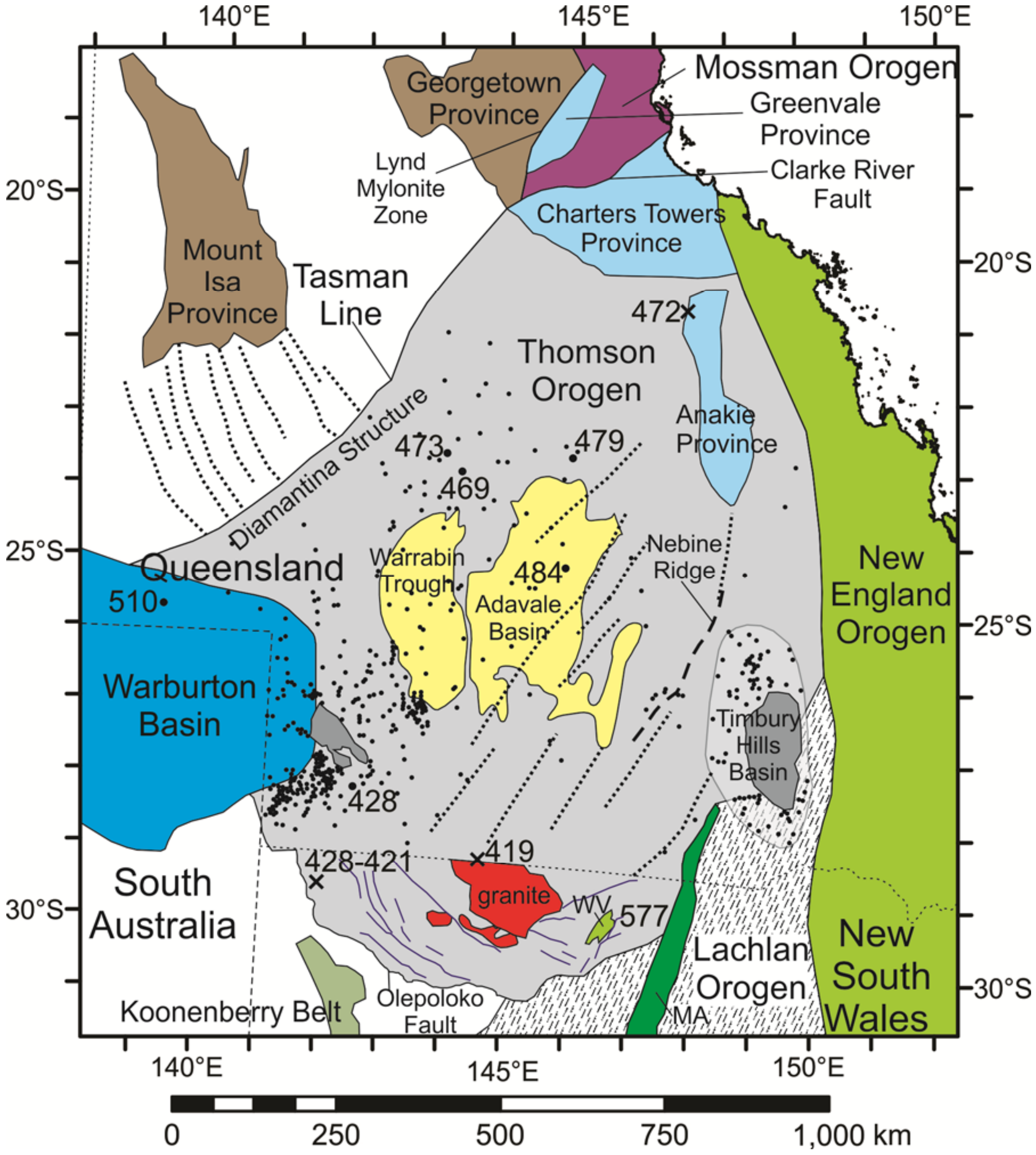


Fig. 4. Main features of the Thomson Orogen in northeastern Australia. Gravity trends in Queensland shown by thick short-dashed lines. Blue lines show magnetic trends in northwestern New South Wales (after Glen et al., 2013). Dots show locations of basement cores in the Thomson Orogen and eastern Warburton Basin in Queensland (from Brown et al., 2012). Dark-shaded regions, including in the Timbury Hills Basin and a region in the southwestern Thomson Orogen, show areas with abundant basement cores. Radiometric ages from basement cores (filled in circles, in Ma) and surface exposures (crosses) shown for the Thomson Orogen in Queensland (Draper, 2006) and northwestern New South Wales (Greenfield et al., 2010, 2011; Glen et al., 2013). For the Thomson Orogen in northwestern New South Wales extent of inferred subsurface granite (red) and main area of inferred subsurface Warraweena Volcanics (green, WV) are shown (after Glen et al., 2013).

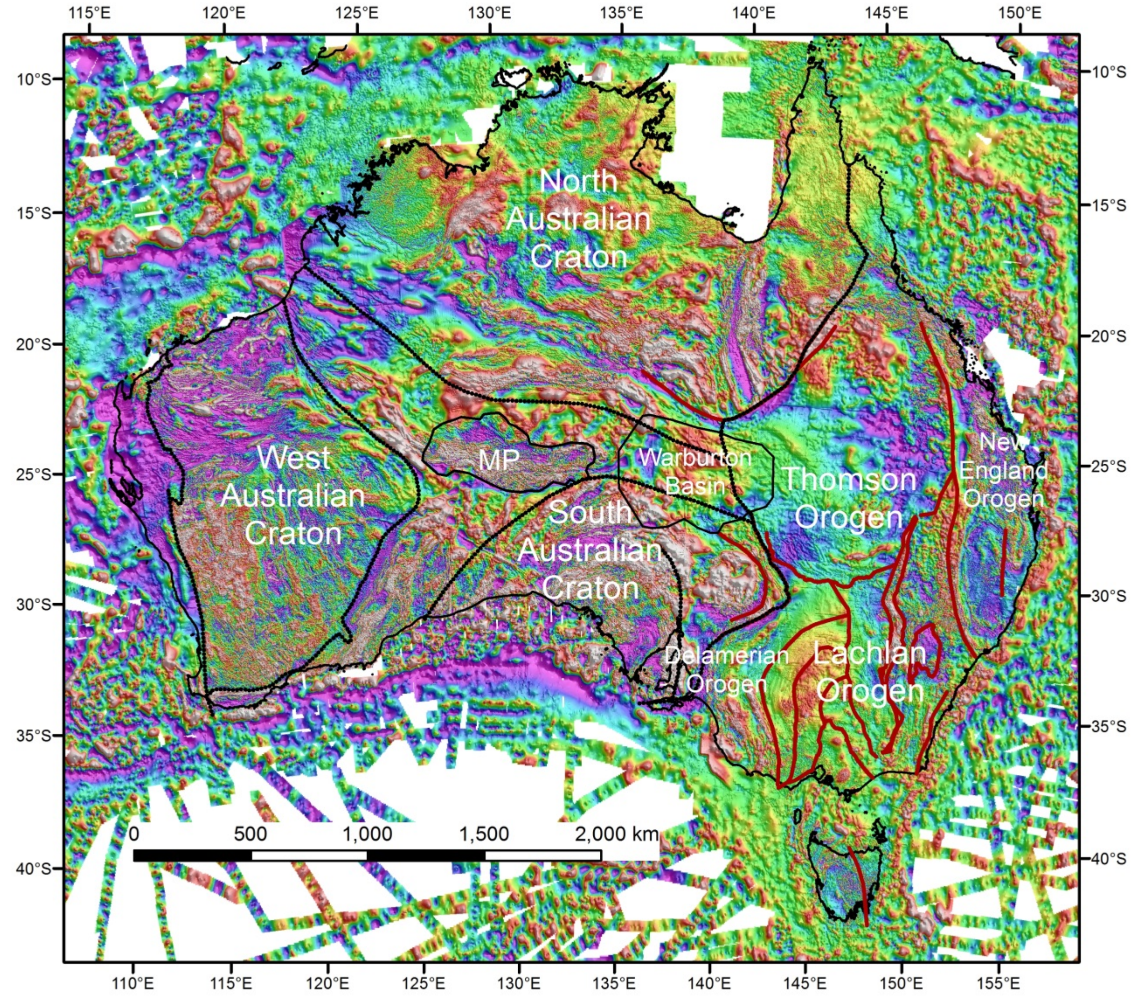


Fig. 5. Map showing magnetic data for Australia and surrounding seas with outlines (black lines) of Precambrian cratons and prominent geophysical lineaments in and at the boundaries of the Tasmanides of eastern Australia (red lines). Magnetic image adapted from the national digital dataset (Kilgour and Hatch, 2002). Abbreviations: MP—Musgrave Province. Note that in this figure and in Fig. 6 that the Musgrave Province has a structural fabric east-west over approximately 1000 km. An eastward extension of this belt is possible but cannot be directly determined because of thick cover including the subsurface Cambrian-Ordovician Warburton Basin.

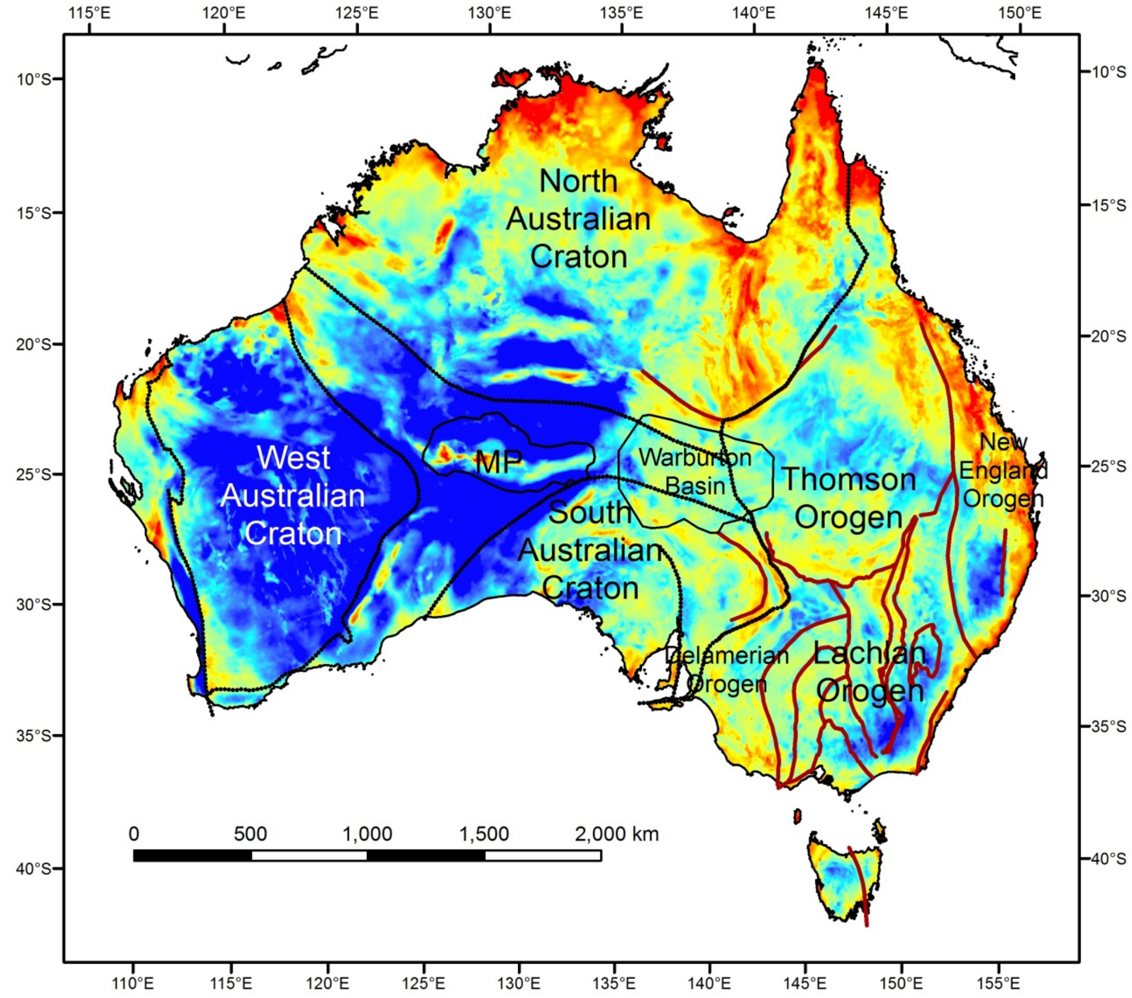
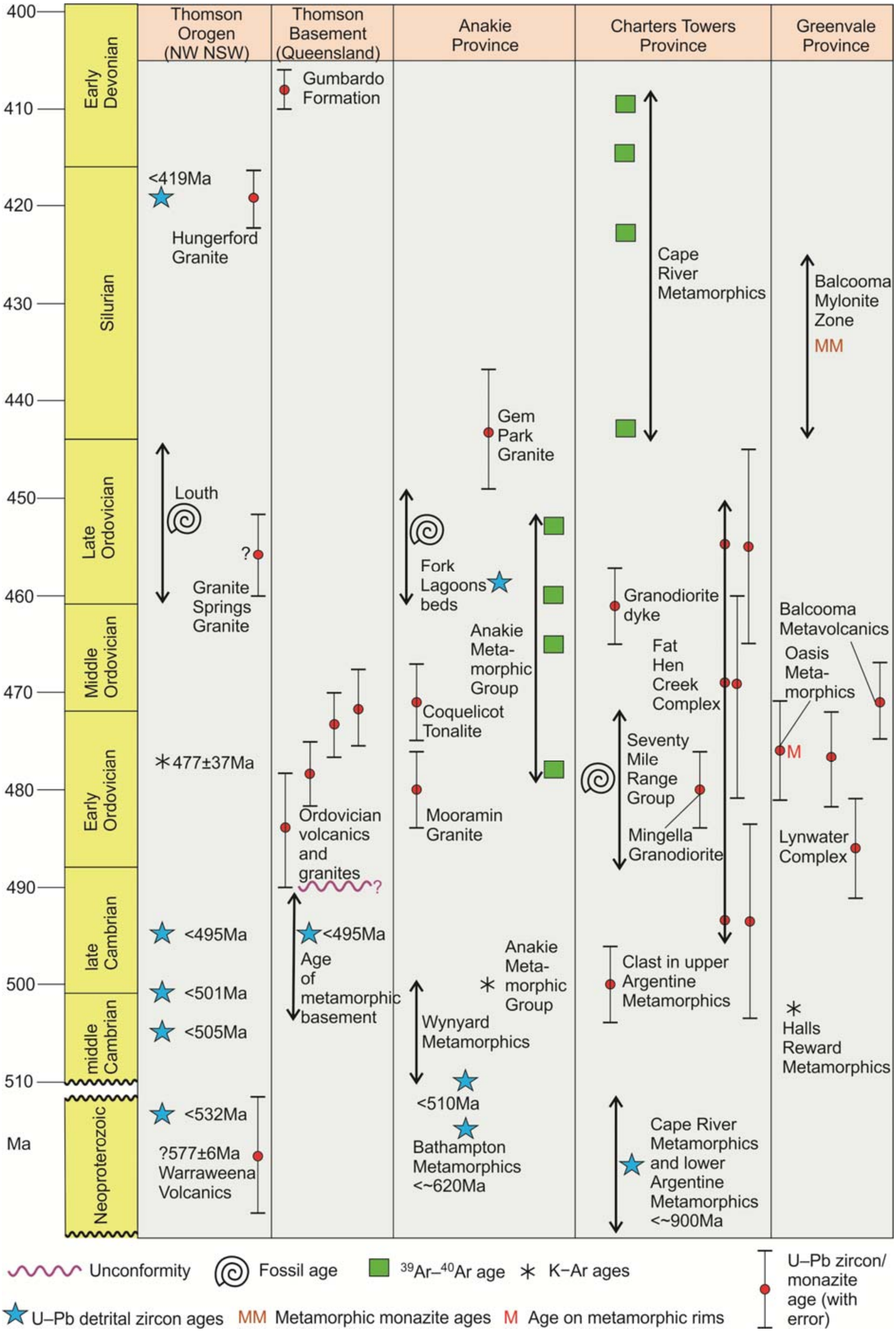


Fig. 6. Map showing gravity data for Australia with outlines (heavy black lines) of Precambrian cratons and prominent geophysical lineaments in and at the boundaries of the Tasmanides of eastern Australia (red lines). Gravity image adapted from the onshore national gravity anomaly dataset (Bacchin, 2009). Abbreviation: MP—Musgrave Province.


400
410
420
430
440
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460
470
480
490
500
510
Ma
Early Devonian
Silurian
Late Ordovician
Middle Ordovician
Early Ordovician
late Cambrian
middle Cambrian
Neoproterozoic
Thomson Orogen (NW NSW)
Thomson Basement (Queensland)
Anakie Province
Charters Towers Province
Greenvale Province
<419Ma
Hungerford Granite
Louth
?
Granite Springs Granite
477±37Ma
<495Ma
<501Ma
<505Ma
<532Ma
?577±6Ma Warraweena Volcanics
Gumbardo Formation
Ordovician volcanics and granites
?
<495Ma
Age of metamorphic basement
Gem Park Granite
Fork Lagoons beds
Anakie Metamorphic Group
Coquelicot Tonalite
Mooramin Granite
Anakie Metamorphic Group
Wynyard Metamorphics
<510Ma
Bathampton Metamorphics <~620Ma
Cape River Metamorphics
Granodiorite dyke
Fat Hen Creek Complex
Seventy Mile Range Group
Mingella Granodiorite
Clast in upper Argentine Metamorphics
Cape River Metamorphics and lower Argentine Metamorphics <~900Ma
Balcooma Mylonite Zone
MM
Balcooma Metavolcanics
Oasis Metamorphics
M
Lynwater Complex
Halls Reward Metamorphics
Unconformity
Fossil age
^{39}Ar–^{40}Ar age
K–Ar ages
U–Pb zircon/monazite age (with error)
U–Pb detrital zircon ages
MM Metamorphic monazite ages
M Age on metamorphic rims

Fig. 7. Time–space plot with most significant radiometric and paleontological age ranges for various parts of the Thomson Orogen. Data sources: Thomson Orogen (northwestern New South Wales) from Glen et al. (2013) with ages of the Hungerford Granite and Granite Springs Granite from Bultitude and Cross (2013). Thomson basement in Queensland (west and southwest of the Anakie Province) – U–Pb zircon ages (Draper, 2006) and detrital zircon ages from Brown et al. (2014), Anakie Province – fossil ages from the Fork Lagoons beds (Withnall et al., 1995), K/Ar ages from the Anakie Metamorphic Group (Withnall et al., 1996), U–Pb detrital zircon ages (Fergusson et al., 2001, 2007a), ^{39}Ar/^{40}Ar cooling ages from the Anakie Metamorphic Group and U–Pb monazite age from the Gem Park Granite (Wood and Lister, 2013), Charters Towers Province – fossil ages from the Seventy Mile Range Group (Henderson, 1983, 1986), U–Pb zircon ages from the Fat Hen Creek Complex (Hutton et al., 1997), ^{39}Ar/^{40}Ar cooling ages from the Cape River Metamorphics (Fergusson et al., 2005a), U–Pb zircon and detrital zircon ages (Fergusson et al., 2007a, b), Greenvale Province – U–Pb zircon age from the Balcooma Metavolcanics (Withnall et al., 1991), K/Ar ages from the Halls Reward Metamorphics (Nishiya et al., 2003), U–Pb zircon ages from the Oasis Metamorphics and Lynwater Complex (Fergusson et al., 2007b), and monazite ages on metamorphism from the Balcooma Metavolcanic Group (Ali, 2010).

In north Queensland, the Thomson Orogen includes the Greenvale Province which is in faulted contact along the Lynd Mylonite Zone with the Paleoproterozoic to Mesoproterozoic Georgetown Province (Fig. 4; Fergusson et al., 2007b). The Lynd Mylonite Zone consists of a steeply, east-dipping, ductile shear zone with the eastern side of Neoproterozoic to early Paleozoic Oasis Metamorphics thrust over the Paleoproterozoic to Mesoproterozoic Einasleigh Metamorphics (Korsch et al., 2012). It is an exposed part of the Tasman Line, the western boundary of the Tasmanides (Direen and Crawford, 2003a), but has an opposite sense of displacement compared to the Tasman Line further north where it is a steeply west-dipping fault with Precambrian rocks in the hanging wall, thrust over the rocks of the Paleozoic Mossman Orogen in the footwall (Henderson et al., 2013). In western Queensland, the Tasman Line is under cover but is remarkably sharp with termination of strong gravity and magnetic trends (Figs. 5 and 6) along the Diamantina Structure (Fig. 4) which marks the southern subsurface extent of the Mt Isa Province (Murray et al., 1989; Withnall and Hutton, 2013). The subsurface Thomson Orogen in southern Queensland is known only from basement cores and is connected to the Cambrian–Ordovician Warburton Basin in northeastern South Australia (Fig. 4), although no definite boundary has been confidently identified between them.

In northwestern New South Wales, the Thomson Orogen consists of a widespread, but poorly exposed, low-grade metasedimentary succession intruded by Paleozoic granites that have been related by Burton (2010) to the Cambrian to Carboniferous Lachlan Orogen but were considered a separate, but in part contemporary orogenic belt with a Late Neoproterozoic – early Paleozoic history by Glen et al. (2013). Based on examination of sparse outcrop, drill-core, U–Pb zircon ages (Fig. 7) and deep seismic reflection profiles in northwestern New South Wales it has been argued that the Thomson Orogen is distinct from the Lachlan Orogen with accretion of some Late Neoproterozoic island arc rocks and possible Early Ordovician deformation (Glen et al., 2013). Structural trends and interpreted units have been inferred on the basis of aeromagnetic data and have a strong WNW–ESE structural grain in the west that curves to an east–west trend in the middle and to a WSW–ENE trend further east (Fig. 4). The boundary between the Thomson Orogen and the Lachlan Orogen to the south is the Olepoloko Fault, which is shown on deep seismic lines as a major, steeply north–dipping fault. Basement rocks of the Thomson Orogen are thrust over Devonian siliciclastic successions of the Darling Basin to the south, indicating movement of Late Devonian to Carboniferous age consistent with the Kanimblan Orogeny of the Lachlan Orogen and the Alice Springs Orogeny in central Australia (Glen et al., 2013). Seismic profiling across the Olepoloko Fault shows an offset of the Moho, with appreciably thicker crust of the Thomson Orogen (~45 km) abutting thinner crust of the Lachlan Orogen (~35 km), indicating an earlier history of substantial movement.

Southwest of the Thomson Orogen and northeast of the Paleoproterozoic–Mesoproterozoic Curnamona Province lies the Koonenberry Belt (Figs. 2 and 4; Greenfield et al., 2011), which is characterised by a strong NNW structural grain evident in magnetic data that to the northwest loses definition beneath the subsurface Warburton Basin (Fig. 5). The Koonenberry Belt is a northern continuation of the Delamerian Orogen in southeastern Australia and preserves a 600–580 Ma sedimentary and volcanic assemblage interpreted as a passive rifted margin succession and succeeded by an early Paleozoic convergent margin assemblage (Greenfield et al., 2010, 2011). These two assemblages are overprinted by strong deformation in the Middle to Late Cambrian Delamerian Orogeny and the Late Ordovician – Early Silurian Benambran Orogeny (Greenfield et al., 2010, 2011).

3. Geological evolution of the late Neoproterozoic to early Paleozoic northeast Gondwana margin

The northeast Gondwana margin in the Late Neoproterozoic to early Paleozoic, as exemplified by the development of the Thomson Orogen, has formed in several discrete phases: (1) a phase of rifting and passive margin development associated with the formation of Late Neoproterozoic sedimentary and mafic igneous units (Direen and Crawford, 2003a, b; Fergusson et al., 2009; Greenfield et al., 2011), (2) Cambrian convergence culminating in the Middle to Late Cambrian Delamerian Orogeny (Foden et al., 2006), an event associated with widespread continental growth in eastern Australia, (3) an Ordovician extensional event associated with backarc sedimentation, deformation and silicic calc-alkaline igneous activity (Fergusson and Henderson, 2013), and (4) compressional deformation and reworking in the Late Ordovician – Early Silurian Benambran Orogeny (Glen, 2005).

Rodinia is considered to have undergone a prolonged breakup at 860 to 570 Ma with several superplume events and related magmatism in the earlier part of this history followed by rifting and formation of the paleo-Pacific Ocean between Australia–East Antarctica, Laurentia and possibly South China (Li et al., 2003, 2008). Evidence for magmatism of this age in South Australia is shown by the Gairdner dyke swarm at 827 Ma (Wingate et al., 1998). Continental breakup with development of the paleo-Pacific Ocean from 750 Ma onwards with wide oceans formed by 720 Ma was favoured by Li et al. (2003, 2008). The most complete record of sedimentation during the Neoproterozoic in Australia is in the Adelaide Rift Complex (Fig. 8) although parts of the succession are poorly dated. Continental breakup has been suggested to have occurred at around 700 Ma prior to the episode of thick continental to shallow marine sedimentation, between the Sturtian and Marinoan glacial episodes, that has been attributed to thermal sag after rifting (Powell et al., 1994; Preiss, 2000). New authigenic monazite ages from the Enorama Shale (earliest generation 680 ± 23 Ma) prior to the Marinoan glacial episode indicate that the Sturtian glaciation was no younger than 690 Ma and possibly older (Mahan et al., 2010). A period of rifting associated with the Sturtian glacial deposits is also documented from the base of the Georgina Basin in southwest Queensland west of the Thomson Orogen (Greene, 2010). No definitive record of this rift event associated with Rodinia breakup is known in the Thomson Orogen. However, thick metasedimentary quartzose psammitic gneisses abound in the Cape River Metamorphics, with possible equivalents in the lower part of the Argentine Metamorphics of the Charters Towers Province (northern Thomson Orogen) and are dominated by detrital zircons with U–Pb ages of 1.3 to 1 Ga, but lack ages younger than 900 Ma (Fig. 9; Fergusson et al., 2001, 2007a). Their age is therefore poorly constrained with a maximum of Early Neoproterozoic and a minimum of latest Neoproterozoic; the possibility remains that these sedimentary rocks date from the early breakup of Rodinia.

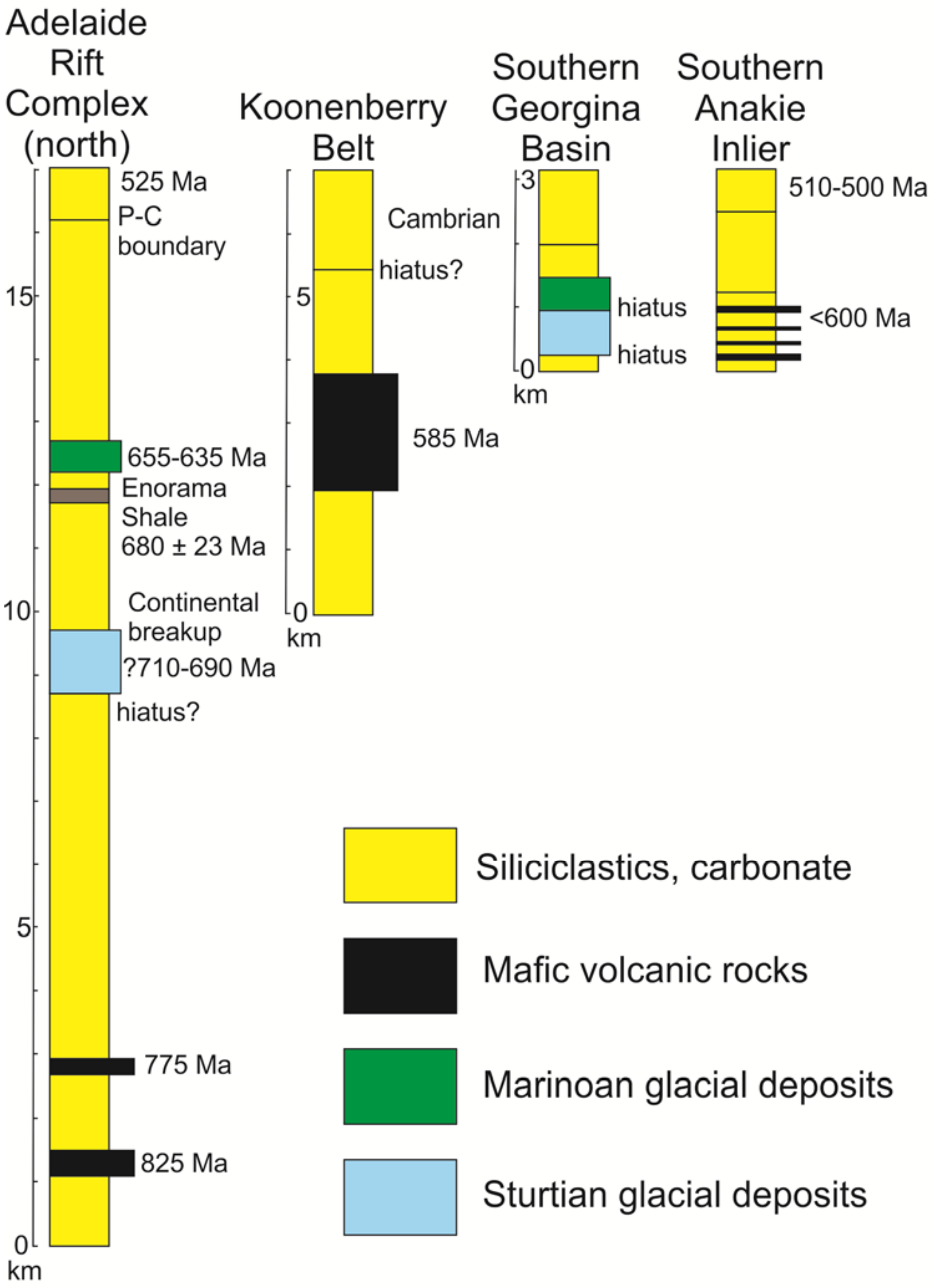
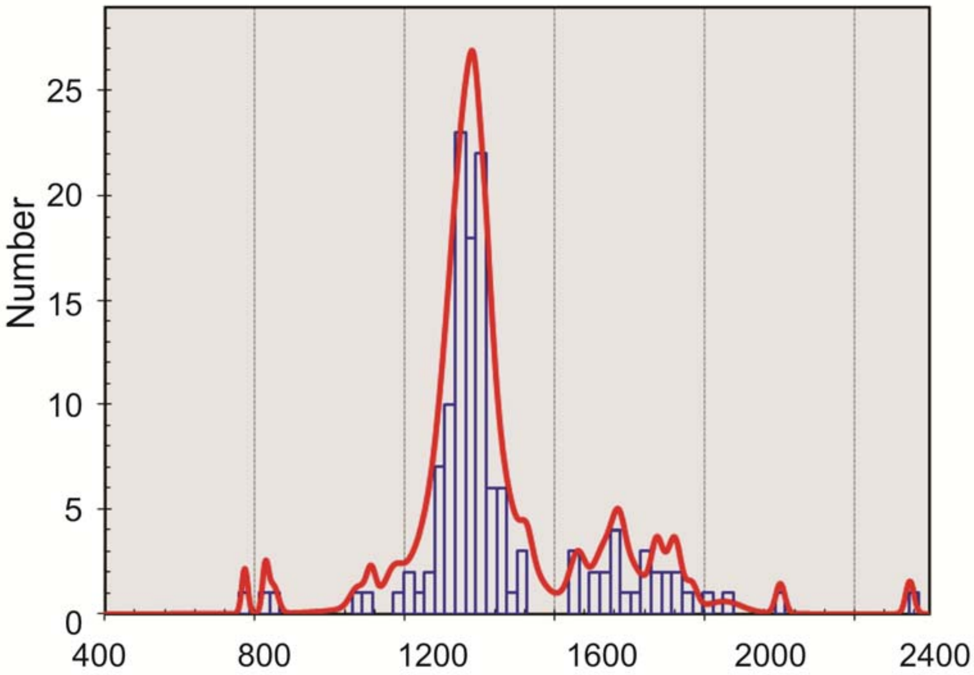


Fig. 8. Stratigraphic columns showing the Neoproterozoic and Cambrian stratigraphy of basinal and reconstructed assemblages along and adjacent to the East Gondwana Pacific margin. Source of data: Adelaide Rift Complex from Preiss (2000) and Mahan et al. (2010), Koonenberry Belt from Greenfield et al. (2010, 2011), southern Georgina Basin from Greene (2010), and southern Anakie Inlier from Fergusson and Henderson (2013).

(a) Anakie Province – Bathampton Metamorphics



(b) Charters Towers Province – Cape River Metamorphics

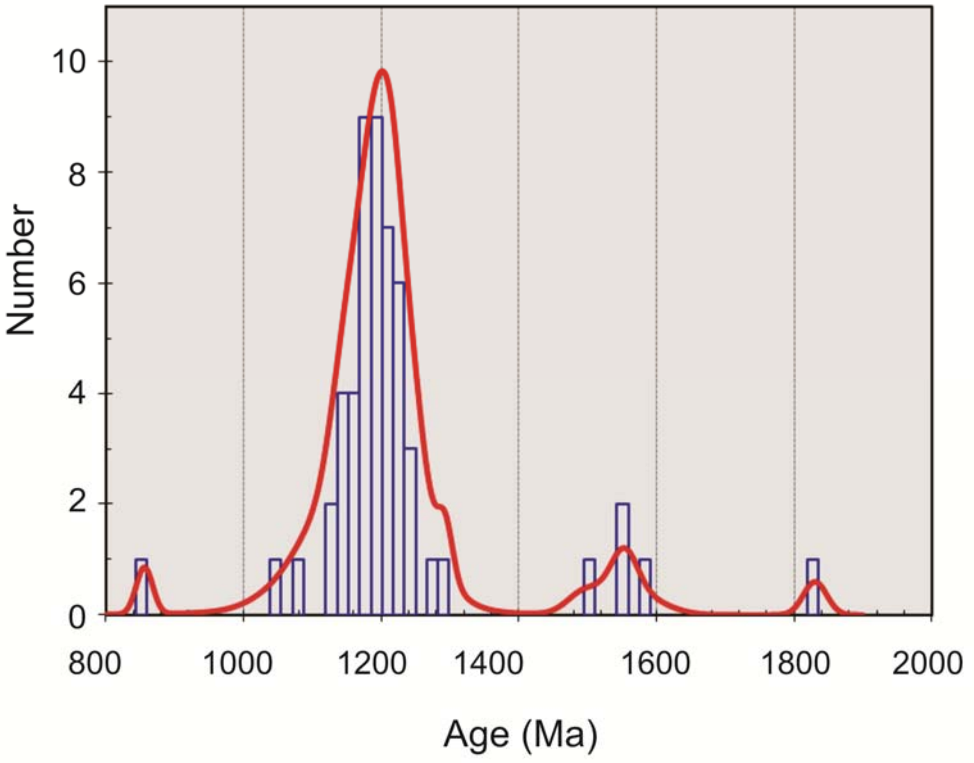


Fig. 9. Compilation of U–Pb detrital zircon ages, as both binned frequency histograms and probability density distributions, showing prominent Grenville 1–1.3 Ga age populations from: (a) the Anakie Province (3 samples, 134 ages, Bathampton Metamorphics, Fergusson et al., 2001), and (b) Charters Towers Province (2 samples, 54 ages, Cape River Metamorphics, Fergusson et al., 2007a). In this compilation age estimates for all individual grain analyses are <10% concordant; ^{206}Pb–^{208}Pb data is used for age estimates >1 Ga.

3a. Latest Neoproterozoic sedimentation and igneous activity

A latest Neoproterozoic rifting event in southeastern Australia was interpreted at 600 to 580 Ma based on tholeiitic and alkaline mafic volcanic rocks in northwestern New South Wales, western Victoria and Tasmania (Fig. 10; Direen and Crawford, 2003a, b; Meffre et al., 2004). These assemblages have restricted exposures but are considered far more widely developed in the subsurface based on magnetic and gravity data (Direen and Crawford, 2003a), although some of these subsurface signatures could represent younger units of a boninite–tholeiite association as suggested for the Dimboola Igneous Complex of western Victoria (VandenBerg et al., 2000, p. 27). Inferred thick successions of mafic volcanic rocks were equated to seaward-dipping reflector sequences found on volcanic passive margins as in the northern North Atlantic Ocean (Direen and Crawford, 2003a). A thick succession of shallow marine quartzose siliciclastics, minor carbonate and interbedded mainly mafic volcanic rocks (Grey Range Group) of Late Neoproterozoic age in the Koonenberry Belt was interpreted as part of a rifted passive margin succession (Fig. 8; Greenfield et al., 2010, 2011). The Mount Arrowsmith Volcanics have an alkaline intraplate character considered characteristic of modern rifts (Greenfield et al., 2011). Rifting in the latest Neoproterozoic is also consistent with a second episode of extension recognised for the Georgina Basin in southwestern Queensland at ~600 Ma by Greene (2010).

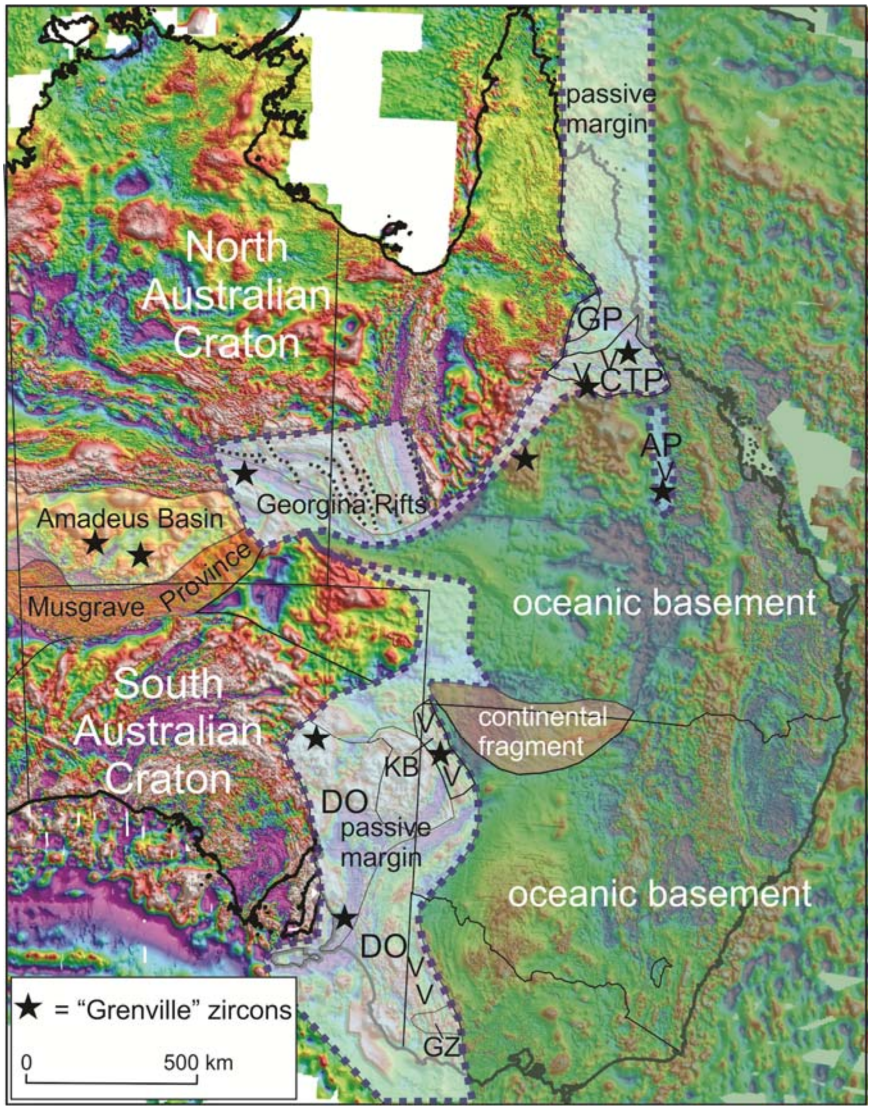


Fig. 10. The rifted East Gondwana margin after the 650–550 Ma intracratonic anticlockwise rotation draped over magnetics (magnetic image adapted from the national digital dataset, Kilgour and Hatch, 2002). Extent of known and inferred passive margin is outlined by deep blue dashed line and includes rift basins in the Georgina Basin (dotted black lines after Greene, 2010). Oceanic basement in east is inferred for much of the Thomson Orogen (see text) and exposed as backarc basin and boninitic rocks in the Lachlan Orogen (Glen, 2013). Rifted continental fragment proposed by Glen et al. (2013). "Grenville-age" zircons (1–1.3 Ga) are abundant in samples from northeastern Australia (Fergusson et al., 2007a; Brown et al., 2014), in the Tasmanides neighbouring the South Australian Craton (Ireland et al., 1998; Johnson et al., 2012), and the Harts Range Group, Amadeus and Georgina basins (Camacho et al., 2002; Maidment et al., 2007, 2013). Abbreviations: AP—Anakie Province, CTP—Charters Towers Province, DO—Delamerian Orogen, GZ—Glenelg Zone, GP—Greenvale Province, KB—Koonenberry Belt.

In the southern Anakie Province of the northeast Thomson Orogen (Figs. 2 and 4), regional mapping has established a major twofold subdivision with a structurally lower unit of quartzose psammite, pelite, quartzite, amphibolite, mafic schist and serpentinite (the Bathampton Metamorphics) and structurally higher units of quartzite, graphitic schist, pelite and lithic psammitic rocks (Withnall et al., 1995; Fergusson and Henderson, 2013). Detrital zircon data show that the lower unit is derived mainly from a "Grenville"-aged orogenic belt with most ages in the range 1.3–1 Ga (Fig. 9a) and provide a maximum depositional age of Late Neoproterozoic indicated by a cluster of 5 grains around ~600 Ma (Fig. 7; Fergusson et al., 2001; Fergusson and Henderson, 2013). Mafic rocks in the Bathampton Metamorphics have a MORB magmatic affinity consistent with an inferred passive margin setting (Fergusson et al., 2009). The upper age limit for these rocks is indicated by K/Ar and ^{40}Ar/^{39}Ar ages on metamorphism at 500 to 480 Ma but they are of inferred Late Neoproterozoic age as the structurally overlying unit contains abundant zircons in the range 600–510 Ma consistent with an age of 510–500 Ma (Fergusson et al., 2001; Fergusson and Henderson, 2013).

While it is possible that a minor rifting event affected the East Gondwana margin at 600 to 580 Ma, two mitigating factors suggest that it was not a major event. Firstly, no major rifted continental fragment has been identified associated with this rifting, although several small continental fragments maybe contained in the subsurface of the Lachlan and Thomson orogens (Fig. 10; Greenfield et al., 2011; Glen et al., 2013). Secondly, despite the presumed extent of this rifted margin no major thermal sag phase of sedimentation has been identified as has been documented from the Adelaide Rift Complex which displays a thick sedimentary succession (Fig. 8; Preiss, 2000).

A distinctive feature of these Late Neoproterozoic successions of the Thomson Orogen and Koonenberry Belt is the abundance of detrital zircons in the metasedimentary rocks with U–Pb zircon ages mainly in the range 1.3–1 Ga as in the Bathampton Group of the Anakie Province (Fergusson et al., 2001). Detrital zircon and rutile ages from the passive margin sedimentary rocks of the Koonenberry Belt are also dominated by a “Grenville” source (Johnson et al., 2012). A similar provenance is indicated for the Late Neoproterozoic Bonney Sandstone, from the Delamerian Orogen in the northern Flinders Ranges of South Australia and in the Heatherdale Shale and Marino Arkose from the Delamerian Orogen further south (Ireland et al., 1998). The prominence of this “Grenvillean” source is also shown by the unimodal zircon ages from the dominant quartz-lithic psammitic gneisses of the Cape River Metamorphics (Fig. 9b) and the lower part of the Argentine Metamorphics in the Charters Towers Block (Fergusson et al., 2007a). The unimodal “Grenvillean” zircon signature is indicative of a local source, whereas a sample of quartzite from the Cape River Metamorphics has a remarkably diffuse pattern which is probably caused by long-distance transport with the most significant peaks at 1800–1895 Ma, ~1110–1265 Ma and ~905–920 Ma (Fergusson et al., 2007a). However, as no zircons younger than 900 Ma occur in these units, their age is only poorly constrained to the Neoproterozoic. Detrital zircons from two basement cores near the northwestern boundary of the Thomson Orogen (the “Machattie Beds”) have unimodal peaks at ~1180 Ma with maximum depositional ages of ~650 Ma (Brown et al., 2014; Carr et al., 2014).

It has been suggested that the “Grenvillean” source for these units is an east to northeast continuation of the Musgrave Province of central Australia (Fig. 3; Fergusson et al., 2007a), which has abundant Mesoproterozoic igneous and metamorphic rocks that provided a unimodal source for units of the Amadeus Basin in the latest Neoproterozoic including Uluru and Kata Tjuta (Camacho et al., 2002). Central Australia is marked by Proterozoic Provinces of the Arunta region at the southern margin of the North Australian Craton that have a strong east-west structural grain as does the Proterozoic–Paleozoic Amadeus Basin and the Musgrave Province (Figs. 5 and 6; Cawood and Korsch, 2008). The eastern extent of the Musgrave Province is unclear from the geophysical data but an eastern continuation seems likely given it strong overall east-west structural grain and this is implicit in the reconstructions of Myers et al. (1996) and Wingate et al. (2002). Any eastern continuation of the Musgrave Province is hidden in the subsurface below Mesozoic and Paleozoic basins in western Queensland and northeastern South Australia as well as being beneath the Thomson Orogen farther to the northeast and is not traceable in regional magnetic and gravity data (Figs. 5 and 6).

The proposal of rifting at 600–580 Ma and uplift of an inferred eastern continuation of the Musgrave Province need to be assessed in the light of the reinterpretation of paired paleomagnetic poles from the North Australian and West Australian cratons that indicate a 40° anticlockwise intracratonic rotation about a Euler pole at 20°S 135°E along a curved "cross-continental megashear zone" in the interval 650–550 Ma (Li and Evans, 2011, p. 39). The best dated pair of poles is provided by the 1.07 Ga Alcurra dykes and sills of the northern Musgrave Province in the extreme south of the North Australian Craton and the Bangemall Basin sills of the West Australian Craton of the same age (Wingate et al., 2002; Schmidt et al., 2006). The youngest pole of three dated sets is the 755 Ma Munding Well dykes of the West Australian Craton (Wingate and Giddings, 2000). Thus the intraplate rotation must postdate 755 Ma. Late Neoproterozoic events in western and central Australia include the Paterson Orogeny at around 650 Ma along the northeastern margin of the West Australian Craton (Czarnota et al., 2009) and the Petermann Orogeny involving upthrust blocks of the Musgrave Province along the southern North Australian Craton at 600–530 Ma (Aitken et al., 2009; Raimondo et al., 2010). Thus, overall the intraplate rotation is considered by Li and Evans (2011) to have occurred along these intracratonic zones of deformation between the North Australian Craton and an amalgam of the West and South Australian cratons in the interval 650–550 Ma. An earlier suggestion by Veevers and Powell (1984, p. 278, reiterated by Veevers, 2004, p. 18) has Neoproterozoic rifting in the western Tasmanides as related to intracratonic deformation along the Paterson and Musgrave belts. It is considered that prior to intracratonic rotation the Musgrave Province continued eastwards into the present-day Thomson Orogen (Fig. 3) and thereby provided a source for 1.3 to 1.0 Ga zircons into units such as the Bathampton Metamorphics of the Anakie Province and also the Koonenberry Belt and other parts of the Delamerian Orogen in South Australia. Its location in the subsurface is not apparent from the geophysical database for the Thomson Orogen and awaits collection of more detailed geophysical data. As the intracratonic rotation developed, the break along the former contact between the North and South Australian cratons propagated eastwards and then in a northeast direction along the Tasman Line, initially as the Diamantina Structure, resulting in rifting of crust, and possibly involving the separation of continental fragments along the East Gondwana margin. The resulting thinned crust provided accommodation space for the eventual development of the Thomson Orogen (Fig. 10). At least locally, rifting appears to have been widely developed early in the intracratonic rotation followed by compressional deformation with abundant crustal scale south-dipping thrusting occurring along the northern side of the Musgrave Province up until 550 to 530 Ma (Raimondo et al., 2010).

An additional complication has been the suggestion by Glen et al. (2013) that the Warraweena Volcanics, which have volcanic arc geochemical signature and occur in the Thomson Orogen of northwestern New South Wales (Figs. 4 and 7), are Late Neoproterozoic in age. The Warraweena Volcanics have only been sampled from drill core but their subsurface distribution is inferred from associated magnetic anomalies and their calc-alkaline geochemistry considered comparable to that of the Ordovician Macquarie Arc by Burton et al. (2008). A Late Neoproterozoic age was proposed by Glen et al. (2013) on the basis of significant peak of U–Pb zircon ages at 577 ± 6 Ma (6 grains) in one sample of Warraweena Volcanics and an age of 594 ± 7 Ma (4 grains) for a gabbroic body considered related to the volcanic rocks. These ages have been disputed by Burton and Trigg (2014) who argued they represent a relict population on the basis of younger grains in both samples that had been dismissed in the age assignments. The Late Neoproterozoic age peaks are the most prominent in both samples and therefore a Late Neoproterozoic age is possible but as noted by Glen et al. (2013) further work is needed on the gabbro sample to explain the presence of younger zircons. However, these rocks are surrounded by low-grade metasedimentary successions that are of latest Cambrian to Ordovician age (Glen et al., 2013), and are likely to be country rock to the gabbro. Given the uncertainty of relationships and the age determinations it is difficult to ascertain the significance of these rocks. Development of a volcanic arc in the Late Neoproterozoic requires incorporation of the arc into basement of the Thomson Orogen prior to widespread deposition of deep-marine sedimentary units in the Late Cambrian to Ordovician. No arc assemblage of this antiquity is known from elsewhere in the Tasmanides.

3b. Cambrian sedimentation and Delamerian Orogeny

A major new development in the understanding of the Thomson Orogen is the recognition that widespread quartzose turbidites in the metamorphic basement, previously considered a northern equivalent of the Ordovician turbidites of the Lachlan Orogen to the south (Murray, 1986, 1994), are of Middle to Late Cambrian age (Figs. 7 and 11). They are the deformed fill of a huge sedimentary basin (Fig. 12) that greatly exceeds the extent of the analogous Middle Cambrian Kanmantoo Group in the southeastern Delamerian Orogen and the Cambrian quartzose turbidites of the Stawell Zone in the Lachlan Orogen of western Victoria (Preiss, 2000; VandenBerg et al., 2000; Squire et al., 2006).

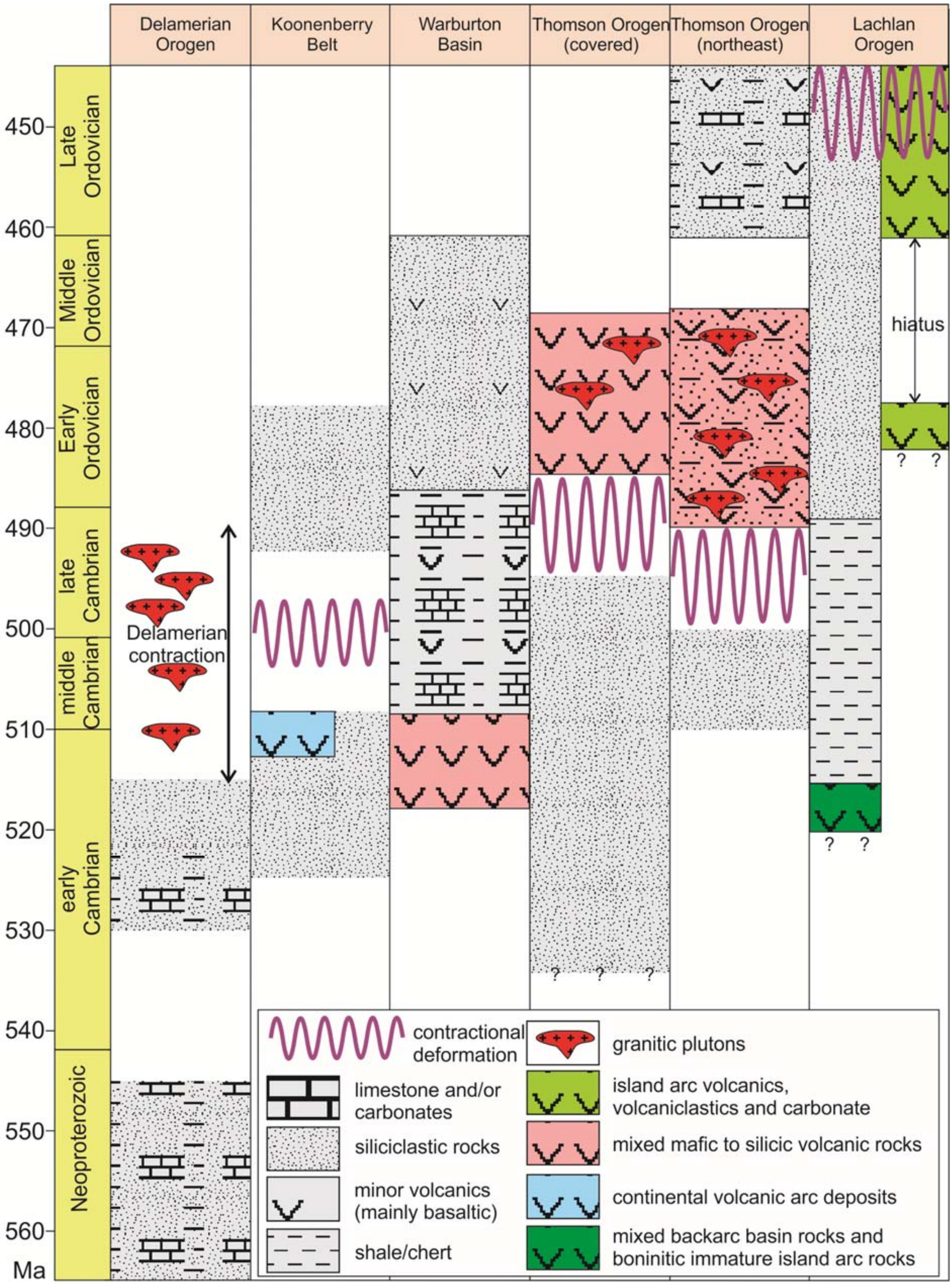


Fig. 11. Time-space plot showing a comparison of the Thomson Orogen to neighbouring elements in eastern Australia. Lachlan Orogen column shows the Macquarie Arc to the right.

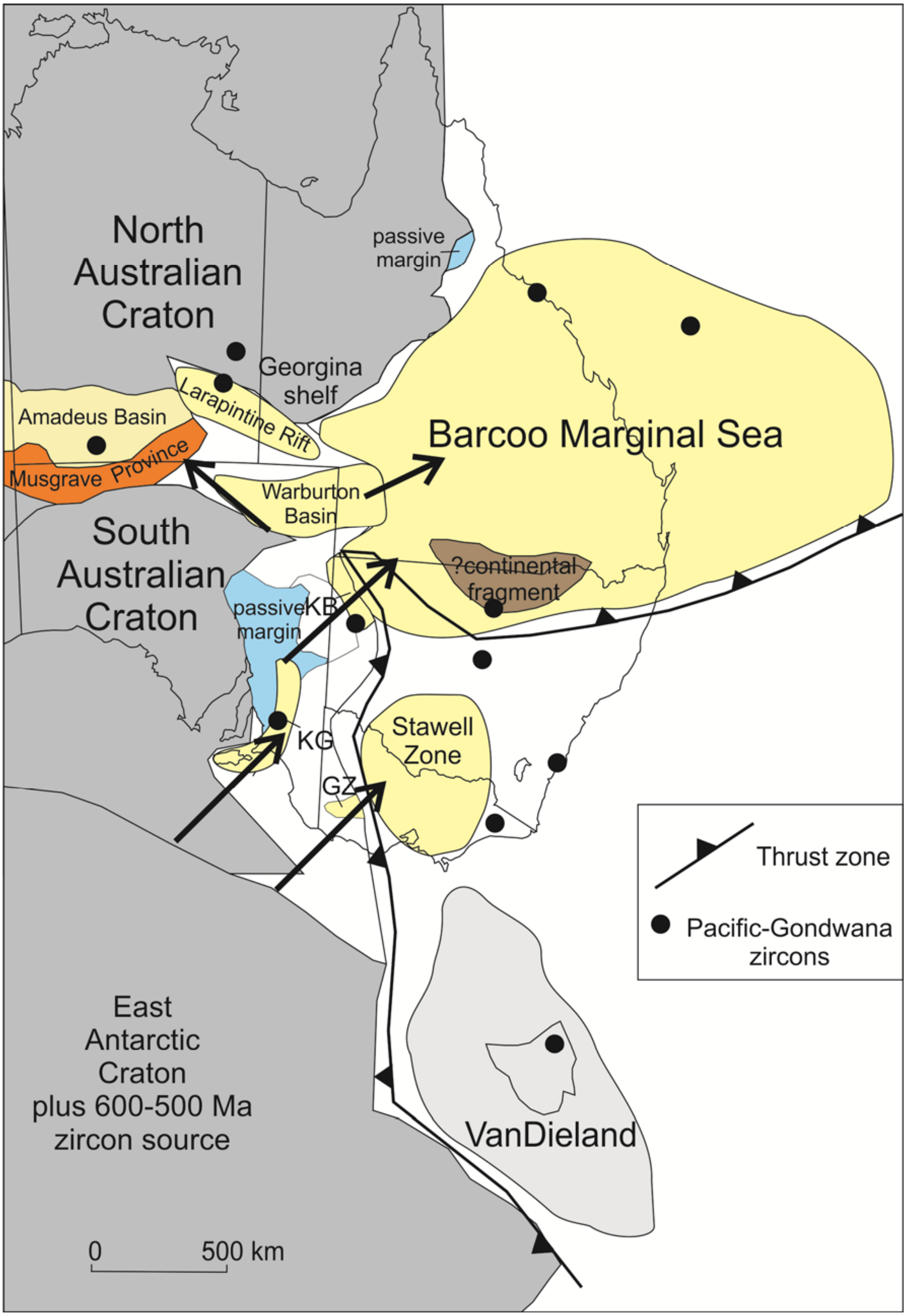
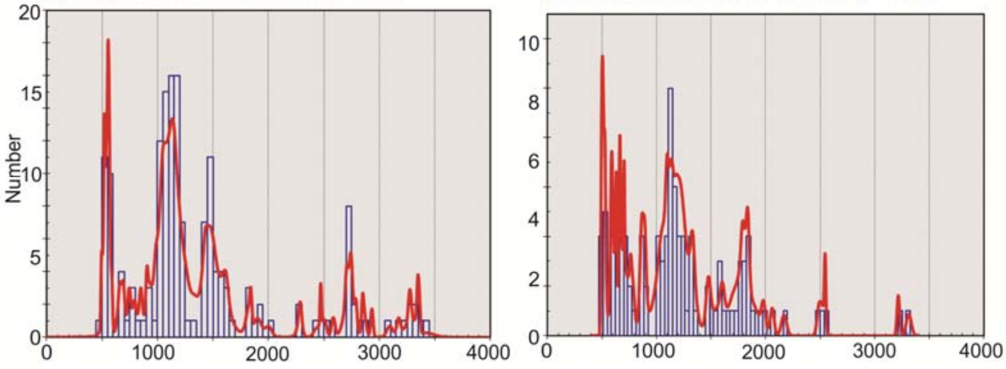


Fig. 12. Reconstruction of the East Gondwana margin for the interval 520–500 Ma showing infilling of the Barcoo Marginal Sea while the Lachlan Orogen to the south has a much more

restricted distribution of quartzose turbidites. Hypothetical continental fragment was proposed by Glen et al. (2013) for the southern Thomson Orogen. Abbreviations: GZ—Glenelg Zone, KB—Koonenberry Belt, KG—Kanmantoo Group. Pacific–Gondwana age zircons (650–500 Ma) are widespread in Early Paleozoic sedimentary sequences of the Tasmanides and central Australian sedimentary basins (Ireland et al., 1998; Fergusson and Fanning, 2002; Black et al., 2004; Buick et al., 2005; Fergusson et al., 2005b, 2007a; Maidment et al., 2007; Greenfield et al., 2010; Glen et al., 2013; Maidment et al., 2013).

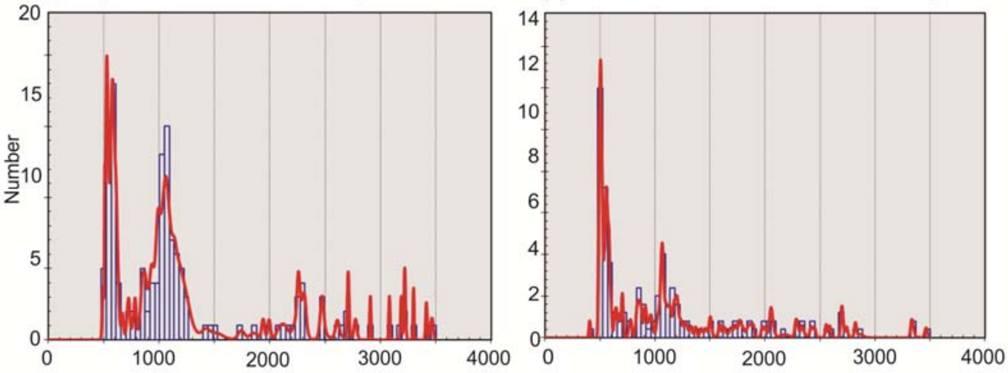
(a) Early Cambrian of the Amadeus Basin

(b) Early Cambrian of the Harts Range Group



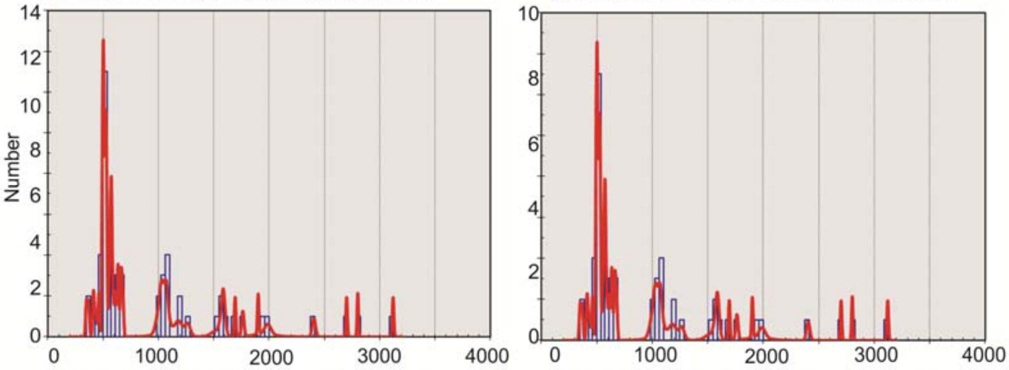
(c) Early Cambrian Kanmantoo Group

(d) ?Cambrian of the southern Thomson Orogen



(e) Cambrian of the Argentine Metamorphics

(f) Cambrian of the Anakie Metamorphic Group



(g) Early to Middle Ordovician Girilambone Group

(h) Late Ordovician from southeastern Lachlan Orogen

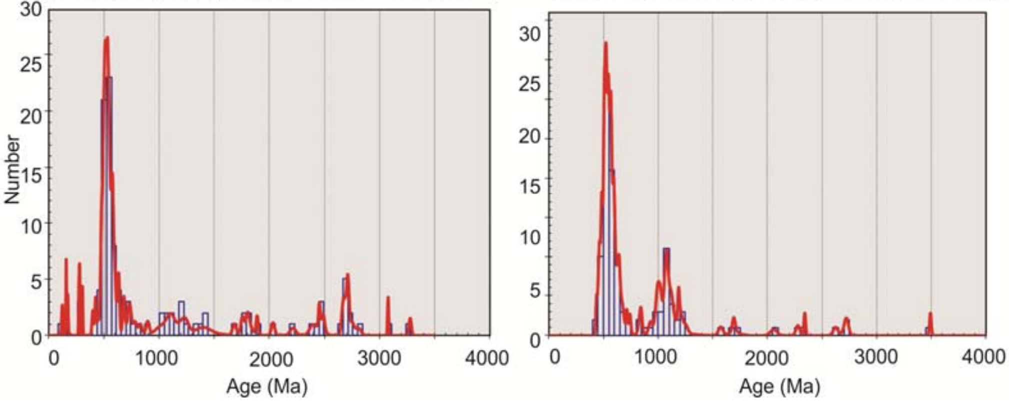


Fig. 13. Compilation of U–Pb detrital zircon ages, as both binned frequency histograms and probability density distributions, showing prominent Pacific–Gondwana (650–500 Ma) populations in samples from the Tasmanides and central Australian basins. (a) Early

Cambrian of the Amadeus Basin (sample of Goyder Formation and two samples of Pacoota Formation, 169 ages, from Buick et al. (2005) and Maidment et al., 2007). (b) Early Cambrian metasedimentary rocks of the Harts Range Group (samples of upper Irindina Gneiss and Brady Gneiss), 105 ages, from Maidment et al. (2013), (c) Early Cambrian Kanmantoo Group, 144 ages from Ireland et al. (1998). (d) ?Cambrian strata from the southern Thomson Orogen (Woodlands and Woodstock drill holes and Kinchela sample), 156 ages from Glen et al. (2013), (e) Cambrian metasedimentary rock from the Argentine Metamorphics, 57 ages from Fergusson et al. (2007a). (f) Cambrian metasedimentary rock from the Anakie Metamorphic Group, 57 ages from Fergusson et al. (2001). (g) Early to Middle Ordovician Girilambone Group (sample of 114 ages from Fergusson et al., 2005a). (h) Late Ordovician samples from the southeastern Lachlan Orogen (samples from the Bumballa Formation and upper Adaminaby Group), 119 ages from Fergusson and Fanning (2002). In this compilation age estimates for all individual grain analyses are <15% concordant; ^{206}Pb–^{208}Pb data is used for age estimates >1Ga.

Evidence for the age of these rocks is provided by exposed Thomson metasedimentary rocks in its northern extent (Fig. 4) from the structurally upper part of the succession in the Anakie Province and samples from the Argentine Metamorphics (Charters Towers Province) and the Oasis Metamorphics (Greenvale Province). In the southern Anakie Province, a lithic psammitic schist of the Wynyard Metamorphics from which samples of detrital zircon and monazite indicate derivation from a prominent source in the range 600–510 Ma (the Pacific–Gondwana signature, Fergusson et al., 2001). A sample of quartzite from the Argentine Metamorphics also has a similar zircon age spectrum with smaller peaks in the range 1300–1000 Ma typical of the “Grenville” source and in the range 1600–1500 Ma consistent with a source from the adjacent North Australian Craton in Queensland (Fergusson et al., 2007a). Many samples of quartz-rich siliciclastic turbidites from basement cores in the covered Thomson Orogen of southern and central Queensland (the Thomson beds) contain abundant detrital zircons with the distinctive Pacific–Gondwana age signature with a maximum depositional age of 495 Ma (Brown et al., 2014; Carr et al., 2014). Upper constraints on the age of these units are provided by metamorphism, unconformably overlying volcanic rocks and granites with ages of 500 to 460 Ma consistent with major deformation and metamorphism occurring in the Middle to Late Cambrian Delamerian Orogeny (Fig. 11; Withnall et al., 1996; Draper, 2006; Fergusson and Henderson, 2013).

The Pacific–Gondwana signature is widely developed in Paleozoic sandstones of eastern Australia (Fig. 13) including the Kanmantoo Group of the Delamerian Orogen in South Australia (Ireland et al. 1998), the Cambrian sedimentary succession of the Koonenberry Belt (Greenfield et al., 2010), the Bengal-fan sized Ordovician turbidite assemblage of the Lachlan Orogen in southeastern Australia (Fergusson and Fanning, 2002; Fergusson et al., 2013) and its extension into eastern Tasmania (Black et al., 2005) as well as Ordovician sandstones and their metasedimentary equivalents in central Australia (Maidment et al., 2013). Samples of quartzose sandstones of known and probable Late Cambrian to Ordovician age in the Thomson Orogen of northwestern New South Wales are also characterised by prominent detrital zircon ages within the 650–500 Ma interval (Glen et al., 2013). Its widespread development throughout the known Thomson Orogen increases the mystery of the source of these zircons. The most favoured location has been considered to lie in East Antarctica west of the Ross Orogen and presently overlain by the East Antarctic ice sheet (Veevers, 2000; Veevers and Saeed, 2008, 2011; Fergusson et al., 2013). Alternatively it has been proposed that these sediments were derived by very long distance transport across the entire East Antarctic continent from the Gondwana suture in the Mozambique belt (Squire et al., 2006; Maidment et al., 2007). A possible, more proximal, potential source is igneous activity associated with late Neoproterozoic intraplate rotation which reactivated an earlier Late Mesoproterozoic suture as discussed above and expressed as the Petermann Orogeny of central Australia.

The idea of a substantial marginal sea as the depositional setting for sedimentary rocks of the Thomson Orogen (Barcoo Marginal Sea, Fig. 12) has persisted following its first suggestion by Harrington (1974), reiterated by Murray (1986, 1994) and more recently by

Glen et al. (2013). The evidence for major intraplate shear within Australia (Li and Evans, 2011) implies substantial new crustal growth coeval with the shear dislocation in the Thomson Orogen prior to the Delamerian Orogeny in the Middle to Late Cambrian (Fig. 3). Accepting the plate architecture required by Late Neoproterozoic intracratonic rotation, only a small part of the Barcoo Marginal Sea could have formed with a rifted cratonic Precambrian crust derived from the neighbouring margin. Much of the basement must have developed in the paleo-Pacific ocean either by sea-floor spreading or by new crustal formation in immature island arcs including boninitic-tholeiitic associations followed by backarc rifting as inferred to have been widespread in the Cambrian of the Lachlan Orogen (Crawford et al., 2003; Glen, 2013). The age constraints for sedimentary rocks of the Barcoo Marginal Sea reviewed above imply deposition of its succession in the interval 550 to 490 Ma. The age of the lower part of the siliciclastic succession of the Thomson Orogen is unconstrained and it almost certainly extends into the Neoproterozoic as argued by Fergusson et al. (2009) for rocks of the Anakie Province and is likely for parts of the succession represented in the Charters Towers Province (Fergusson et al. 2007a), coeval with sedimentary successions in the Koonenberry Belt and southern Georgina Basin (Greene, 2010; Greenfield et al., 2011). This older part of the marginal sea succession appears to have been exhumed as higher grade metasedimentary rocks (upper greenschist and amphibolite facies) once deeply buried in the more eastern part of the Thomson Orogen and now exposed in the Anakie and Charters Towers provinces. In contrast to the Barcoo Marginal Sea where Late Cambrian ages apply to the upper part of the succession, major deposition ceased somewhat earlier in the Delamerian Orogen of South Australia where the Kanmantoo Group, with up to 8000 m of siliciclastic turbidites and local shallow marine sedimentary rocks, was deposited between 524–514 Ma (Haines and Flöttmann, 1998). Kanmantoo sedimentation is thought to have been in a foreland setting reflecting an extensional event (Haines and

Flöttmann, 1998) followed by shortening during Delamerian orogenesis at ~514–490 Ma (Foden et al., 2006).

Pre-Delamerian units of Early to Middle Cambrian age in the Koonenberry Belt include widespread quartzose turbidites of the Teltawongee Group and the much more restricted Mt Wright Volcanics (Greenfield et al., 2010). The volcanic rocks are interpreted as having formed in an arc environment associated with southwest-dipping subduction, but they have restricted surface exposures and are considered to have greater extent based on buried magnetic anomalies especially under the Devonian fill of the Bancannia Trough (Greenfield et al., 2011). The northeastern belt of Teltawongee Group turbidites is interpreted as a subduction complex (Greenfield et al., 2011). The convergent margin system was terminated by the Delamerian Orogeny, which is well constrained at 503–499 Ma by SHRIMP U–Pb ages obtained from volcanic rocks, as well as radiometric ages on metamorphism, and radiometric and paleontological ages of the overlying post-Delamerian successions containing abundant Late Cambrian faunas (Greenfield et al., 2011). Thus the Delamerian Orogeny in the Koonenberry Belt was initiated later than that in the Kanmantoo Group of South Australia which had commenced by at least ~514 Ma (Foden et al., 2006).

A similar younger initiation of the Delamerian Orogeny is apparent in the Thomson Orogen where the Delamerian Orogeny is less well constrained but began no earlier than the maximum depositional ages provide by detrital zircons in the Anakie Metamorphic Group and Argentine Metamorphics that record the youngest zircon ages at ~510 Ma and ~500 Ma respectively (Fergusson et al., 2001, 2007c) and even younger ages (495 Ma) from the basement cores to the southwest (Brown et al., 2014; Carr et al., 2014). Upper constraints are the K/Ar and ^{40}Ar/^{39}Ar 'plateau' ages from the southern Anakie Province that indicate metamorphic cooling at 500 Ma and 478 to 460 Ma respectively in rocks of greenschist to amphibolite grade (Withnall et al., 1996; Wood and Lister, 2013) and predating plutonic and volcanic rocks of ~485 to 460 Ma in the Charters Towers Province (Fergusson et al., 2007c; Fergusson and Henderson, 2013). The nature of the Delamerian Orogeny in the Thomson Orogen is poorly known because of the widespread cover. In the Anakie Province increasing pressure conditions during multiple deformation indicates substantial crustal thickening in association with the generation of an intense subhorizontal foliation (Offler et al., 2011). Crustal thickening in the southern Andes in association with Cretaceous compressional deformation, formation of the Darwin Metamorphic Complex and closure of the Rocas Verdes backarc basin has formed analogous low-angle foliation (Klepeis et al., 2010; Maloney et al., 2011). In the Charters Towers and Greenvale provinces inferred Delamerian structures are strongly overprinted by Early Ordovician extensional ductile fabrics and locally intense Benambran convergent structures (Fergusson et al. 2007b, c).

Metamorphic basement with grades similar to the Anakie Metamorphic Group has been found in boreholes located ~350 km SSW of the Anakie Province along the Nebine Ridge in southern Queensland (Fig. 4; Murray, 1986, 1994; Brown et al., 2012) but their age is poorly constrained. The low-grade quartzose siliciclastic rocks widely found in the basement cores of the central and southern Thomson Orogen west of the Anakie Province and Nebine Ridge are all typically steeply dipping with slaty cleavage and/or foliation (Murray, 1994; Brown et al., 2012) and in GSQ Maneroo these rocks are overlain by flat-lying Ordovician volcanic rocks with a U–Pb zircon SHRIMP age of 473 ± 3 Ma indicating Late Cambrian to Early Ordovician deformation (Draper, 2006). The decreasing metamorphic grade and intensity of deformation towards the southwest and west across the Thomson Orogen are consistent with effects of the orogeny dying out which is not evident in the Warburton Basin at its western extremity (Fig. 4). This supports closure of the Barcoo Marginal Sea by a major accretionary event, although whether this has involved development of subduction complexes along short-lived subduction zones as suggested for the Lachlan Orogen in the later Benambran Orogeny

(Gray and Foster, 2004; Fergusson, 2014) is unknown. The major northeast-trending gravity trends of the Thomson Orogen have been considered to reflect the regional structural grain (Murray, 1986) presumably developed in this Delamerian event.

Located in northeastern South Australia, the Middle Cambrian to Middle Ordovician Warburton Basin lies in a pivotal position between the Thomson Orogen and the Delamerian Orogen to the southeast (Koonenberry Belt, Figs. 12 and 14). It has been explored remotely using seismic reflection profiles and has numerous deep wells. The basin consists of basal mafic to silicic volcanic rocks dated at 510 and 517 Ma (Draper, 2006, 2013a; PIRSA, 2007) overlain by Late Cambrian to Middle Ordovician carbonate to siliciclastic sedimentary rocks deposited in deltaic, shallow to deep-marine environments with intercalated basaltic lava flows (Radke, 2009). The Warburton Basin lacks evidence for the Delamerian and Benambran orogenies as found in the Thomson Orogen to the east and northeast and also well documented in the Koonenberry Belt to the southeast in northwestern New South Wales (Greenfield et al., 2010, 2011). Delamerian deformation is also expressed as shear zones in the Proterozoic Curnamona Province to the west of the Koonenberry Belt (Dutch et al., 2005). Thus a deformation front must exist somewhere between the Warburton Basin and the Thomson Orogen but is very poorly defined because of the thick cover. The Warburton Basin remained undeformed while neighbouring regions were strongly overprinted by these deformational episodes implying that it developed on cold cratonic basement of unknown age, but could include an eastern continuation of the Musgrave Province (Figs. 3, 5 and 6).

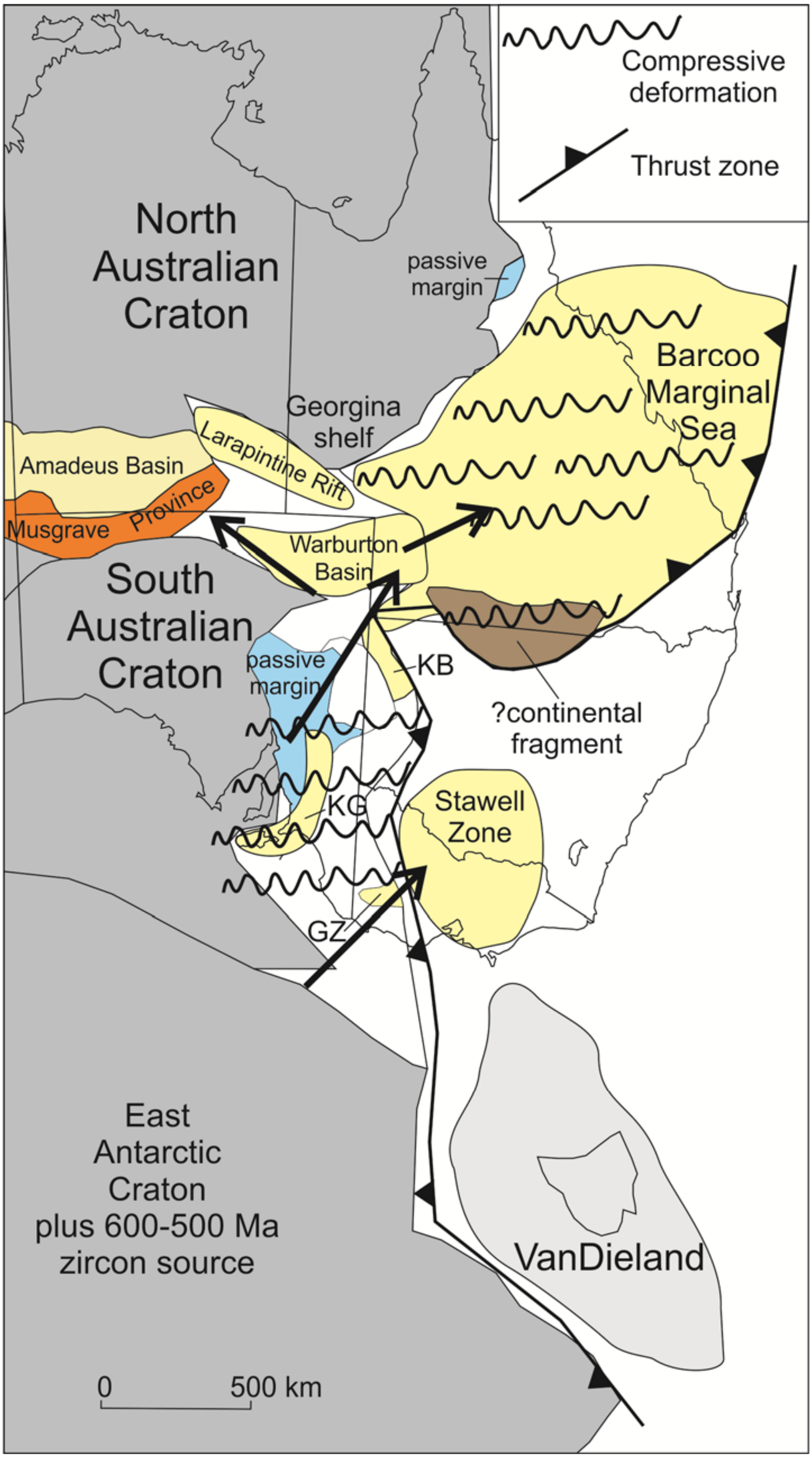


Fig. 14. Reconstruction of the Australian and part of the East Antarctic sectors of the East Gondwana margin for the interval 505–490 Ma showing deformation in the Barcoo Marginal

Sea (North Delamerides). The hypothetical transform fault and position of VanDieland are after Cayley (2011). Arrows show directions of inferred sediment transport. Abbreviations: GZ—Glenelg Zone, KB—Koonenberry Belt, KG—Kanmantoo Group.

In summary, the development of the Barcoo Marginal Sea and its subsequent closure in the Delamerian Orogeny (Figs. 12 and 14) indicates a major phase of rapid continental growth, similar to, but in an earlier cycle than the Lachlan Orogen (Glen et al., 2009; Fergusson, 2014). The intracratonic rotation within Australia along the extended shear zone south of the Musgrave Province (Li and Evans, 2011) implies that the basement of the Barcoo Marginal Sea is largely of 650 to 550 Ma age. However fragments of Precambrian continental crust derived from the East Gondwana margin, broken off in Neoproterozoic rifting events may be present within the Thomson Orogen similar to features such as the Selwyn Block of the Lachlan Orogen (Cayley, 2011; Moore et al., 2013). Rapid closure of the Barcoo Marginal Sea in the interval 510 to 480 Ma was presumably enabled by convergent margin processes that remain poorly understood due to the paucity of exposure. A second episode of shortening occurred in the Benambran Orogeny at ~440–430 Ma. Given that metamorphic overprint is typical of the sedimentary pile developed in the Barcoo Marginal Sea, with upper greenschist to amphibolite facies developed in its more eastern parts, its scale and content is comparable to that of the marginal sea forerunner of the Lachlan Orogen. Based on that comparison and the degree of shortening assigned to the Lachlan Orogen (Gray and Foster, 2004) the Barcoo Marginal Sea was considerably larger than the Thomson Orogen which succeeded it. It was the repository of a Neoproterozoic–Cambrian sedimentary apron of vast size and volume.

3c. Ordovician extension

In the Early to Middle Ordovician, widespread igneous activity affected the northern and central parts of the Thomson Orogen, post-dating newly developed continental crust consolidated and thickened in the Late Cambrian Delamerian Orogeny. The igneous activity is considered to be related to backarc extension concurrent with subduction to the east (Fig. 15; Henderson, 1986; Fergusson and Henderson, 2013). Outboard assemblages of the subduction system are unknown and are either in the subsurface or have been lost during subduction-related tectonic erosion.

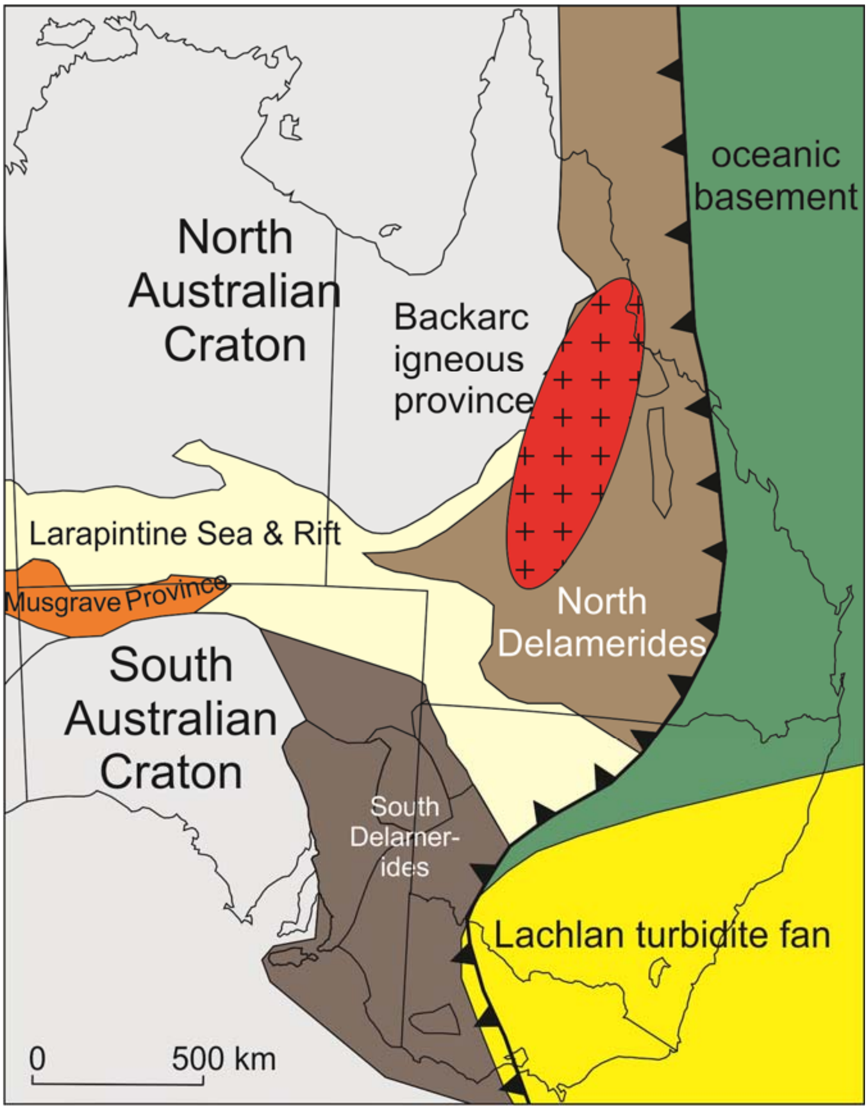


Fig. 15. Reconstruction of the Australian sector of the East Gondwana margin for the interval 485–460 Ma with development of a major backarc igneous province in the Thomson Orogen associated with an inferred subduction to the east concurrent with widespread quartzose turbidite deposition in the Lachlan Orogen to the south (Fergusson, 2009) and shallow marine sedimentation through the Larapintine Sea and rift (Maidment et al., 2013).

In the Charters Towers Province, a large-scale rift, which initiated in the Late Cambrian, has an infill thickness exceeding 14 km of volcanic and sedimentary rocks of the Seventy Mile Range Group (Henderson, 1986; Stolz, 1995). It contains Early Ordovician graptolites and pelagic trilobites in its upper parts (Henderson, 1983). The oldest fossil assemblage is basal Ordovician (Lancefieldian) and is supported by a U–Pb age of 479 ± 5 Ma on volcanic rocks (Perkins, 1995), also from the upper part of the succession. Siliciclastic rocks comprising the lower part of the succession have no age control but must extend into the Late Cambrian. The base of the Seventy Mile Range Group is stoped out by younger granitoids of the Ravenswood Batholith and directly underlying basement to it is unknown. Reworking of deeper metamorphic units during the deposition of the Seventy Mile Range Group is indicated by coeval plutonic rocks of the Ravenswood Batholith with ages ranging between 510 and 460 Ma (Fergusson and Henderson, 2013) emplaced within nearby metamorphic basement, such as in the Charters Towers, Cape River and Argentine metamorphics. These plutonic rocks are typically strongly deformed consistent with syntectonic emplacement but lack kinematic indicators. They have been interpreted as being emplaced during extension which resulted in the basinal repository of the Seventy Mile Range Group (Fergusson et al., 2007b, c; Fergusson and Henderson, 2013).

In the Greenvale Province, the Balcooma Metavolcanic Group formed at 480 to 470 Ma (Fergusson and Henderson, 2013) somewhat later than the volcanism in the Seventy Mile Range Group of the Charters Towers Province. In the western part of the Greenvale Province adjacent to the Lynd Mylonite Zone (Fig. 4), samples of the Oasis Metamorphics and Lynwater Complex have ages indicating peak metamorphism and igneous activity in the

Early Ordovician at 485 to 475 Ma with detrital zircons showing partial sediment derivation from Late Mesoproterozoic rocks (Fergusson et al., 2007b). Upper constraints on depositional ages provided by detrital zircon, zircon metamorphic rims, granitic intrusions and K/Ar and ^{40}Ar/^{39}Ar cooling ages for metasedimentary rocks in the Charters Towers and Greenvale provinces (Fergusson et al., 2007a, b, c; Fergusson and Henderson, 2013) are consistent with their deposition continuing until 510 to 490 Ma immediately preceding and synchronous with the Delamerian Orogeny. These rocks are considered to represent basement to extensional basins with volcanic infill developed in the latest Cambrian and Early Ordovician.

Early Ordovician (473–463 Ma) tectonised granite is known from the eastern Anakie Province (Richards et al., 2013). Four basement cores from some 300 km west of the inlier, beneath the northern parts of the Late Paleozoic Adavale and Drummond basins, contain Early Ordovician granite and volcanic rocks with U–Pb zircon ages of 484 to 469 Ma (Draper, 2006). The latter were previously considered part of the volcanic succession in the Devonian Drummond and Adavale basin successions (Murray, 1986, 1994).

In the southern Anakie Province (Fig. 4), the Upper Ordovician Fork Lagoons beds consist of a varied unit of slate, quartz-rich turbidites, shallow marine limestone, mafic volcanic rocks, rare serpentinite and silicic volcaniclastic rocks (Fergusson and Henderson, 2013). The unit is relatively poorly exposed but the shallow marine limestone, which contains Late Ordovician fossils, is thought to form allochthonous blocks surrounded by deep-marine siliciclastics (Fergusson and Henderson, 2013). A sample from a quartzite unit has most dated zircon grains in the range 540–410 Ma (39 grains) with a less prominent peak at 1125–930 Ma (7 grains, Fergusson et al., 2007a). This is consistent with prominent Late Cambrian to Ordovician igneous sources which are developed in the northern Thomson Orogen (Fergusson and Henderson, 2013). A sample of quartz-lithic sandstone has the youngest cluster at 467–457 Ma (4 grains), consistent with the Late Ordovician biostratigraphic age from limestone blocks, with two main groups at 505–435 Ma and 630–540 Ma (12 grains each). The latter represents a Pacific–Gondwana provenance which is characteristic of the Thomson Orogen and is likely to reflect recycling. Both samples are consistent with derivation of igneous zircon from granitic rocks of 500 to 440 Ma which are characteristic of the northern Thomson Orogen (Fergusson et al., 2007a).

3d. Late Ordovician – Early Silurian Benambran Orogeny and subsequent deformation

Following extensional tectonics in the Early to Middle Ordovician with igneous activity and sedimentation in different parts of the northern and central Thomson Orogen, an interval of convergent deformation followed in the Late Ordovician – Early Silurian that is related to more widely documented events of a similar age in the Lachlan Orogen known as the Benambran Orogeny (Gray and Foster, 1997; Fergusson, 2014; Glen, 2005, 2013). Southeast of the Greenvale Province in the Graveyard Creek Subprovince of the Mossman Orogen (Fig. 4), the Benambran Orogeny is reflected by accretion of a Late Ordovician island arc to the continental margin marked by the Ordovician quartz-rich turbidites of the Judea Formation (Henderson et al., 2011). Further inboard, in the Greenvale Province, the Benambran Orogeny was associated with inversion of a pre-existing rift resulting in deep burial, significant shortening and uplift with exhumation of amphibolite facies metamorphic rocks of the Balcooma Metavolcanic Group and related units with metamorphism dated at ~443–425 Ma (Ali, 2010) and overlapping intrusion of major plutonic units such as the Dido Tonalite at ~430 Ma (Hutton et al., 1997).

Further south in the southern Anakie Province, the Benambran Orogeny is associated with strong shortening in the Fork Lagoons beds (Withnall et al., 1995; Fergusson and Henderson,

2013) and consistent with the 443 ± 6 Ma monazite age determined for the Gem Park Granite that occurs in the eastern part of the Anakie Metamorphic Group adjacent to the Fork Lagoons beds (Wood and Lister, 2013). To the west, Benambran deformation in the region north of the sub-surface Adavale Basin appears absent as indicated by the relatively undeformed Ordovician volcanic rocks found in basement cores. Following intrusion of plutons related to the Benambran Orogeny, such as the Dido Tonalite and Gem Park Granite in the Greenvale Province and Anakie Province respectively, no evidence has been found for any Silurian igneous activity or sedimentation in the Thomson Orogen. This contrasts with the Lachlan Orogen where there was widespread Middle to Late Silurian sedimentation and igneous activity (Glen, 2005; Fergusson, 2010). The Mossman Orogen in north Queensland also has a substantial Silurian succession deposited in the Broken River Province following the Benambran Orogeny in a forearc setting (Henderson et al., 2011, 2013).

Unlike the Lachlan Orogen where a long history of broad-scale contractional and extensional tectonism post-dated Benambran orogenesis, such contractional episodes influenced only the eastern and southern margins of the Thomson Orogen. Deposition of the Devonian Adavale Basin extensively developed over the central part of the Thomson Orogen (Fig. 4), commenced in the Pragian prior to the Middle Devonian Tabberabberan Orogeny and is weakly deformed (McKillop, 2013). Similarly the small Belyando Basin developed above the northeastern part of the orogen, known only from seismic records and inferred to be of a similar history to the Adavale Basin, is largely undisturbed (Draper, 2013b). Most of the Late Devonian – Mississippian Drummond Basin, extensively developed over the northeastern part of the Thomson Orogen, is weakly deformed (Henderson and Blake, 2013). Its eastern margin shows open folding due in part to mid Carboniferous Kanimblan deformation and in part to Permian–Triassic Hunter–Bowen Orogeny which terminated development of the Late Paleozoic New England Orogen to the east (Fig. 2). The subsurface

Timbury Hills Basin developed near the southeastern margin of the Thomson Orogen (Fig. 4) contains deformed Devonian strata (Fergusson and Henderson, 2013). The Early Devonian – Mississippian Burdekin Basin developed within the Charters Towers Province at the northeastern margin of the orogen shows open folding and thrust faulting attributed to Kanimblan shortening (Henderson, 2013). Middle Devonian outliers of Conjuboy Formation within the Greenvale Province, at the northeastern extremity of the Thomson Orogen, are little disturbed by tectonism (Henderson, 2013).

4. Discussion

Several issues concerning development of the Thomson Orogen and its wider setting remain in question and need additional consideration, namely:

(1) the sediment source and transport of the voluminous quartzose detritus that makes up much the Thomson Orogen,

(2) the assessment of Thomson Orogen crustal architecture from deep seismic data,

(3) contractional reorganisation and thickening of Thomson Orogen crust in relation to development of the Tasmanides more generally,

(4) the nature of the northwestern margin of the Thomson Orogen, and

(5) relations between the Australian Precambrian cratons and the Tasmanides and their connection to Rodinia.

4a. Sediment sources and pathways

Detrital zircon ages have shown that the metasedimentary succession of the Thomson Orogen has a characteristic Pacific–Gondwana signature with abundant zircons in the range

650–500 Ma in its younger part and a prominent Grenville (1.3–1.0 Ga) component in its older part (Fergusson et al., 2001, 2007a; Brown et al., 2014). These signatures are widespread in Cambrian and Ordovician sedimentary rocks in eastern and central Australia. They have been found in the Amadeus and Georgina basins and their metasedimentary equivalents in the adjacent Harts Range representing exhumed and tectonised deep basinal assemblages (Maidment et al. 2007, 2013) as well as successions of the Delamerian and Lachlan orogens (Ireland et al., 1997; Fergusson et al., 2013) and Early Paleozoic strata of Tasmania (Black et al., 2004). Sediment produced during Pacific–Gondwana and Grenville times was a significant contributor to continental growth within the Tasmanides, and to central Australian cratonic basins. Its origin reflects episodes of extensive mountain building accompanied by the generation of igneous rocks and the delivery of erosion products across eastern and central Australia.

The Pacific–Gondwana signature is also prominent in younger units in southeastern Australia such as the Triassic Hawkesbury Sandstone and in modern beach sands reworked from Paleozoic successions (Sircombe, 1999; Veevers, 2000; Veevers et al., 2006). It has been considered sourced from East Antarctica from rocks now buried under the ice sheet (Veevers and Saeed, 2008, 2011). Extensive Pan African belts are considered to underlie ice-covered East Antarctica, based on rock systems exposed at the continental periphery, and is consistent with a Pacific–Gondwana population in zircon eroded from the Antarctic interior and deposited at the continental margins (Harley et al., 2013). Alternatively a much more distant source has been suggested involving the collision belt of East and West Gondwana along the East African Orogen (Squire et al., 2006; Maidment et al., 2013). The fact that this detrital signature is widely developed in Gondwana including northern Africa, the Middle East and the north Indian Tethyan margin (Cawood et al., 2007; Meinhold et al., 2013), and that both 1.3–1.0 Ga and 600–500 Ma orogenic belts are widely developed across Gondwana, is consistent with several, including more regional, sources rather than just the one source. Although the preserved Neoproterozoic rock systems of eastern and central Australia contain scant evidence of igneous assemblages, major crustal dislocation in northern Australia (Fig. 3), as suggested by Li and Evans (2011) and expressed as the Petermann Orogeny, could well have generated igneous rocks now lost through erosion.

Given that any potential for Neoproterozoic igneous input is limited to northern Australia, and that Pacific–Gondwana detrital zircon signatures in Paleozoic sedimentary rocks extend to the southern margin of Australia and Tasmania, a major northerly-directed sediment distributary system must have existed along the ancient East Gondwana margin. Its likely source was East Antarctica and this distributary system made a substantial contribution to Late Neoproterozoic – Cambrian sediment represented in the Delamerian and Thomson orogens (Fig. 12) with supply continuing to feed sediment to the Lachlan Orogen in the Ordovician. Long distance riverine transport is required but coastal processes, involving longshore drift, may have also played a part. A modern analogue of transport along a coastline of comparable scale is provided by modern longshore drift along the eastern Australian coastline which results in large-scale transport of sand over some 1500 km from the Sydney Basin in New South Wales to Fraser Island in Queensland and it subsequent passage by gravity-driven processes to form deep-water sediment bodies in the Tasman Sea (Boyd et al., 2008).

The Grenville detrital age signature has a more tangible source. The Grenville Orogeny is regarded as perhaps the most significant event of crustal reorganisation in Earth history (Van Kranendonk and Kirkland, 2013) with global effects which embraced the Albany–Fraser–Musgrave belt which extends obliquely across Australia (Smits et al., 2014). The age diversity apparent for Australian Precambrian terrains lying to the west of the Tasmanides coupled with the tight, unimodal Grenville age distributions shown by zircon age spectra from some Thomson Orogen samples (Fig. 9), strongly supports the contention of a local source involving an eastern extension of the Musgrave Province into the Thomson Orogen.

4b. Crustal interpretation from deep seismic profiling

A long deep reflection seismic profile was obtained across southern Queensland and extends from west of the Warrabin Trough to Brisbane, it traverses approximately 500 km across the subsurface part of the Thomson Orogen (Finlayson, 1990). The Foyleview Structure, a prominent, gently west-dipping mid crustal feature imaged beneath the Nebine Ridge, was interpreted by Finlayson et al. (1990) as separating the Thomson Orogen from crust tectonised in the Late Paleozoic. The profile shows the nearly flat-lying Late Paleozoic and Mesozoic sedimentary basins overlying the Thomson Orogen including the Eromanga Basin and the underlying Warrabin Trough and Adavale Basin but the upper part of the Thomson Orogen itself is largely unreflective. In contrast the lower crust has many reflectors and this distinguishes it from the unreflective upper mantle and thereby highlights the Moho which increases in depth from 36 km under the western Eromanga Basin to a depth of 44 km under the Nebine Ridge in the eastern Thomson Orogen (Finlayson et al., 1990). The seismic profile may be compared with another profile across the Lachlan Orogen in central Victoria where the reflective lower crust is locally traced to the surface at the Heathcote Greenstone Belt in the hanging wall of the Mt William thrust thereby implying that the lower crust is made of mafic igneous rocks (Cayley et al., 2011). However, deep seismic profiles from north Queensland, including across the Charters Towers Province, show that much of the lower crust in the Tasmanides and in the North Australian Craton is largely reflective whereas the upper crust is largely transparent (Korsch et al., 2012). Assisted by gravity modelling matched to observed gravity data, these authors interpreted reflective lower crust as continental.

Based on deep seismic profiling reported by Finlayson et al. (1990), Glen et al. (2013) suggested that the lower crust of the southern Thomson Orogen may be in part oceanic. These authors also interpreted gravity data to suggest that a substantial tract of rifted continental crust may also be represented in the lower crust of the southern Thomson Orogen. However, similarly reflective lower crust elsewhere in eastern Australia has been interpreted differently (Finlayson, 1990; Korsch et al., 2012) and the interpretation of gravity data with respect to the nature and origin of the lower crustal rocks remains speculative. Thus these suggestions await validation.

4c. Contractional restructuring of the Tasmanide crust

The Delamerian Orogeny in the Thomson Orogen developed in the Late Cambrian to earliest Ordovician and therefore was initiated later than for the Delamerian Orogen in South Australia and the Koonenberry Belt in northwestern New South Wales (Figs. 7 and 12). In South Australia, most authors favour widespread shortening in the interval 520 to 490 Ma (Haines and Flöttmann, 1998; Preiss, 2000), whereas in the Koonenberry Belt Delamerian shortening is constrained more tightly to a 5 to 10 Ma interval around 500 Ma (Greenfield et al., 2011). In the Thomson Orogen, Delamerian contraction is most tightly constrained in the Charters Towers Province where depositional ages of 500 Ma in the basement metamorphic rocks are intruded by granites with U–Pb zircon ages of 510 to 480 Ma straddling the orogenic episode, with the Seventy Mile Range Group postdating the shortening and having a thick unfossiliferous succession underlying an earliest Ordovician volcanic and sedimentary succession (Fig. 7; Henderson, 1986). This is consistent with deformation at 500 to 490 Ma and implies rapid structural thickening and continental crust development in the Late Cambrian.

Rapid crustal restructuring in the overall development of the Tasmanides characterises both the Delamerian Orogeny in the Thomson Orogen as well as the Late Ordovician to Early Silurian Benambran Orogeny in the Lachlan Orogen that was associated with accretion of widespread Ordovician quartz turbidites and the Macquarie Arc (Glen et al., 2009; Fergusson, 2009, 2014). Given the lack of exposure over much of the Thomson Orogen the process of contractional reorganisation remains largely unknown. Structures in metamorphic rocks in the Anakie and Charters Towers provinces are dominated by early flat-lying structures with recumbent folds and strong schistosity and have been interpreted as related to both convergent and extensional strain regimes (Fergusson et al., 2005a; Offler et al., 2011). Metamorphic data from the southern Anakie Province shows structural thickening accompanying the first two deformations (Offler et al., 2011) and is consistent with convergent deformation perhaps in an evolving active continental margin as was associated with development of the Darwin Metamorphic Complex in the Cretaceous southern Andes (Maloney et al., 2011).

4d. Northwestern margin of the Thomson Orogen

Truncation of gravity and magnetic trends along the Diamantina Structure (Figs. 4, 5 and 6) at, or adjacent to, the northwestern margin of the Thomson Orogen is a striking linear discontinuity in the geophysical fabric of the Australian continent. Following Li and Evans (2011) we see it as part of a megashear which translocated the South Australian Craton relative to the North and West Australian cratons at 650–550 Ma and responsible for the ~570–530 Ma Petermann Orogeny which affected basement rocks of the northern Musgrave

Province and Neoproterozoic sedimentary rocks of the adjacent Amadeus Basin (Sandiford et al., 2001). We infer from detrital zircon data, which show that some samples from the northern Thomson Orogen have a striking Grenville-aged source, that the megashear adjacent to and extending along the Diamantina Structure reactivated a pre-existing Grenville-age suture as expressed by the Musgrave Province further to the west. It is conceivable that a tract of upland containing late Mesoproterozoic igneous rocks developed in the Neoproterozoic at the northeastern margin of the Thomson Orogen, potentially restructured by rifting as the megashear offset continued and progressively onlapped by the sediment apron developed in the Barcoo Marginal Sea. Presently, the geophysical database for central and eastern Australia is unable to constrain how the Musgrave Province may have continued eastwards into the Thomson Orogen and resolution of this problem awaits collection of more detailed information.

The Diamantina Structure broadly aligns with the Clarke River Fault (Fig. 4), a crustal-scale structure which terminated the Mossman Orogen by sinistral offset in the Devonian Tabberabberan Orogeny (Henderson et al., 2013). We suggest that the Grenvillian Musgrave suture and its hypothetical eastward continuation into Queensland was reused as a zone of crustal weakness in the Neoproterozoic by the intracratonic megashear proposed by Li and Evans (2011) and reactivated in mid Paleozoic Tabberabberan contraction which tectonised the Mossman Orogen (Fig. 16). The present physiography of the north Queensland continental margin may also carry the signature of this long-lived zone of crustal weakness. The Queensland Trough and basin, a large scale rift complex which separates the Queensland and Marion Plateau and thought to have formed in the late Mesozoic through oblique extension (Jell, 2013) broadly aligns with the Clarke River Fault Zone.

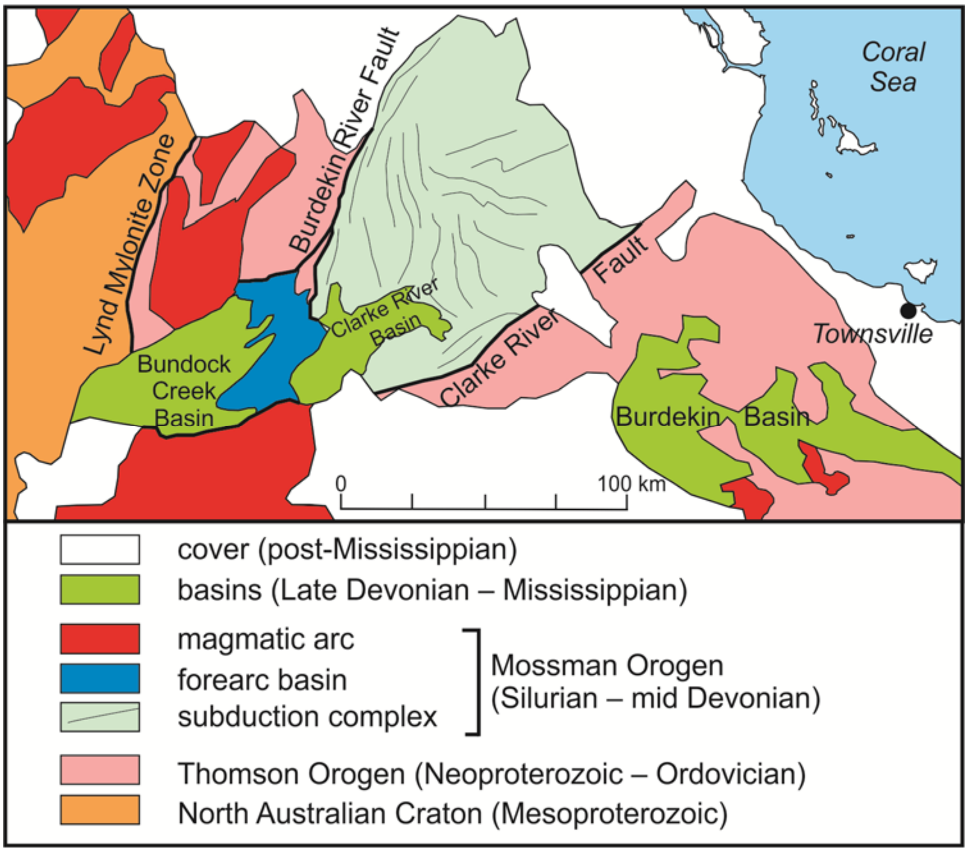


Fig. 16. Pre-Pennsylvannian geology of the region west of Townsville showing termination of the Siluro-Devonian Mossman Orogen at the Clarke River Fault against rocks of the Thomson Orogen, represented by the Charters Towers Province. The sedimentary succession of the Burdekin Basin closely matches that of the Bundock Creek Basin, consistent with these elements once having been closely adjacent and now offset by sinistral movement on the Clarke River Fault. The ages of folded strata in the Bundock Basin truncated by the fault, together with those of Clarke River Basin overlapping the fault, constrain strike slip movement on it to the Late Devonian (Frasnian). Structural trends are shown in the subduction complex of the Mossman Orogen (generalized from Fig. 3 in Arnold and Fawckner, 1980).

4e. Implications for NAC–WAC–SAC connections and Rodinia

An earlier interpretation presented by Myers et al. (1996) showed that Australia formed by assembly along a late Mesoproterozoic suture stretching from the Albany–Fraser Province in southern Western Australia to the Musgrave Province of central Australia. Thus the North Australian Craton with its core of Palaeoproterozoic rocks and the West Australian Craton containing the assembled Archean Yilgarn and Pilbara cratons were joined to the South

Australian Craton, which at that time was part of the Mawson Craton with a core of Archean and Paleoproterozoic rocks, at 1.3 to 1.1 Ga prior to merging with other fragments to form Rodinia (Li et al., 2008). This suggestion was subsequently overlooked with emphasis placed on Paleoproterozoic connections between the North and South Australian cratons (Betts and Giles, 2006; Cawood and Korsch, 2008). However new isotopic data supports the interpretation of the Musgrave–Albany–Fraser belt as a collisional suture formed in the final assembly of the Australian continent in Grenville time (Smits et al., 2014). This interpretation is also supported by a contemporary review of the Musgrave Province (Howard et al., 2015) which describes a complex orogenic history, with major episodes of igneous activity between 1345 and 1150 Ma followed by rift-related bimodal magmatism at ~1090–1040 Ma.

The Mt Isa Province in northwestern Queensland has been linked to the Curnamona Province in western New South Wales and northeastern South Australia (Laing, 1996). Various arguments have been made that these regions were juxtaposed (Giles et al., 2004; Foster and Austin, 2008; Gibson et al., 2012) or developed with similar styles as widely separated parts of the same rift system (Gibson et al., 2008). If they developed as adjacent regions of the same continental fragment, then rifting with a Bay of Biscay style opening (García-Mondéjar, 1996) must have accompanied clockwise rotation of the South Australian Craton away from the Mt Isa Orogen of the North Australian Craton (Giles et al., 2004; Aitken and Betts, 2009). In this model development of the Albany–Fraser and Musgrave provinces reflects clockwise rotation of the South Australian Craton and collision with the combined North and West Australian cratons.

The 40° intraplate rotation of the North Australian Craton relative to the combined West and South Australian cratons at 650 to 550 Ma (Li and Evans, 2011) has not been considered in relation to these proposals. We favour development of the intraplate megashear along the former suture between the North Australian Craton and a combined West and South

Australian cratons (Myers et al., 1996). Under this scenario, the Curnamona Province would align with the Georgetown Inlier at the eastern margin of the North Australian Craton in northeastern Queensland which records a geological history strikingly similar to that of the Mount Isa Province (Cawood and Korsch, 2008). Crustal reactivation and uplift due to the megashear offers an explanation for the Grenville-age detrital zircon signature widely developed in central Australia and along the western margin of the Tasmanides including the Thomson Orogen (Figs. 9 and 10). A proposed eastward extension of the central Australian Musgrave Province is consistent with the AUSMEX reconstruction of Rodinia with a link to the Grenville Orogen of eastern Laurentia (Wingate et al., 2002; Pisarevsky et al., 2003; Smits et al., 2014) but not considered in other syntheses of the Rodinia reconstruction (Li et al., 2008).

The summary of detrital zircon age data we present for the Tasmanides contrasts with similar data from the North China Block. The Tasmanides lack an early Neoproterozoic population (~970 Ma) which is prominent for South China (Li et al., 2014). As a consequence the South China Block is unlikely to have been positioned adjacent to eastern Australia as advocated by Li et al. (2008).

5. Conclusions

The Thomson Orogen of northeastern Australia dominates the northern part of the Tasmanides and has formed mainly by shortening of siliciclastic turbidite successions in the Middle to Late Cambrian Delamerian Orogeny, which along with the Ross Orogeny of East Antarctica, represents an episode of rapid continental growth along the East Gondwana Pacific-facing margin. Within the Thomson Orogen, metasedimentary siliciclastic rocks and associated mafic metaigneous rocks are represented in two main successions. An older succession is found in the lower part of the metamorphic complex in the Anakie Province and parts of the Charters Towers Province in the northern part of the Thomson Orogen and detrital zircon ages indicate derivation from a Grenville-aged orogenic belt which we interpret as a probable eastern extension of the Musgrave Province of the southern North Australian Craton in central Australia. The younger succession contains the Pacific-Gondwana detrital zircon age signature (650–500 Ma) and has been recently widely documented in basement cores throughout the Queensland portion of the Thomson Orogen and in northwestern New South Wales (Glen et al., 2013; Brown et al., 2014). In Queensland, the younger succession has a maximum depositional age of 510 to 495 Ma and shows intense tectonism in the northeast that dies out to the southwest into the Warburton Basin in northeastern South Australia where the succession lacks evidence for the Delamerian deformation in contrast to the Delamerian Orogen further south. Postdating these two metamorphic basement successions in the Late Cambrian to Ordovician was widespread igneous activity and the development of a substantial rift succession in the Charters Towers Province with over 14 km of sedimentary and volcanic rocks (Seventy Mile Range Group). This assemblage is related to a backarc extensional setting that accompanied development of a Late Cambrian to Late Ordovician active margin that is no longer preserved. Following a hiatus in the Silurian, Devonian to Carboniferous volcanic and sedimentary successions formed in backarc setting of the East Gondwana active margin.

Development of the Thomson Orogen is intimately connected with Neoproterozoic to Cambrian events that affected the North, West and South Australian cratons. Three pairs of paleomagnetic poles indicate an intraplate 40° rotation shearing event along the southern boundary of the North Australian Craton in the interval 650 to 550 Ma (Li and Evans, 2011). The implication of this event is that much of the Thomson Orogen must have developed as new crust (Fig. 3) with minimal reworking of pre-1000 Ma crust that makes up the Australian lithosphere west of the Tasmanides. We argue that the prevalence of the Grenville-age detrital zircon signature in the older succession of the Thomson Orogen indicates a possible eastward extension to the Musgrave Province into eastern Australia and that this has formed an anisotropy that controlled younger intraplate rotation. Thus we consider that the original suggestion of Myers et al. (1996) that the Australian cratons formed by suturing in the Mesoproterozoic still merits attention in spite of numerous attempts to link the Curnamona and Mt Isa provinces. Note that this does not necessarily imply that no link exists between these fragments, but merely that connections based on either present-day geography or only slightly modified present-day geography are over simplified. The line of intraplate rotation controlled the northwestern margin of the Thomson Orogen with Proterozoic crust of the Mt Isa Block along the Diamantina Structure, continuation of which appears to have influenced Paleozoic and late Mesozoic structuring of the northeast Australian continental margin.

Mismatch in detrital zircon signatures between eastern Australia and the South China Block argues against the Rodinia assembly advocated by Li et al. (2008) in regard to the location of the South China Block. The potential presence of a Mesoproterozoic orogenic belt in northeast Gondwana has previously been hypothesised as the AUSMEX reconstruction for Rodinia with northeastern Australia connected to the Grenville orogenic belt along the southeastern margin of Laurentia (Wingate et al., 2002; Williams et al., 2012; Schmidt, 2014) and has only been strengthened by our increased understanding of the Thomson Orogen. However, as noted by Harley et al. (2013), Rodinia assembly needs ongoing re-evaluation as more data comes to hand and remains a work in progress.

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