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Mesoproterozoic plume-modified orogenesis in eastern Precambrian Australia

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[1] Tectonic models for the latest Paleoproterozoic to earliest Mesoproterozoic evolution of eastern Australia (circa 1620–1500 Ma) are diverse and either emphasize plume or plate margin activity, neither of which satisfactorily explains all geological observations. The dichotomy is largely attributed to geochemical, spatial and temporal data that suggest voluminous A-type felsic magmas are plume related, whereas distribution of arc-related magmas and intense orogenic overprint suggest plate margin activity. The salient geological events include arc-related magmatism at circa 1620–1610 Ma followed by a magmatic hiatus coincident with north-south crustal shortening (1610–1590 Ma) and a magmatic flare-up of A-type felsic magmas throughout the Gawler Craton (circa 1595–1575 Ma). These magmas form the oldest component of a northward younging hot spot track that extends to the Mount Isa Inlier. At circa 1590–1550 Ma, arc magmatism resumed along the northern margin of the Gawler Craton and the rest of eastern Australia records a 90° shift in the regional shortening direction related to activity along the eastern margin of the Australian continent. A plume-modified orogenic setting satisfies all of the spatial and temporal relationships between magma generation and orogenic activity. In this model, the Gawler Craton and the adjacent subduction zone migrated over a mantle plume (circa 1620–1610 Ma). Resultant flat subduction caused transient orogenesis (1610–1595 Ma) in the overriding plate. Slab delamination and thermal assimilation of the plume and the subducting slab caused a switch to crustal extension in the overriding plate, resulting in extensive mantle-derived and crustal melting in the Gawler Craton (1595–1575 Ma).

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1. Introduction

[2] Compared with modern tectonic systems, the geological record of Precambrian tectonic systems is often sparsely preserved, temporal constraints are often fuzzy or lacking, and there is greater potential for reworking during younger tectonic activity. Consequently, tectonic interpretations for Precambrian events are often ambiguous and subject to high degrees of uncertainty. The latest Paleoproterozoic to early Mesoproterozoic (1620–1500 Ma) evolution of eastern and central Australia (Figure 1) is characterized by continental-scale tectonic events that affected almost a third of the continent and lasted approximately 100 Ma. Tectonism associated with these events is variably expressed but includes the development of large felsic igneous provinces [*Betts et al.*, 2007; *Creaser*, 1995, 1996; *Creaser and White*, 1991; *Fanning et al.*, 2007; *Mark*, 2001; K. Stewart and J. Foden, Primary Industry and Resources South Australia, University of Adelaide, The Mesoproterozoic granites of South Australia, unpublished report, 2001], widespread high-temperature metamorphism [*Daly et al.*, 1998; *Forbes et al.*, 2008; *Giles et al.*, 2006b; *Hand et al.*, 2007; *Loosveld*, 1989; *McLaren et al.*, 2005; *Rubatto et al.*, 2001; *Rubenach*, 1992; *Rubenach and Barker*, 1998; *Rubenach et al.*, 2008; *Stüwe and Ehlers*, 1997; *Teasdale*, 1997; *Vry et al.*, 1996] and polycyclic orogenesis over large areas of the continent [*Betts et al.*, 2006; *Blenkinsop et al.*, 2008; *Clarke et al.*, 1986; *Collins and Shaw*, 1995; *Daly et al.*, 1998; *Forbes and Betts*, 2004; *Forbes et al.*, 2004; *Giles et al.*, 2006a; *Hand et al.*, 2007; *O'Dea et al.*, 1997b; *Withnall et al.*, 1988]. The extent and duration of this episode of tectonism places it as the single largest Mesoproterozoic event to impact the evolution of the Australian continent and is one of the largest thermal recorded in the entire geological evolution of the Australian continent [*Betts et al.*, 2002]. From a global perspective, this episode is not recorded elsewhere on the planet, despite many reconstruction models placing eastern Australia proximal to Antarctica and Laurentia at this time [*Betts et al.*, 2008; *Burrett and Berry*, 2000; *Karlstrom et al.*, 2001]. In this context, the late Paleoproterozoic evolution of Australia, Laurentia, and

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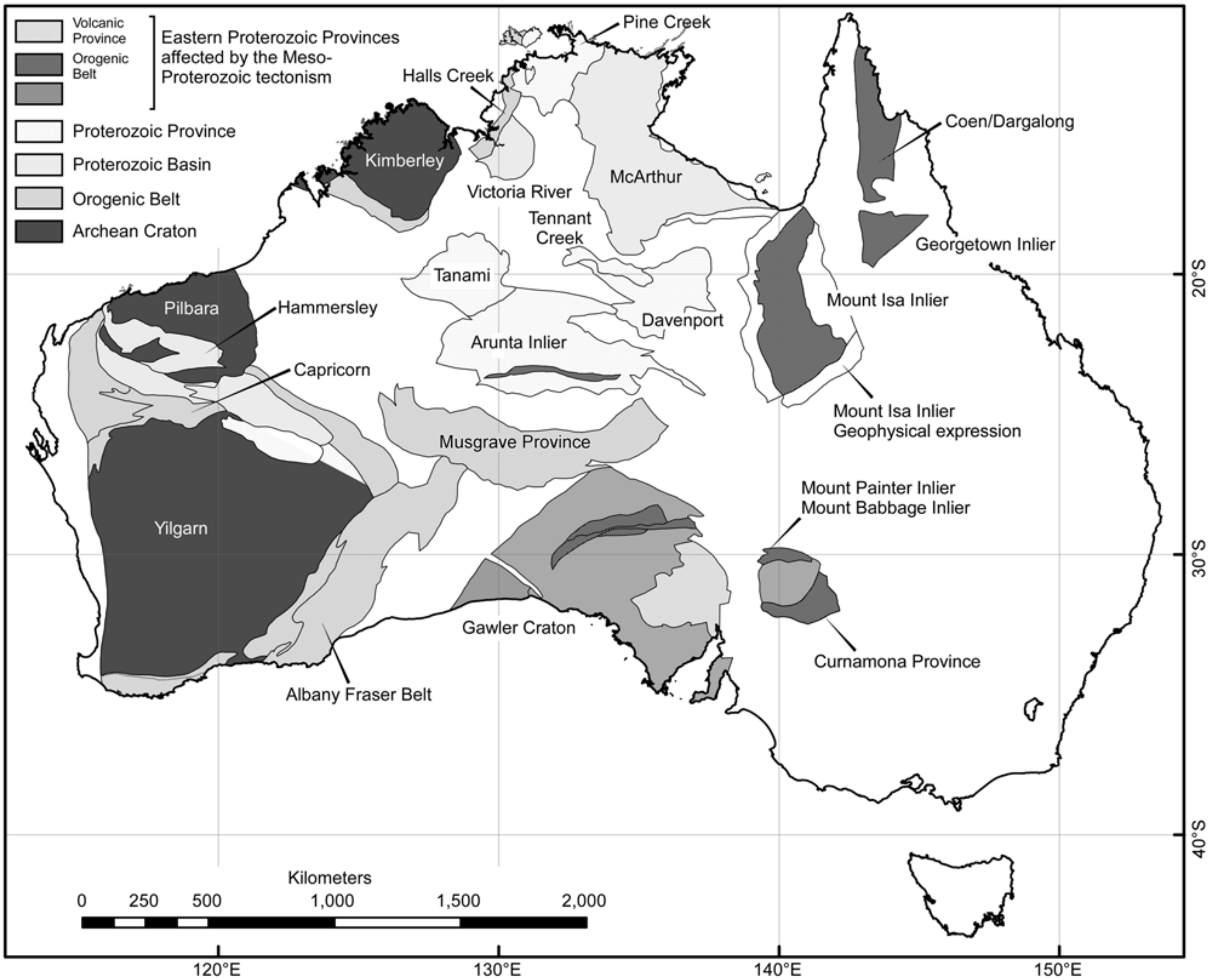

Figure 1. Simplified geological map of the major Archean and Paleoproterozoic to Mesoproterozoic geological provinces of Australia.

Antarctica is characterized by accretion of reworked and juvenile crust along the margin [*Betts and Giles*, 2006; *Betts et al.*, 2008; *Condie*, 1992; *Karlstrom et al.*, 2001]. Given the similarity in the tectonic evolution of Australia and Laurentia leading to the Mesoproterozoic and compelling paleomagnetic evidence for a connection between Australia and Laurentia as a single continental mass [*Betts et al.*, 2008; *Burrett and Berry*, 2000; *Karlstrom et al.*, 2001], it is perplexing that such a large thermal event is only locally preserved along the eastern margin of the Australia and not along the entire margin (including Laurentia), which otherwise was experiencing relative tectonic quiescence [*Duebendorfer et al.*, 2006]. Any tectonic models and reconstructions related to the transition from the supercontinent Columbia (or Nuna) [*Zhao et al.*, 2002, 2004, 2006] to Rodinia [*Li et al.*, 2008] need to consider how Mesoproterozoic tectonism in eastern and central Australia relates to global tectonic events.

[3] The numerous attempts to place Mesoproterozoic eastern Australia into broader tectonic complex have been hampered because the geological record of the event is spread across the entire continent, with large tracts of appropriately aged crust buried or reworked during younger tectonic events. Evidence for plate and terrane margins are cryptic and poorly resolved, and the preserved geological record is complex. Nevertheless, two end-member tectonic models have emerged to reconcile various observations related to the 1620–1500 Ma tectonic evolution of central and eastern Australia: (1) Plume-driven magmatism that is responsible for widespread voluminous felsic A-type magmatism in the Gawler Craton, Curnamona Province, and the Mount Inlier [*Betts et al.*, 2007; *Giles*, 1988; K. Stewart and J. Foden, unpublished report, 2001] (Figure 1) and (2) plate margin models that suggest that tectonic evolution of eastern Australia was driven by processes operating at one or more proximal plate margins [*Betts and Giles*, 2006; *Betts et al.*, 2002; *Cawood and Korsch*, 2008; *Gibson et al.*, 2008; *Hand et al.*, 2007; *Swain et al.*, 2008; *Wade et al.*, 2006]. These end-member models are at the opposite spectrum of possible tectonic interpretations and require

very different tectonic drivers. They have been derived from research that emphasizes different observations. In this paper we address all of the observations related to the 1620–1500 Ma evolution of central and eastern Australia (Figure 1) and present a self-consistent and holistic tectonic model that accounts for all of the geological observations. We argue a hybrid tectonic model of plume modified orogenesis to explain the temporal and spatial evolution of magmatic and orogenic events. This tectonic interpretation allows Australia to be placed in a broader context of Mesoproterozic evolution for Earth and enables assessment of its relationship with other continents.

2. End-Member Tectonic Models

2.1. Plume Model

[4] Proponents of Mesoproterozoic plume tectonics have largely derived their interpretations from detailed geochemical analysis from individual magmatic provinces, particularly the Gawler Craton [e.g., *Blissett et al.*, 1993; *Giles*, 1988; K. Stewart and J. Foden, unpublished report, 2001], and spatiotemporal distribution of A-type magmatic systems at the scale of the Australian continent [e.g., *Betts et al.*, 2007] (Figure 2). *Betts et al.* [2007] used the plate reconstruction of *Giles et al.* [2004] to show that circa 1595–1500 Ma A-type magmatic rocks formed a curvilinear belt that extended from the Gawler Craton, through the Curnamona Province, and into the Mount Isa Inlier (Figure 3). The oldest magmas (circa 1595–1575 Ma) are voluminous A-type magmas (Hiltaba Granite Suite) [*Creaser*, 1996; K. Stewart and J. Foden, unpublished report, 2001] that were emplaced throughout the Gawler Craton (Figures 2 and 4). Coeval with the Hiltaba Granite Suite was the eruption of >25,000 km^2 of dominantly felsic lavas (circa 1595–1590 Ma) throughout the central craton [*Allen et al.*, 2003; *Blissett*, 1975]. These lavas form a semicircular volcanic province characterized by a series of radiating lobate flows (Figure 5a) (M. Pankhurst et al., A Mesoproterozoic continental flood rhyolite province: The end member example of the large igneous province clan, submitted to *Terra Nova*, 2008). The scale of this volcanic province is enormous with individual flow fronts varying between 60 and 120 km long, and lobe fronts and associated terminal lobes between 30 and 120 km wide (Figure 5a). The Hiltaba Suite granites and the Gawler Range Volcanics were emplaced over an area of ~320,000 km^2 and form a large subcircular felsic igneous province ~500 km in diameter (Figure 4).

[5] In the central part of the Curnamona Province is a bimodal volcanic succession termed the Benagerie Volcanics (Figures 5b and 6) [*Robertson et al.*, 1998; *Williams et al.*, 2009]. This succession is buried beneath a shallow veneer of Cambrian and Phanerozoic cover and is inferred from sparse drill hole intersections and regional aeromagnetic data (Figure 5b) [*Williams et al.*, 2009]. The Benagerie Volcanics comprises A-type porphyritic rhyolite, rhyodacite, trachyte, and andesite, with rare chlorite-sericite altered basalt [*Teale and Flint*, 1993]. The Benagerie Volcanics cover an area of approximately 20,000 km^2 and potential field modeling estimate the total volume of the volcanic pile to be 23,000 km^3 [*Williams et al.*, 2009]. U-Pb SHRIMP geochronology of the felsic member yields an age of 1580 ± 2 Ma [*Fanning et al.*, 1998]. In the Mount Painter and Mount Babbage inliers (Figure 6), northern Curnamona Province, volumetrically A-type granites and felsic volcanic successions were emplaced between circa 1575 Ma and 1555 Ma [*Teale*, 1993] (Figure 2).

[6] In the Eastern Fold Belt (Mount Isa Inlier), an episode of circa 1550–1500 Ma A-type pluton emplacement (Williams/Naraku Batholith) (Figures 2 and 7) [*Page and Sun*, 1998], resulted in the development of a ~80 km wide, north trending magmatic belt [*Mark*, 1998, 2001]. Plutons emplaced at this time cover an area of 2100 km^2; however, regional Bouguer gravity data suggest that this belt extends to the south of the present-day exposures (Figure 8).

[7] This spatial and temporal distribution of A-type magmas from the Gawler Craton, Curnamona Province and the Mount Isa Inlier were interpreted as the remnants of a 1500 km segment of a continental hot spot track (Figure 3) that developed as eastern Mesoproterozoic Australia migrated southward at ~1.5 cm/a over a stationary plume [*Betts et al.*, 2007]. The decrease in the width of the hot spot track from ~500 km in the Gawler Craton to ~80 km in the Mount Isa Inlier was interpreted as the plume head interacting with the Gawler Craton continental lithosphere and the plume tail interacting with the Mount Isa Inlier continental lithosphere [*Betts et al.*, 2007]. *Betts et al.* [2007] supported this interpretation with paleomagnetic data by demonstrating the A-type magmatic belt was positioned on the same trajectory as that defined by North Australian Craton apparent polar wander path leading up to magmatism (circa 1640–1590 Ma).

[8] A characteristic of the A-type magmas along this belt is their elevated eruption and emplacement temperatures. Geothermometry and phase equilibria studies for the upper Gawler Range Volcanics (Figure 2) suggest eruption temperatures between 900°C and 1100°C [*Creaser and White*, 1991; *Stewart*, 1994; Pankhurst et al., submitted manuscript, 2008]. These data were collected at terminal portions of the lava lobes located at a considerable distance (50–100 km) from the interpreted eruption center (Pankhurst et al., submitted manuscript, 2008). Lavas are therefore likely to have cooled before lava flow arrest, and thus eruption temperature were likely to be in excess of 1100°C [*Creaser and White*, 1991], essentially reflecting mantle temperatures. Zirconium saturation temperatures derived from the granite Zr content indicate that the Mount Neill Suite (Figure 2) within the Mount Painter Inlier was emplaced at temperature of ~900°C, the Yerila Granite type at 800°C, and the Box Bore Granite at 850°C (K. Stewart and J. Foden, unpublished report, 2001).

[9] The eruption temperature data combined with the elevated halogen contents of the Upper Gawler Range Volcanics (Pankhurst et al., submitted manuscript, 2008) were used as the primary constraints for combined temperature-composition-volatile non-Arrhenian melt viscosity modeling [*Giordano et al.*, 2006; *Giordano and Dingwell*, 2003]. The models revealed the viscosities of the felsic

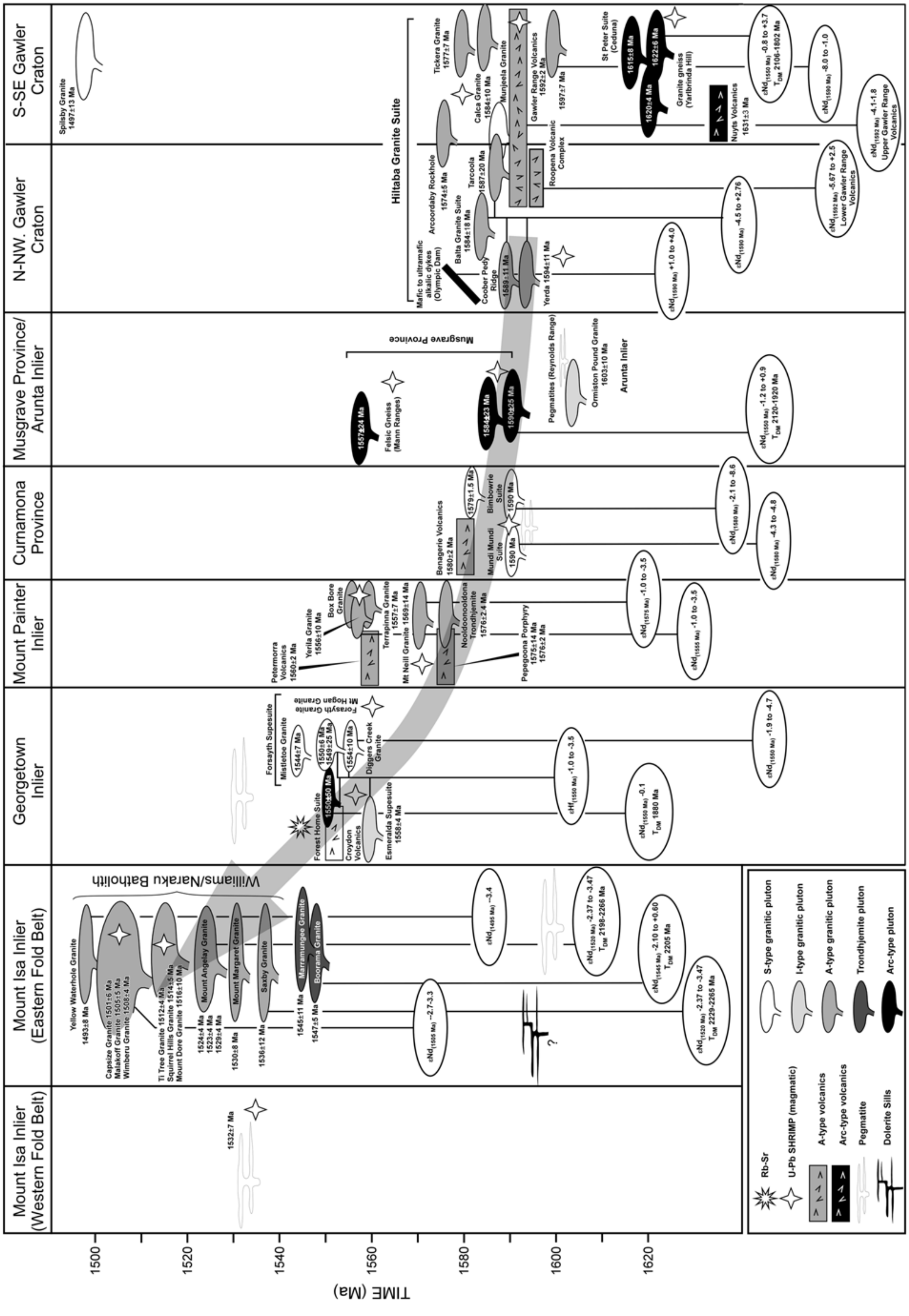
Mount Isa Inlier (Western Fold Belt)
Mount Isa Inlier (Eastern Fold Belt)
Georgetown Inlier
Mount Painter Inlier
Curnamona Province
Musgrave Province/ Arunta Inlier
N-NW. Gawler Craton
S-SE Gawler Craton
TIME (Ma)
1500
1520
1540
1560
1580
1600
1620
1532±7 Ma
Yellow Waterhole Granite 1493±8 Ma
Capsize Granite 1501±6 Ma
Malakoff Granite 1505±5 Ma
Wimberu Granite 1508±4 Ma
Ti Tree Granite 1512±4 Ma
Squirrel Hills Granite 1514±5 Ma
Mount Dore Granite 1516±10 Ma
1524±4 Ma
1523±4 Ma
1529±4 Ma
Mount Angelay Granite
1530±8 Ma
Mount Margaret Granite
1536±12 Ma
Saxby Granite
1545±11 Ma
1547±5 Ma
Marramungee Granite
Boorama Granite
Williams/Naraku Batholith
εNd(1505 Ma) −2.7-3.3
εNd(1495 Ma) −3.4
εNd(1520 Ma) −2.37 to −3.47 TDM 2198-2266 Ma
εNd(1545 Ma) −2.10 to +0.60 TDM 2205 Ma
εNd(1520 Ma) −2.37 to −3.47 TDM 2229-2265 Ma
?
Forest Home Suite
1550±50 Ma
Croydon Volcanics
Esmeralda Supesuite 1558±4 Ma
Forsayth Supesuite
Mistletoe Granite
1544±7 Ma
1550±6 Ma
1549±25 Ma
1554±10 Ma
Diggers Creek Granite
Forsayth Granite
Mt Hogan Granite
εHf(1550 Ma) −1.0 to −3.5
εNd(1550 Ma) −0.1 TDM 1880 Ma
εNd(1550 Ma) −1.9 to −4.7
Petermorra Volcanics 1560±2 Ma
Yerila Granite 1556±10 Ma
Box Bore Granite
Terrapinna Granite 1557±7 Ma
Mt Neill Granite 1569±14 Ma
Nooldoonooldona Trondhjemite 1576±2.4 Ma
Pepegoona Porphyry 1575±14 Ma 1576±2 Ma
εNd(1575 Ma) −1.0 to −3.5
εNd(1555 Ma) −1.0 to −3.5
Benagerie Volcanics 1580±2 Ma
1579±1.5 Ma
Bimbowrie Suite 1590 Ma
Mundi Mundi Suite 1590 Ma
εNd(1580 Ma) −2.1 to −8.6
εNd(1580 Ma) −4.3 to −4.8
1557±24 Ma
Felsic Gneiss (Mann Ranges)
Musgrave Province
1584±23 Ma
1590±25 Ma
Pegmatites (Reynolds Range)
Ormiston Pound Granite 1603±10 Ma
Arunta Inlier
εNd(1590 Ma) −1.2 to +0.9 TDM 2120-1920 Ma
Mafic to ultramafic alkalic dykes (Olympic Dam)
Balta Granite Suite 1584±18 Ma
Coober Pedy Ridge
1589±11 Ma
Yerda 1594±11 Ma
Arcoordaby Rockhole 1574±5 Ma
Tarcoola 1587±20 Ma
Roopena Volcanic Complex
Hiltaba Granite Suite
εNd(1590 Ma) +1.0 to +4.0
εNd(1590 Ma) −4.5 to +2.76
εNd(1592 Ma) −5.67 to +2.5 Lower Gawler Range Volcanics
εNd(1592 Ma) −4.1-1.8 Upper Gawler Range Volcanics
Spilsby Granite 1497±13 Ma
Tickera Granite 1577±7 Ma
Calca Granite 1584±10 Ma
Munjeela Granite
Gawler Range Volcanics 1592±2 Ma
1597±7 Ma
St Peter Suite (Ceduna)
1615±8 Ma
1620±4 Ma
1622±6 Ma
Granite gneiss (Yarbrinda Hill)
Nuyts Volcanics 1631±3 Ma
εNd(1550 Ma) −0.8 to +3.7 TDM 2106-1802 Ma
εNd(1590 Ma) −8.0 to −1.0
Rb-Sr
U-Pb SHRIMP (magmatic)
A-type volcanics
Arc-type volcanics
Pegmatite
Dolerite Sills
S-type granitic pluton
I-type granitic pluton
A-type granitic pluton
Trondhjemite pluton
Arc-type pluton

Figure 2

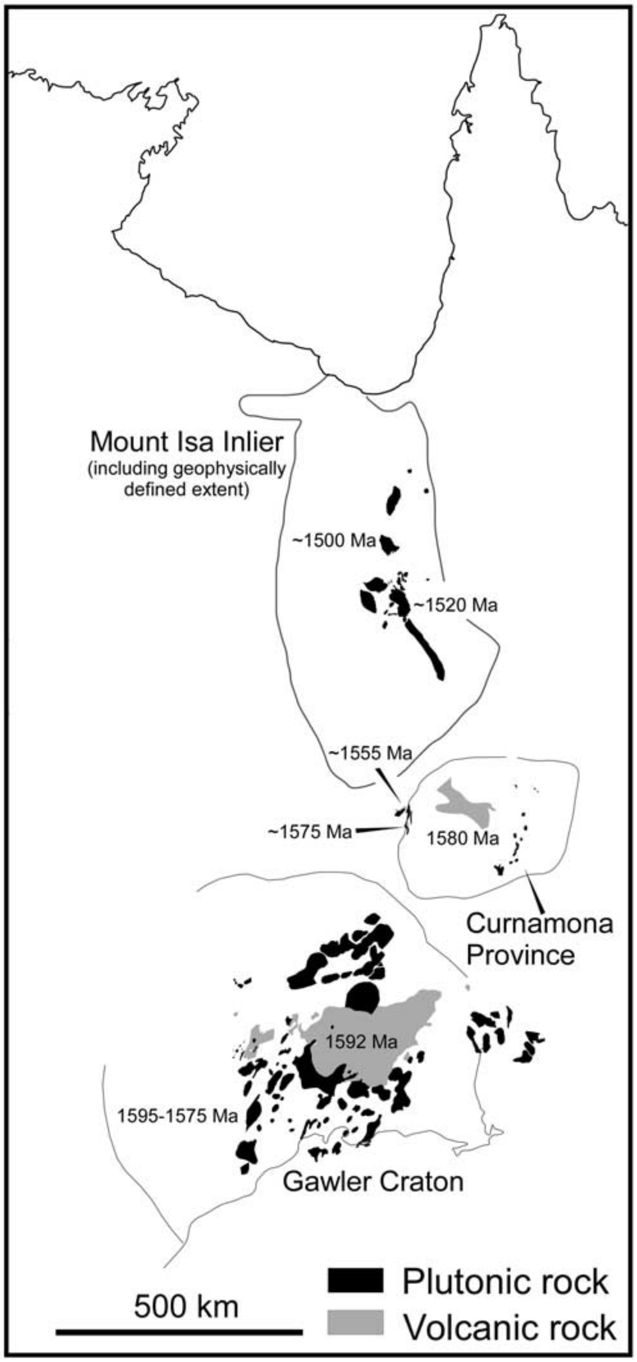

Figure 3. Geological map showing the distribution of A-type magmatism throughout eastern Proterozoic Australia after *Betts et al.* [2007]. The distribution presented uses *Giles et al.*'s [2004] reconstruction of the South Australian Craton.

melts ($<3.5 \log_{10}[\eta(\text{Pa s})]$) corresponded to viscosities of basalt. This unusual physiochemical characteristic for the felsic lavas of the upper Gawler Range Volcanics explains the enormous size of the volcanic province and the melt flux required to build the province over the relatively short interval of ~5 Ma. It therefore appears that the Gawler Range Volcanics represents a highly unusual and rare felsic end-member of the Large Igneous Province and that it formed in manner analogous to mafic large igneous provinces (Pankhurst et al., submitted manuscript, 2008) (Figure 4).

[10] Proponents for the plume orogen for the Hiltaba Granite Suite and the Gawler Range Volcanics have developed their models on the basis of geochemical criteria [*Creaser and White*, 1991; *Daly et al.*, 1998; *Giles*, 1988; K. Stewart and J. Foden, unpublished report, 2001]. Sm-Nd analysis of various Hiltaba Granite Suite from the eastern Gawler Craton show relatively evolved $\varepsilon\text{Nd}_{(1590)}$ values between -1 and -14.3 (Figure 2), indicating derivation from partial melting of existing crust [*Creaser*, 1995; K. Stewart and J. Foden, unpublished report, 2001]. In the western Gawler Craton the granites have I-type chemical affinities and tend to be less evolved compared with the A-type granites in the central and eastern Gawler Craton [*Budd*, 2006]. Within the evolved granites there is a strongly fractioned population (Malbooma) characterized by positive $\varepsilon\text{Nd}_{(1590)}$ values (0 to +2.76) and a moderately fractioned population (Jenners) characterized by negative $\varepsilon\text{Nd}_{(1590)}$ values (-3.5 to -4.5) (Figure 2). A similar isotopic pattern occur in the chemically and isotopically heterogeneous tholeiitic basalt, andesite, dacite, rhyodacite and rhyolite of the Lower Gawler Range Volcanics [*Blissett*, 1975; *Blissett et al.*, 1993] or "development phase" [*Stewart*, 1994]. Negative $\varepsilon\text{Nd}_{(1592)}$ (-1.07 to -6.92) and $\varepsilon\text{Hf}_{(1592)}$ (-2.1 to -6.7) (Figure 2) values from basaltic and andesitic flows of the Chitanilga and the Glyde Hill volcanic complex (Figure 4) indicate crustal contamination from the same magma source. Geochemically and isotopically homogeneous lavas of the felsic Upper Gawler Range Volcanics [*Allen and McPhie*, 2002; *Allen et al.*, 2003, 2008] yield $\varepsilon\text{Nd}_{(1592)}$ value between -4.1 and -1.8 (Figure 2), suggesting partial melting from a Neoarchean source [*Creaser*, 1995; *Stewart*, 1994]. Components from the Hiltaba-Gawler Range Volcanic magmas also display elevated $\varepsilon\text{Nd}_{(1592)}$ values suggesting derivation from mantle-derived source. Basaltic rocks from the Roopena Volcanic Complex of the Lower Gawler Range Volcanics [*Fricke*, 2005] (Figure 4) display $\varepsilon\text{Nd}_{(1592)}$ values between -5.67 and $+2.50$ and positive $\varepsilon\text{Hf}_{(1592)}$ values between $+0.8$ and $+7.4$ [*Fricke*, 2005] (Figure 2). Negative $\varepsilon\text{Nd}_{(1592)}$ (-5.67) values are prevalent in the lower flows and positive $\varepsilon\text{Nd}_{(1592)}$ values ($+2.50$) are restricted to the upper flows. This suggests a

Figure 2. Time-space diagram with the age, style, and isotopic characteristics of magmatism throughout the eastern Australian Proterozoic geological provinces [*Adshead-Bell and Bell*, 1999; *Budd*, 2006; *Champion*, 1991; *Creaser*, 1995, 1996; *Creaser and Cooper*, 1993; *Creaser and White*, 1991; *Elburg et al.*, 2001; *Fanning et al.*, 1998, 1988, 2007; *Ferris*, 2001; *Flint*, 1993; *Fricke*, 2005, 2006; *Giles and Nutman*, 2002, 2003; *Mark*, 2001; *Murgulov et al.*, 2007; *Page and Laing*, 1992; *Page et al.*, 2005b; *Page and Sun*, 1998; *Pollard et al.*, 1998; *Robertson et al.*, 1998; *Stewart*, 1994; *Swain et al.*, 2008; *Wade et al.*, 2006; K. Stewart and J. Foden, unpublished report, 2001].

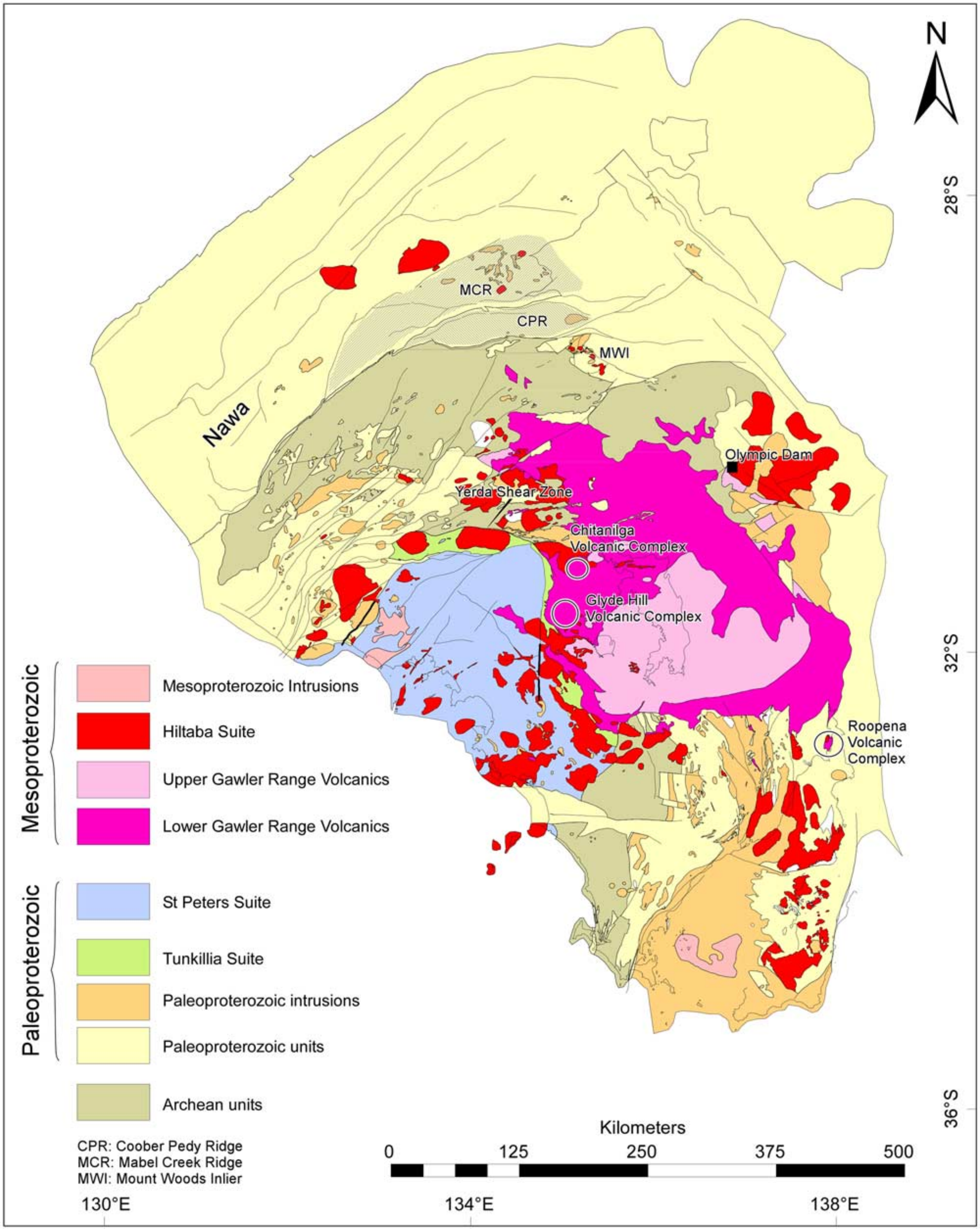

Figure 4. Simplified geology map of the Gawler Craton. The map highlights the distribution of St. Peter Suite, Hiltaba Granite Suite, and the Gawler Range Volcanics. Locality is shown in Figure 1.

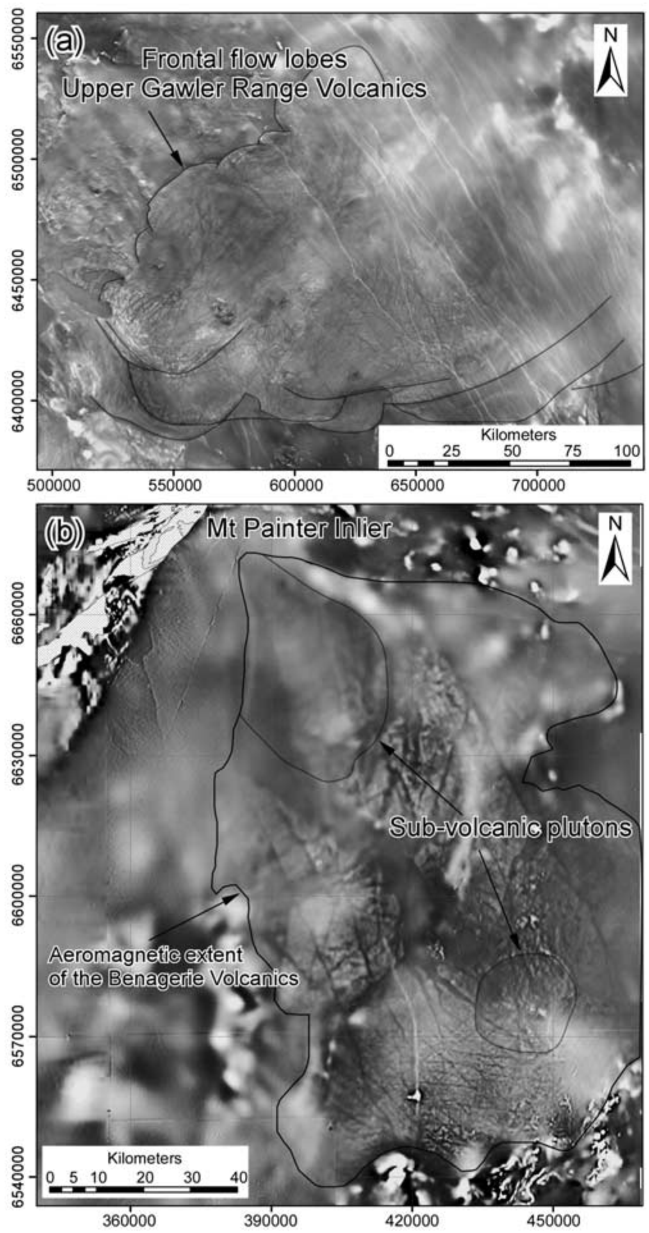

Figure 5. (a) Reduced to the pole grey scale aeromagnetic data of the Gawler Range Volcanics in the Gawler Craton highlighting the architecture of radial lobe fronts and the distribution of flows. Location of the Upper Gawler Range Volcanics is shown in Figure 4. (b) First vertical derivative image of the central parts of the Curnamona Province showing the distribution of the Benagerie Volcanic Province. Location of the Benagerie Volcanics is presented in Figure 6.

transition from a magma source contaminated by crustal material or assimilated crustal material to a mantle-derived source with little or no crustal contamination [*Fricke*, 2005]. A mantle source has been interpreted for extensively altered mafic to ultramafic alkalic dykes that intruded into the brecciated Roxby Downs Granite within the Olympic Dam deposit (Figure 4) [*Johnson and McCulloch*, 1995]. The dykes are volumetrically small and their regional significance is uncertain. Nevertheless, Sm-Nd analysis of these dykes yield $\varepsilon\mathrm{Nd}_{(1590)}$ values between +0.1 and +4.0 (Figure 2) with the least altered samples exhibit the highest $\varepsilon\mathrm{Nd}_{(1590)}$ values [*Johnson and McCulloch*, 1995].

[11] K. Stewart and J. Foden (unpublished report, 2001) suggest that the Hiltaba Granites and the Gawler Range Volcanics formed via a combination of fractionation, crustal contamination and recharge of mafic magmas and mixing. Geochemical modeling suggests that maximum amount of crustal end-member for any of the Lower Gawler Range Volcanics is <30% (K. Stewart and J. Foden, unpublished report, 2001).

[12] Comparable isotopic signatures occur in the Mount Painter and Mount Babbage inliers (Figure 6) where the circa 1575 Ma and 1560 Ma Mount Neill and the Moolawatana suites are preserved [*Teale*, 1993]. The Mount Neill Suite (circa 1575 Ma) [*Elburg et al.*, 2001; *Teale*, 1993] comprises rapakivi-like granites, subvolcanic granite, and porphrytic rhyolite (K. Stewart and J. Foden, unpublished report, 2001), suggesting emplacement at shallow crustal levels. The Mount Neill Suite is dominated by potassic A-type granites that are locally influenced by sodic alteration (e.g., Nooldoonooldoona Trondhjemite) [*Elburg et al.*, 2001]. Sm-Nd isotope analysis shows relatively homogeneous $\varepsilon\mathrm{Nd}_{(1590)}$ values between -1.45 and -3.25 (K. Stewart and J. Foden, unpublished report, 2001) (Figure 2), suggesting crustal contamination during emplacement.

[13] The Moolawatana Suite [*Sheard et al.*, 1992] (Figures 2 and 6) comprises the I-type Yerila Granite (circa 1555 Ma) (C. M. Fanning, Geochronological synthesis of southern Australia. Part 1, The Curnamona Province, Adelaide, South Australia, unpublished open file envelope, Department of Mines and Energy, 1995), the volumetrically dominant Terrapinna/Wattleowie granites (circa 1555–1560 Ma), the Petermorra Volcanics (circa 1560 Ma), and the Box Bore Granite (circa 1555 Ma) (K. Stewart and J. Foden, unpublished report, 2001). Sm-Nd isotope analysis of these granites show a narrow range of $\varepsilon\mathrm{Nd}_{(1555)}$ between -1.8 and -2.0 over a wide range of compositions (K. Stewart and J. Foden, unpublished report, 2001) (Figure 2).

[14] In the Eastern Fold Belt, the oldest suite of Mesoproterozoic igneous intrusions is represented by the circa 1550 Ma trondhjemite-tonalite-granodiorite (TTG) group [*Mark*, 2001; *Page and Sun*, 1998; *Pollard et al.*, 1998]. This group is derived from high-pressure (>8–10 kbar) partial melting of garnet-bearing mafic, mantle-derived rock [*Mark*, 2001; *Wyborn*, 1998a]. A suite of K-rich, "A-type," granitoids that include the Capsize Creek Granodiorite, Mount Angelay Granite, Saxby Granite, Squirrel Hills Granite, Yellow Waterhole Granite, and Wimberu Granite (Figures 2 and 7) were emplaced during several discrete events at circa 1540–1520 Ma, 1520–1510 Ma, and 1510–1500 Ma (Figure 2). The $\varepsilon\mathrm{Nd}_{(t)}$ values for these granites vary from -1 to -3.8 [*Mark*, 2001; *Page and Sun*, 1998] (Figure 2) and formed by a combination of fractionation and localized magma mixing and mingling [*Pollard et al.*, 1998]. A-type granites were derived from high-temperature

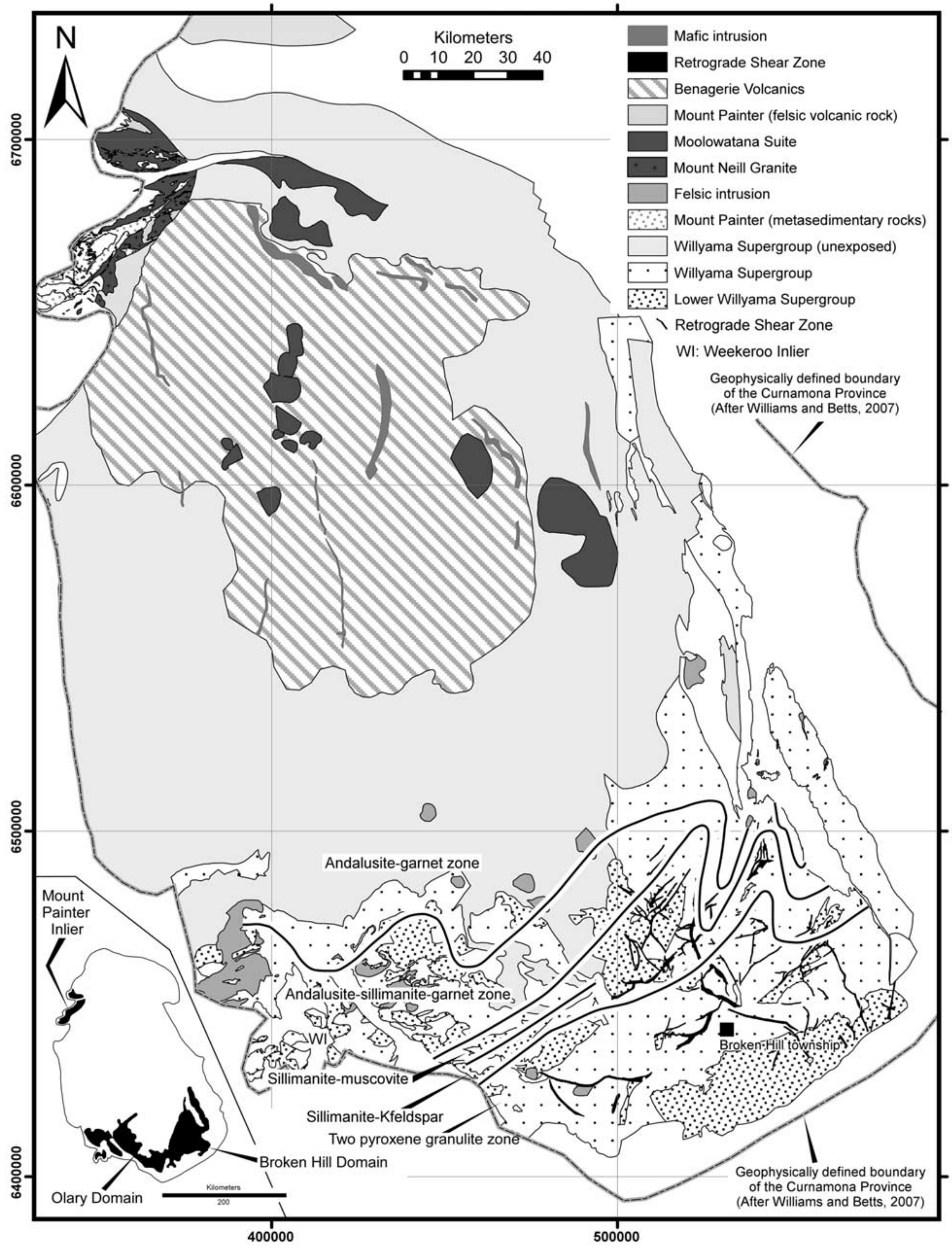

Figure 6. Simplified geological map of the Curnamona Province with superimposed metamorphic isograds of the southern Curnamona Province [*Webb and Crooks*, 2005]. Inset shows the outcrop distribution of the Curnamona Province. Locality is shown in Figure 1.

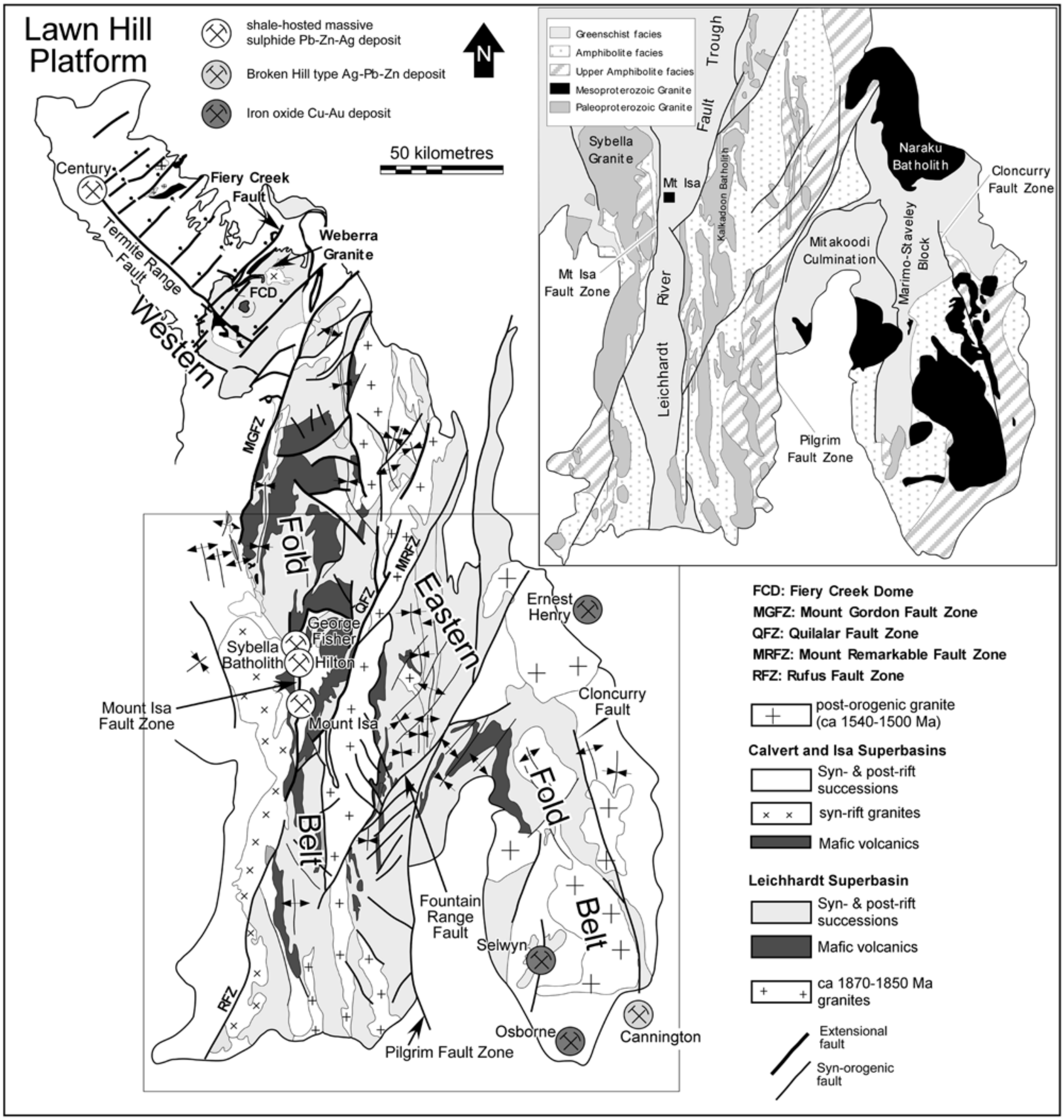

Figure 7. Simplified geological map of the Mount Isa Inlier with the major structural and basin elements. Inset shows simplified distribution of the metamorphic grade in the southern part of the inlier (modified after *Foster and Rubenach* [2006]). Locality is shown in Figure 1.

(>850–900°C) partial melting of tonalitic crust at pressures of <8–10 kbar [*Wyborn*, 1998b]. They are characterized by elevated LILE and HFSE concentrations, enrichment in Co and Sr and negative Ba, Nd, Sr, Eu, and Ti. These limitations suggest that hot mantle-derived material ponded at depths of <30 km during each phase of partial melting and granite emplacement.

2.2. Plate Margin Models

[15] Advocates of the plate margin models for the Mesoproterozoic evolution of the eastern and central Australia have derived their interpretations from the spatial and temporal patterns of orogenesis and associated metamorphism [*Betts and Giles*, 2006; *Cawood and Korsch*, 2008; *Hand et al.*, 2007], as well as geochemical data suggesting

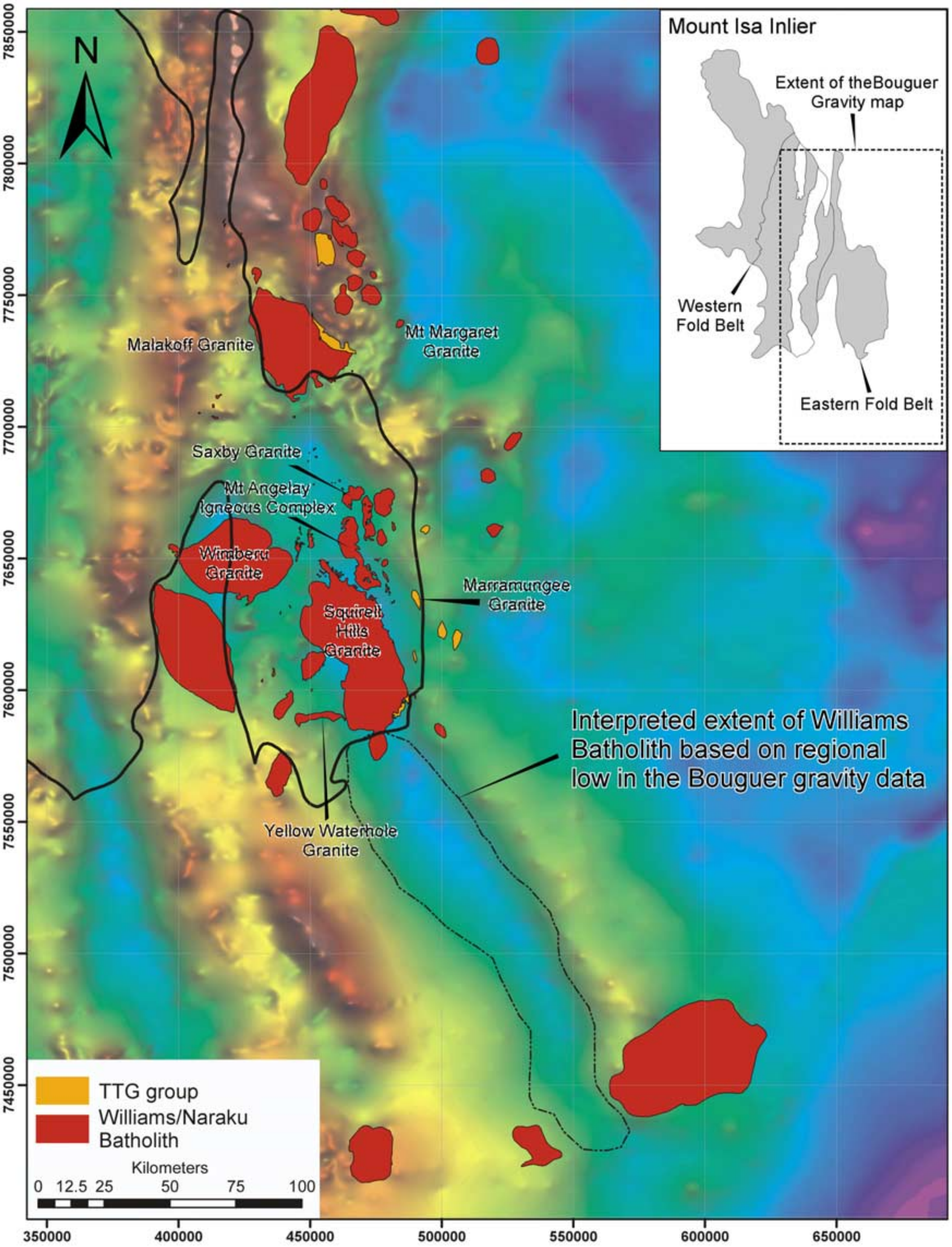

Figure 8. Regional Bouguer gravity map of southeastern Mount Isa Inlier with the distribution of A-type magmatism superimposed. Blue shades represent low-density values, whereas yellow and red shades represent medium- to high-density rocks.

the presence juvenile magmatic arcs proximal to the plate margin [*Champion*, 1991; *Swain et al.*, 2008; *Wade et al.*, 2006]. There is no unified tectonic interpretation that explains the spatial and temporal distribution of the magmatic arcs and orogenic belts [*Betts and Giles*, 2006; *Swain et al.*, 2008; *Wade et al.*, 2006]. Plate margin models proposed for this time interval fit into two general categories. The first involves subduction and accretion along the southern margin of the Australian continent, and the second, a complicated variant of the first, has an additional subduction zone along the eastern margin of the continent [*Betts and Giles*, 2006; *Betts et al.*, 2002].

[16] Evidence for arc-related magmatism is preserved in the three discrete regions, the southern Gawler Craton (St Peter Suite), the Musgrave Province, and the Georgetown Inlier (Forest Home Suite) (Figure 1). The St Peter Suite magmas comprise variably intermingled granite, tonalite, granodiorite, diorite, and gabbro emplaced between circa 1620 Ma and 1610 Ma [*Swain et al.*, 2008]. St Peter Suite magmas are preserved as a shear zone-bounded, triangular block (Figure 4). It is considered to have formed by fractionation of a chemically enriched mantle metasomatized by slab-derived fluids or silica-rich melts [*Swain et al.*, 2008]. Felsic to intermediate magmatic compositions display calc-alkaline affinities that are characterized by an expanded SiO_2 range (61–77 wt%). They are sodic (Na/K >1), and show high Sr, K/Rb and Sr/Y and relatively low K_2O, Rb/Sr, Th, U (i.e., low heat-producing granites), REE, and Nb [*Ferris*, 2001]. The St Peter Suite is LREE enriched, and HREE and Y-depleted [*Ferris*, 2001; *Swain et al.*, 2008], with fractionated units displaying modest negative Eu anomalies [*Swain et al.*, 2008]. The $\varepsilon Nd_{(1620)}$ values for the St Peter Suite are relatively juvenile varying between −0.8 and +3.7 [*Swain et al.*, 2008] (Figure 2). Depleted mantle model ages (T_{DM}) for this suite vary between 2106 and 1802 Ma [*Swain et al.*, 2008] (Figure 2), which is relatively young in the context of Proterozoic Australia. *Swain et al.* [2008] proposed that the St Peter Suite formed outboard of the Gawler Craton on the overriding plate of south dipping subduction zone and was accreted to the southern Gawler Craton during collision between East Antarctica (Mawson Continent) and the Gawler Craton.

[17] A suite of granulite to amphibolite facies felsic orthogneisses from the Mann Ranges of the Musgrave Province in central Australia (Figure 1) [*Wade et al.*, 2006] are interpreted as the reworked remnants of island arc rocks emplaced between circa 1590 and 1550 Ma [*Camacho and Fanning*, 1995; *Wade et al.*, 2006]. These rocks display SiO_2 values between 66 and 76%, and are characterized by negative anomalies in Nb, Ti, and Y [*Wade et al.*, 2006]. *Wade et al.* [2006] subdivided the suite into Yb-enriched samples which vary in composition from quartz monzonites to tonalities, and Yb-depleted samples, which are granitic to quartz monozonitic in composition. Yb-deleted samples have positive Eu anomalies, whereas the Yb-enriched samples have slightly positive to slightly negative Eu anomalies. All samples are REE-enriched [*Wade et al.*, 2006]. The $\varepsilon Nd_{(1550)}$ values for these rocks are relatively juvenile between −1.2 and +0.9 and depleted mantle model ages (T_{DM}) vary between 2120 and 1920 Ma [*Wade et al.*, 2006] (Figure 2). While, the felsic suite is relatively juvenile, *Wade et al.* [2006] speculated that samples with more negative $\varepsilon Nd_{(1550)}$ values (−1.2) may have been contaminated by evolved Archaean or Paleoproterozoic samples. The absence of zircon populations older than 1590 Ma [*Camacho and Fanning*, 1995] was used to interpret contamination during slab sediment subduction rather than crustal assimilation [*Wade et al.*, 2006]. This suite of arc-related rocks was interpreted to be positioned outboard of the northern margin of the Gawler Craton at the time of emplacement, where it evolved in the overriding plate of a south dipping subduction zone. The arc amalgamated with the northern Gawler Craton after circa 1580 Ma during collision between the Gawler Craton and the North Australian Craton.

[18] A third potential magmatic arc is represented by the volumetrically small trondhjemitic I-type Forest Home Supersuite (Figures 2 and 9), which was emplaced into poly deformed gneissic rocks of the Georgetown Inlier at circa 1560–1545 Ma [*Black and Withnall*, 1993; *Champion*, 1991]. The Forest Home Supersuite is characterized relatively juvenile −0.1 $\varepsilon Nd_{(1550)}$ values for this suite and a depleted mantle model age (T_{DM}) of 1880 Ma [*Black and McCulloch*, 1990]. *Black and McCulloch* [1990] proposed that this isotopic signal was caused by mixing of primitive circa 1550 Ma mafic crust with older and more evolved felsic crust (circa 2100 Ma). Hf isotope analysis of zircon collected from present-day stream sediments indicates a relatively juvenile signature in circa 1550 Ma zircon populations [*Murgulov et al.*, 2007], presumably from the relatively juvenile I-type Forest Home Suite. T_{DM} model ages range from 1605 Ma to 3270 Ma, indicating involvement of Archaean crustal component, but more importantly highlight a significant juvenile mantle input [*Murgulov et al.*, 2007]. The Forest Home Supersuite also has geochemical affinities with subduction-related magmas [*Champion*, 1991]. This interpretation led *Betts et al.* [2002] and *Betts and Giles* [2006] to propose a west dipping subduction zone to the east of the Georgetown Inlier at circa 1550 Ma.

[19] At the onset of the Mesoproterozoic large tracts of central and eastern Australia underwent a period of orogenesis (circa 1620 and 1580 Ma) (Figure 10). The orogenic history is preserved in the Arunta Inlier (Chewings Orogeny), Curnamona Province (Olarian Orogeny), Gawler Craton (Kararan Orogeny), Mount Isa Inlier (Isan Orogeny) and Georgetown Inlier (Jana Orogeny) [*Betts et al.*, 2006; *Blenkinsop et al.*, 2008; *Cihan et al.*, 2006; *Cihan and Parsons*, 2005; *Collins et al.*, 1995; *Daly et al.*, 1998; *Forbes et al.*, 2004, 2007; *Gibson et al.*, 2008; *Giles et al.*, 2006b; *Hand et al.*, 2007; *MacCready*, 2006a; *O'Dea et al.*, 1997b, 2006; *Potma and Betts*, 2006; *Rubatto et al.*, 2001; *Vry et al.*, 1996] (Figures 1 and 10). The circa 1610–1560 Ma Chewings Orogeny [*Collins and Shaw*, 1995] is characterized by early thin-skinned deformation and nappe emplacement during north directed thrusting [*Teyssier et al.*, 1988], followed by the development of upright, shallowly plunging folds with ~east-west trending axial traces [*Collins and Shaw*, 1995]. Geochronology of metamorphic zircon and monazite suggest that granulite facies metamorphism occurred between circa 1587 Ma and circa 1557 Ma [*Rubatto et al.*, 2001; *Vry et al.*, 1996].

[20] In the Curnamona Province initial crustal shortening during the Olarian Orogeny (Figure 10) involved thin-skinned deformation and lateral translations of Willyama Supergroup in which shallowly inclined to recumbent folds and nappes developed [*Clarke et al.*, 1986; *Forbes and Betts*,

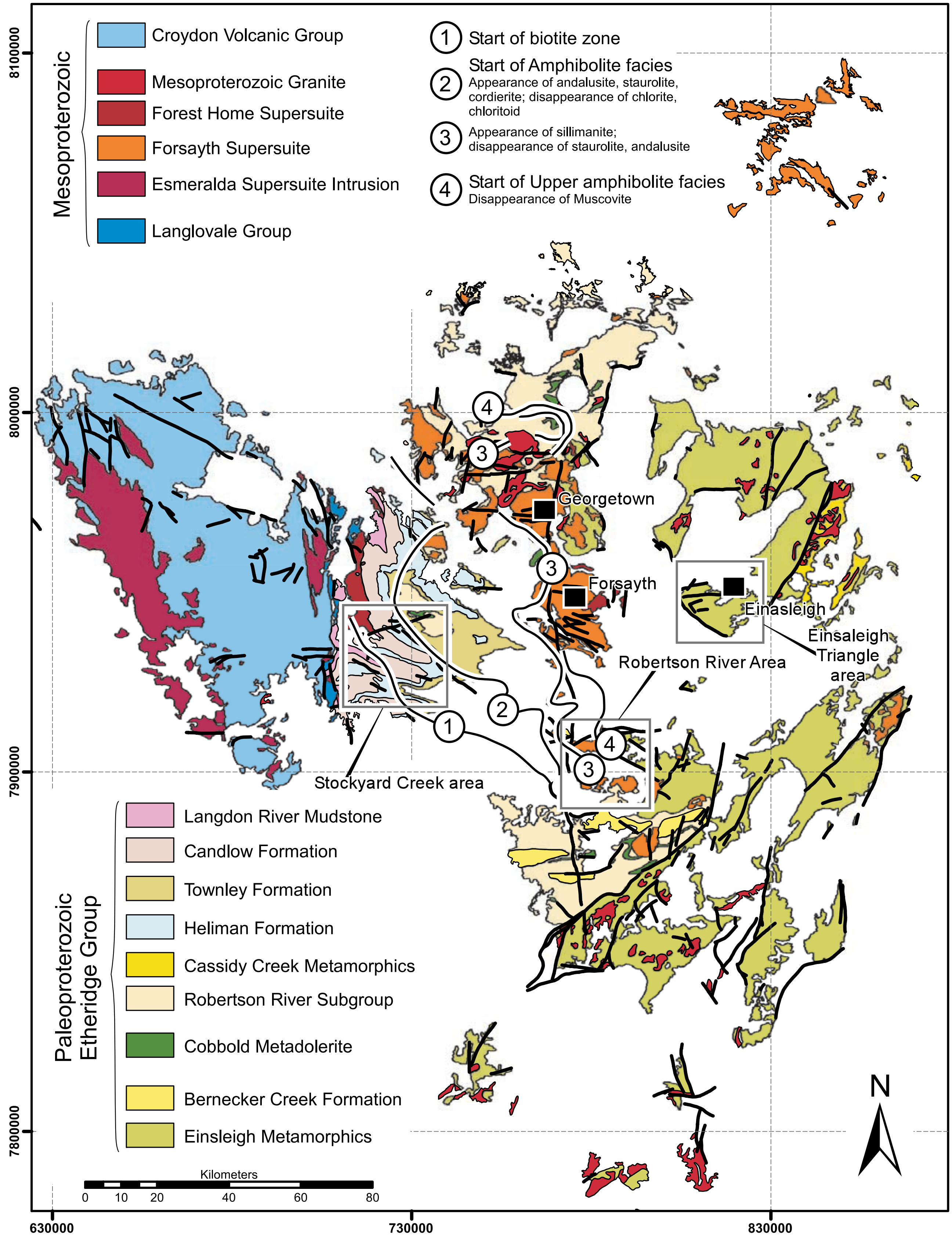

Figure 9. Simplified geological map of the Georgetown Inlier highlighting the distribution of circa 1550 Ma magmatic rocks. Locality is shown in Figure 1.

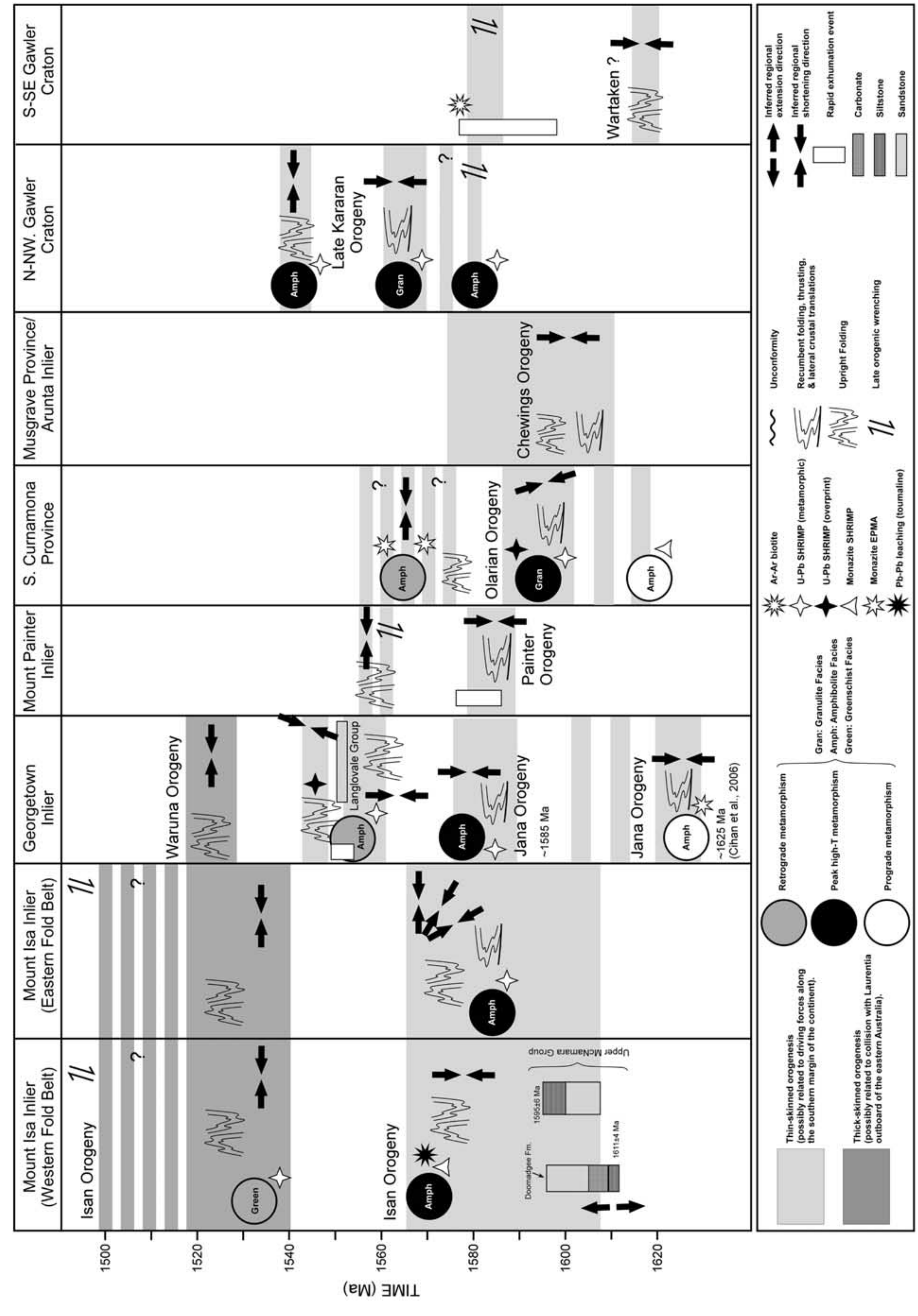
TIME (Ma)
1500
1520
1540
1560
1580
1600
1620
Mount Isa Inlier (Western Fold Belt)
Mount Isa Inlier (Eastern Fold Belt)
Georgetown Inlier
Mount Painter Inlier
S. Curnamona Province
Musgrave Province/ Arunta Inlier
N-NW. Gawler Craton
S-SE Gawler Craton
Isan Orogeny
Isan Orogeny
Green
Amph
Doomadgee Fm.
1611±4 Ma
1595±6 Ma
Upper McNamara Group
?
Waruna Orogeny
Langlovale Group
Amph
Jana Orogeny
~1585 Ma
Jana Orogeny
~1625 Ma
(Cihan et al., 2006)
Painter Orogeny
Olarian Orogeny
Gran
?
Chewings Orogeny
Late Kararan Orogeny
Gran
Wartaken ?
Thin-skinned orogenesis (possibly related to driving forces along the southern margin of the continent).
Thick-skinned orogenesis (possibly related to collision with Laurentia outboard of the eastern Australia).
Retrograde metamorphism
Peak high-T metamorphism
Prograde metamorphism
Gran: Granulite Facies
Amph: Amphibolite Facies
Green: Greenschist Facies
Ar-Ar biotite
U-Pb SHRIMP (metamorphic)
U-Pb SHRIMP (overprint)
Monazite SHRIMP
Monazite EPMA
Pb-Pb leaching (toumaline)
Unconformity
Recumbent folding, thrusting, & lateral crustal translations
Upright Folding
Late orogenic wrenching
Inferred regional extension direction
Inferred regional shortening direction
Rapid exhumation event
Carbonate
Siltstone
Sandstone

Figure 10

2004; *Forbes et al.*, 2004; *Gibson and Nutman*, 2004; *Laing et al.*, 1978; *Marjoribanks et al.*, 1980]. Regional fold interference patterns suggest that nappes were highly noncylindrical [*Forbes and Betts*, 2004; *Forbes et al.*, 2004] and were produced during south-over-north transport along high-temperature shear zones [*Forbes and Betts*, 2004; *Ganne et al.*, 2005]. The later stages of the Olarian Orogeny are characterized by thick-skinned deformation and the development of upright to steeply inclined folds with north to northeast trending axial traces (Figure 4) [*Webster*, 1996; *Wilson and Powell*, 2001]. The timing of upright folding is constrained by the emplacement of the circa 1596–1591 Ma Mundi Mundi Suite Granites in the Broken Hill Block [*Page et al.*, 2005a], the Bimbowrie Suite S-type granites in the Olary Domain [*Fricke*, 2006] (Figure 2) and metamorphic monazite that suggest that deformation may have lasted until at least circa 1550 Ma [*Rutherford et al.*, 2007].

[21] In the Mount Isa Inlier, the Isan Orogeny [*Bell*, 1983; *Betts et al.*, 2006; *Blake and Stewart*, 1992; *O'Dea et al.*, 1997b; *Page and Bell*, 1986] has been interpreted to span more than 100 Ma (Figure 10) but most likely represents multiple orogenic events [*Betts et al.*, 2000, 2006; *Giles et al.*, 2006a; *O'Dea et al.*, 2006; *Sayab*, 2008] with several discrete episodes of metamorphism [*Connors and Page*, 1995; *Foster and Rubenach*, 2006; *Giles et al.*, 2006b; *Giles and Nutman*, 2002, 2003; *Page and Sun*, 1998; *Rubenach*, 1992; *Rubenach and Barker*, 1998; *Rubenach and Lewthwaite*, 2002]. In the relatively low strain regions of the Western Fold Belt the early stages of the Isan Orogeny involved inversion of the rift-sag basins during both north-south and east-west shortening resulting in normal fault reactivation, development of localized foliations and development of north to northeast trending upright folds (Figure 7) [*Betts et al.*, 2004; *Lister et al.*, 1999; *O'Dea and Lister*, 1995; *O'Dea et al.*, 1997a]. In the Eastern Fold Belt, early north-south shortening resulted in the development of a north-northwest vergent thin-skinned midcrustal fold and thrust belt [*Betts et al.*, 2000; *Giles et al.*, 2006a, 2006b; *O'Dea et al.*, 2006] and inversion of basin successions [*Blenkinsop et al.*, 2008; *Potma and Betts*, 2006]. During inversion the upper parts of the Eastern Fold Belt stratigraphy [*Foster and Austin*, 2008] were thrust over older successions of the stratigraphy via nappe tectonics [*Giles et al.*, 2006a, 2006b; *O'Dea et al.*, 2006] above a midcrustal decollement, which developed at the interface between the crystalline basement and overlying sedimentary successions [*MacCready*, 2006a; *MacCready et al.*, 1998, 2006]. Nappe formation was accompanied by the development of upright folding in the frontal crumple zone of the nappe [*Giles et al.*, 2006a] or as large anticlinal culminations above thrust ramps [*O'Dea et al.*, 2006]. U-Pb SHRIMP studies indicate an episode of syndeformational metamorphic zircon and monazite growth at ~1585–1580 Ma [*Giles and Nutman*, 2002, 2003; *Page and Sun*, 1998; *Rubenach et al.*, 2008], although recent geochronology analysis (EPMA and SHRIMP) of metamorphic monazite suggest slightly older ages between 1600 and 1630 Ma [*Rubenach et al.*, 2008] (Figure 10), similar to ages determined in the southern Curnamona Province [*Forbes et al.*, 2007].

[22] The Georgetown, Coen, Yambo, and Dargalong inliers in far northeast Queensland (Figure 1) record an orogenic evolution between circa 1625 and 1500 Ma (Figure 10) [*Black et al.*, 1979; *Cihan et al.*, 2006; *Hills*, 2004; *Withnall*, 1996]. Within the amphibolite facies rocks of the eastern parts of the Georgetown Inlier [*Davis*, 1996; *Withnall*, 1996] north-south shortening during the Jana Orogeny (Figure 10) resulted in development of mesoscale recumbent to shallowly inclined isoclinal folds with ~east-west trending axial traces. The timing of deformation is constrained by a Rb-Sr total rock isochron which yielded an age of 1570 ± 20 Ma [*Black et al.*, 1979]. This is indistinguishable from the circa 1585 Ma SHRIMP U-Pb age of metamorphic zircons in the adjacent Dargalong and Yambo inliers [*Blewett et al.*, 1998] (Figure 1). Following the Jana Orogeny, an episode of exhumation ensued in which ~12 km of upper crust was removed [*Boger and Hansen*, 2004]. Metamorphic evidence of this exhumation is preserved in the Robertson River and Einasleigh Triangle areas where andalusite replacing staurolite indicates ~4 kbar of isothermal decompression. In the western part of the Georgetown Inlier (Stockyard Creek area) sedimentary rocks of the Langlovale Group were deposited unconformably onto the metasedimentary rocks of the Upper Etheridge

Figure 10. Time-space diagram with the age and style of orogenesis throughout eastern Australian Proterozoic geological provinces [*Bell*, 1983; *Betts et al.*, 2000; *Binns*, 1964; *Blake*, 1987; *Blewett and Black*, 1998; *Blewett et al.*, 1998; *Boger and Hansen*, 2004; *Cihan et al.*, 2006; *Cihan and Parsons*, 2005; *Clark et al.*, 2006a, 2006b; 1986, 1987; *Collins and Shaw*, 1995; *Collins et al.*, 1995; *Connors and Page*, 1995; *Daly et al.*, 1998; *Davis et al.*, 2001; *De Jong and Williams*, 1995; *Etheridge and Cooper*, 1981; *Forbes and Betts*, 2004; *Forbes et al.*, 2004, 2005, 2007; *Ganne et al.*, 2005; *Gibson and Nutman*, 2004; *Gibson et al.*, 2004; *Giles et al.*, 2006a, 2006b; *Giles and Nutman*, 2002, 2003; *Hills*, 2004; *Hobbs et al.*, 1984; *Laing et al.*, 1978; *Lewthwaite*, 2001; *Lister et al.*, 1999; *Loosveld*, 1992; *MacCready*, 2006a, 2006b; *MacCready et al.*, 1998, 2006; *Marjoribanks et al.*, 1980; *McLean and Betts*, 2003; *O'Dea et al.*, 2006; *O'Dea and Lister*, 1995; *O'Dea et al.*, 1997a; *Oliver et al.*, 1998; *Foster and Rubenach*, 2006; *Page et al.*, 2005a; *Page and Laing*, 1992; *Potma and Betts*, 2006; *Raetz et al.*, 2002; *Reinhardt*, 1992; *Reinhardt and Rubenach*, 1989; *Rubenach*, 1992; *Rubenach and Barker*, 1998; *Rubenach and Lewthwaite*, 2002; *Sayab*, 2006, 2008; *Spikings et al.*, 2006; *Stevens*, 1986, 1996; *Swain et al.*, 2005; *Teasdale*, 1997; *Teyssier et al.*, 1988; *Vernon and Ransom*, 1971; *Wade et al.*, 2006; *White et al.*, 1995; *Wilson and Powell*, 2001; *Withnall*, 1996; *Withnall et al.*, 1988, 1997; K. Ehlers and A. P. Nutman, Thermochronological evolution of the Willyama Complex, paper presented at Geodynamics and Ore Deposits, Australian Geodynamic Cooperative Research Centre, Ballarat, Victoria, Australia, 1997; Hand and Rubatto, presented paper, 2002].

Subgroup in a orogenic foreland setting (Figures 9 and 10) [*Hills*, 2004]. *Cihan et al.* [2006] recognized a flat-lying foliation, which was dated at circa 1555 Ma using EPMA on monazite and interpreted to define an orogenic collapse event [*Cihan et al.*, 2006].

[23] An episode of circa 1585–1540 Ma orogenesis is recognized in the buried northern Gawler Craton (Figures 4 and 10). This event has been informally termed the "Late Kararan Orogeny" [*Betts and Giles*, 2006] or Kararan Orogeny [*Hand et al.*, 2007]. The timing of this event was constrained using U-Pb SHRIMP analysis of metamorphic zircons taken from drill hole samples in the Coober Pedy Ridge and the Mabel Creek Ridge (Figure 4) [*Daly et al.*, 1998; *Fanning et al.*, 2007; *Hand et al.*, 2007]. Interpretation of high-resolution aeromagnetic data [*Betts*, 2000] suggests that the Coober Pedy Ridge comprises iron formations, paragneisses, and calc-silicates that are refolded about an isoclinal nappe bound by east-west trending thrusts and reverse faults (Figure 4). Calc-silicates, gneisses, cherts, and banded iron formations from adjacent Mabel Creek Ridge preserve evidence for interference between tight ~east-west trending upright to inclined folds and open to tight ~north-south trending inclined to upright folds [*Betts*, 2000].

[24] A characteristic feature of the Mesoproterozoic orogenic systems of eastern Australia is the high-temperature, low- to medium-pressure metamorphic conditions in which the orogens evolved (Figure 10). The high-temperature metamorphic belt extends from as far east as the Curnamona Province and the Georgetown Inlier through to the Arunta Inlier (Figure 1). The conditions of metamorphism within individual geological terranes and provinces can be highly variable, with the highest metamorphic grades preserved in regions of highest strain and lower grades preserved in the distal hinterland of the orogens. The timing of metamorphism is restricted between circa 1595–1570 Ma. The highest metamorphic conditions occurred in the northern Gawler Craton where granulite facies conditions (900°C and 9 kbar) are preserved within the Coober Pedy Ridge [*Daly et al.*, 1998]. High-temperature metamorphism also affected the western Gawler Craton and the Mount Woods Inlier [*Payne et al.*, 2008; *Skirrow et al.*, 2006; *Teasdale*, 1997] (Figure 4). In the southern Reynolds Ranges granulite facies metamorphism (750–800°C and 4.5–5 kbar) occurred during the circa 1610–1570 Ma Chewings Orogeny [*Collins and Shaw*, 1995; *Rubatto et al.*, 2001] (Figure 10). In the Curnamona Province, circa 1600–1595 Ma [*Page et al.*, 2005a; *Page and Laing*, 1992] peak high-temperature, low- to medium-pressure [*Binns*, 1964; *Clarke et al.*, 1987; *Forbes et al.*, 2005; *Phillips and Wall*, 1981; *Powell and Downes*, 1990; *Stüwe and Ehlers*, 1997; *Vernon et al.*, 2008; *White et al.*, 1995] granulite facies metamorphism occurred in the Broken Hill Domain (740°C and 840°C; ~5–7 kbar) [*Cartwright*, 1999; *Forbes et al.*, 2005; *Phillips and Wall*, 1981; *Powell and Downes*, 1990; *Vernon et al.*, 2008] but decreases to the west in the Olary Domain (~530°C; ~5 kbar)[*Clark et al.*, 2006a] (Figure 6). Toward the central part of the province where Willyama Supergroup succession buried beneath the Benagerie Volcanics are essentially unmetamorphosed [*Robertson et al.*, 1998] (Figure 6). A similar metamorphic pattern occurs in the Mount Isa Inlier where peak high-temperature, low-pressure amphibolite facies metamorphic conditions [*Giles and Nutman*, 2002, 2003; *Page and Sun*, 1998; *Rubenach et al.*, 2008; M. Hand and D. Rubatto, The scale of the thermal problem in the Mount Isa Inlier, paper presented at Australian Geological Convention, Geological Society of Australia, Adelaide, South Australia, 2002] were attained in southeastern parts of the Eastern Fold Belt at circa 1585–1580 Ma (~700°C; 4–6 kbar) [*Giles et al.*, 2006b] (Figure 7), and with the exception of a narrow belt of amphibolite facies rocks to the west of the Mount Isa Fault Zone, adjacent to the Sybella Granite (~600°C; 4 kbar) [*Foster and Rubenach*, 2006; *Rubenach*, 1992], the metamorphic grade generally decreases to greenschist [*Foster and Rubenach*, 2006; *Rubenach*, 1992] and subgreenschist facies [*Blake*, 1987] to the north and west of the inlier [*Foster and Rubenach*, 2006; *Giles et al.*, 2006b; *Rubenach et al.*, 2008] (Figure 7). In the Georgetown Inlier, circa 1580 Ma high-temperature metamorphic conditions vary from 600 to 650°C and 6–7 kbar (Roberston River area) in the west to 750–800°C and slightly higher pressures of 8–9 kbar in the east (Einsleigh area) (Figure 9) [*Boger and Hansen*, 2004] [see also *Cihan et al.*, 2006].

[25] Extensive anatexis of upper amphibolite facies rocks [*White et al.*, 2005, 2004] resulted in the emplacement of circa 1590–1580 Ma [*Cook and Ashley*, 1992; *Ludwig and Cooper*, 1984; *Page et al.*, 2005a] S-type Bimbowrie Suite (Olary Domain) [*Fricke*, 2006; K. Stewart and J. Foden, unpublished report, 2001] and Mundi Mundi Suite (Broken Hill Domain) granites [*Raveggi et al.*, 2008; *Stevens*, 1986] (Figure 6) and the eruption and emplacement of the S-type granites of the Forsayth and Esmeralda supersuites, and subaerial rhyolites to dacitic ignimbrites of the Croydon Volcanics (circa 1560–1545 Ma) in the Georgetown Inlier [*Withnall et al.*, 1996, 1997] (Figures 2 and 9). Sm-Nd isotopic analysis for the S-type granites in the Curnamona Province ($\varepsilon\mathrm{Nd}_{(1580)}$: between −2.1 and −8.6) [*Raveggi et al.*, 2008; K. Barovich and M. Hand, A geochemical and isotopic perspective on the early development of the Willyama Supergroup, Curnamona Province, paper presented at 17th Australian Geological Convention, Geological Society of Australia, Hobart, Tasmania, Austraila, 2004] suggest they are derived from the Willyama Supergroup, which have similar $\varepsilon\mathrm{Nd}_{(1580)}$ values (K. Stewart and J. Foden, unpublished report, 2001; Barovich and Hand, presented paper, 2004) (Figure 2). The S-type magmas in the Georgetown Inlier area characterized by negative $\varepsilon\mathrm{Nd}_{(1550)}$ values (−1.9: Croydon Volcanics, −2.4: Esmeralda Suite; −3.1 to −4.5: Forsyth Supersuite) and depleted mantle model age (T_{DM}) between 2000 and 2210 [*Black and McCulloch*, 1990] (Figure 2), and have been interpreted to be derived from the metamorphic pile, particularly the biotite and calc-silicate gneiss in the Einsleigh metamorphics [*Champion*, 1991].

[26] Inferred tectonic drivers for high-temperature metamorphism include emplacement of large volumes of tholeiitic magmas into the lower crust and advective heat transport [*Foster and Rubenach*, 2006], radiogenic heating

of older high heat-producing granites in the upper crust and subsequent burial by thermally insulating sediments [*McLaren et al.*, 1999], and preorogenic lithospheric extension and associated elevated geothermal gradients [*Forbes et al.*, 2005, 2007, 2008; *Gibson et al.*, 2008; *O'Dea et al.*, 2006]. Preorogenic crustal extension is an appealing thermal driver because it is the process that best explains how high-temperature metamorphism affected large areas of central and eastern Australia, although there may have been local contributions to the thermal budget. There are several important observations that support inheritance of the high-temperature metamorphic conditions leading to circa 1600–1570 Ma crustal shortening. In the Georgetown Inlier, peak metamorphic isograds are folded about the earliest generation east-west folds [*Reinhardt and Rubenach*, 1989] (Figure 9), suggesting that orogenesis occurred post-peak to late peak metamorphism. This interpretation is supported by circa 1625 Ma EPMA geochronology of monazites preserved as inclusion trails of metamorphic porphyroblasts [*Cihan et al.*, 2006]. U-Pb SHRIMP ages of metamorphic monazite armoured by peak metamorphic garnet and K-feldspar porphyroblasts yielded an age of 1620 ± 7 Ma [*Forbes et al.*, 2007]. This age is interpreted as the timing of prograde amphibolite metamorphism within the southern Broken Hill Block (M1 event of *Forbes et al.* [2004, 2005]). *Forbes et al.* [2008] interpreted the circa 1620 Ma event to be associated with transient midcrustal extension that maintained already elevated geothermal gradients inherited from an earlier extensional event(s) (possibly rifting associated with deposition of the Willyama Supergroup) [*Gibson and Nutman*, 2004; *Gibson et al.*, 2004]. In the Eastern Fold Belt basin inversion [*Blenkinsop et al.*, 2008; *Giles et al.*, 2006a; *O'Dea et al.*, 2006] resulted in younger, hotter rocks being thrust over older, colder rocks along an east dipping thrust(s) [*O'Dea et al.*, 2006]. The higher metamorphic grades in the younger successions are interpreted to reflect thrusting of sedimentary successions from deeper crustal levels, and elevated geothermal gradients caused by lithospheric thinning and a regional heat source such as mafic intrusions or an underplate. In this context, the elevated temperatures in the hanging walls of major thrusts resulted from preorogenic heating, rather than as a direct consequence of orogenesis [*O'Dea et al.*, 2006].

[27] Several tectonic models have proposed an additional convergent margin along the eastern edge of the Mesoproterozoic Australian continent [*Betts and Giles*, 2006; *Betts et al.*, 2003; *Betts et al.*, 2002, 2006; *Boger and Hansen*, 2004; *Gibson et al.*, 2008; *MacCready et al.*, 1998, 2006]. The exact position of the margin is poorly resolved, although the presence of arc-related magmatism in the Georgetown Inlier at circa 1555 Ma (Forest Home Suite) [*Champion*, 1991] (Figure 2) suggests it was located further to the east. The major defining characteristic of this margin is the 90° shift to east-west regional crustal shortening and change in the mode of shortening to thick-skinned deformation that produced upright folding and reverse faulting in the Mount Isa Inlier [*Betts et al.*, 2000; *Blenkinsop et al.*, 2008; *MacCready et al.*, 1998; *O'Dea et al.*, 2006] and the Georgetown Inlier [*Blewett and Black*, 1998; *Withnall*, 1996; *Withnall et al.*, 1988]. In the Georgetown Inlier, this orogenic event is termed the Waruna Orogeny [*Cihan et al.*, 2006; *Hills*, 2004]. This orogeny postdates the Croydon Volcanics and Langlovale Group (Figure 9), which were deposited unconformably onto the metasedimentary rocks deformed during the Jana Orogeny (Figure 10) [*Hills*, 2004]. The Waruna Orogeny is characterized by the development of open to locally isoclinal upright folds [*Blewett and Black*, 1998; *Withnall*, 1996; *Withnall et al.*, 1988], dome and basin fold interference patterns, and retrograde metamorphism [*Bell and Rubenach*, 1983; *Reinhardt and Rubenach*, 1989]. The timing of deformation is constrained between circa 1542 Ma and circa 1530 Ma using EPMA geochronology of monazite [*Cihan et al.*, 2006] and U-Pb SHRIMP geochronology of pegmatite emplaced during semibrittle deformation [*Hills*, 2004] (Figure 10).

[28] Steeply dipping tectonic fabrics [*De Jong and Williams*, 1995] developed in the circa 1545 Ma Marramungi Granite [*Page and Sun*, 1998] (Figure 2) provide the maximum age for thick-skinned deformation in the Mount Isa Inlier (Figure 7). In the southern Curnamona Province postpeak metamorphic deformation is characterized by development of upright to steeply inclined folds with north to northeast trending axial traces during retrograde metamorphic conditions [*Forbes and Betts*, 2004](Figure 10). Chemical dating of syndeformational monazite, indicates that deformation continued after 1590 Ma and may have lasted until at least circa 1550 Ma [*Rutherford et al.*, 2007]. This places thick-skinned deformation contemporaneous with the Georgetown and Mount Isa inlier, suggesting that together they may have formed the distal hinterland of orogenic system located east of the Georgetown Inlier and Curnamona Province.

3. Plume-Modified Orogenesis

[29] In this section we propose an alternative hybrid plume modified orogenic model to explain the tectonic evolution of the Mesoproterozoic eastern and central Australia. This model considers the elements of the plume and plate margin interpretations and the temporal variation in tectonic events. We also advocate the *Giles et al.* [2004] tectonic reconstruction of Australia at 1600 Ma, in which there is a 52° counterclockwise rotation of the Gawler Craton relative to the North Australian Craton [see also *Wingate and Evans*, 2003]. The salient temporal and spatial geological observations (Figures 2 and 10) used to constrain the plume modified orogenic model include (1) the presence of circa 1620–1610 Ma juvenile arc magmatism of the St. Peter Suite along the southern margin of the Gawler Craton and the unusual nonlinear or sublinear distribution of this suite, (2) the cessation of plate margin-related magmatism at circa 1610 Ma and a transition to intraplate style magmatism throughout the Gawler Craton at circa 1595–1575 Ma with a 10–15 Ma magmatic hiatus in between, (3) the onset of far-field orogenesis up to 2000 km into the continental interior at circa 1610–1590 Ma, (4) the voluminous postorogenic igneous flare-up characterized by dominantly felsic volcanism and granite emplacement (Hiltaba

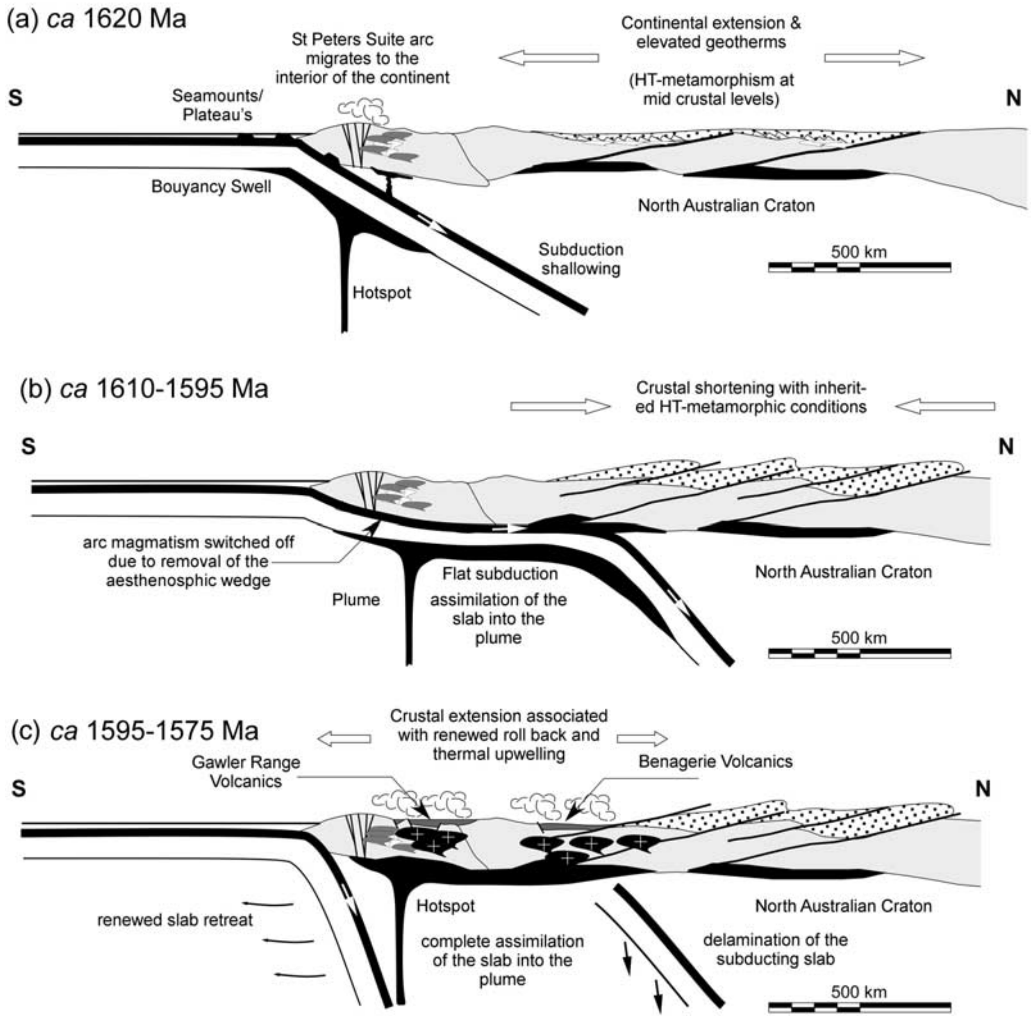

Figure 11. Tectonic cross sections through the Gawler Craton and southern North Australian Craton illustrating the tectonic evolution between circa 1620 Ma and 1575 Ma. (a) Migration of the juvenile arc-related magmas of the circa 1620 Ma St Peter Suite toward the interior of the upper plate caused by the onset of flat subduction associated plume impingement on the subducting slab. (b) Circa 1610–1590 Ma flat subduction and coupling of oceanic lithosphere and continental lithosphere as the subduction hinge migrates over the mantle plume. The resultant orogenesis is focused along thermally weakened crust in the continental back arc regions of the North Australian Craton. (c) Assimilation of the slab with the mantle plume resulting in slab delamination and the onset of renewed extension. The mantle plume interacts with the continental lithosphere resulting in mafic underplating, crustal melting and voluminous circa 1595–1590 Ma volcanism (Gawler Range Volcanics) and circa 1590–1575 Ma emplacement of A-type granite throughout the Gawler Craton and the Curnamona Province.

Event) following a major episode of north-south directed shortening in the Curnamona Province, (5) the geochemical signature of magmas emplaced during the Hiltaba Event, which reflects interaction between continental lithosphere and a mantle plume or hot spot (K. Stewart and J. Foden, unpublished report, 2001), and the spatial and temporal distribution of A-type magmas that indicates a hot spot track from the Gawler Craton to the Mount Isa Inlier [*Betts et al.*, 2007], (6) the trajectory of the hot spot train being orthogonal to the interpreted plate margin, and (7) the presence of circa 1550 Ma arc-related magmatism reworked in the Musgravian Orogen [*Wade et al.*, 2006].

[30] We suggest that the sequence of geological events and the spatial distribution of these events can be explained by plume-modified orogenesis [*Dalziel et al.*, 2000; *Murphy et al.*, 1998; *Oppliger et al.*, 1997; *Xue and Allen*, 2007] (Figure 11), in which a north to northeast dipping subduction zone either migrated over an oceanic plume (during roll back), or a mantle plume arrived beneath a subducting slab at circa 1620–1610 Ma along the margin (or just outboard)

of the Gawler Craton. There is insufficient data to distinguish between these subtly different models; nevertheless the tectonic response in the overriding plate would essentially be the same.

[31] Our interpretation is that that arc magmas of the St Peter Suite formed throughout the southern margin of the currently exposed Gawler Craton during north dipping subduction (Figure 11a). However, the geometry of the arc is atypical, as it not narrow and linear but is preserved as an irregular trapezium bounded by faults that active subsequent to the arc formation [*Fraser and Lyons*, 2006; *McLean and Betts*, 2003; *Swain et al.*, 2005] (Figure 4). We attribute the geometry of the St Peter Suite arc to a combination of factors including: dismembering of the arc by subsequent faulting [*Direen et al.*, 2005; *Fraser and Lyons*, 2006]; and arc migration toward the interior of the continent. Such arc migrations on the modern Earth are often associated with flat subduction, which can be caused by subduction of buoyant oceanic lithosphere [*van Hunen et al.*, 2002]; rapid motion of the upper plate, which overrides the oceanic lithosphere faster than the slab can sink [*Cross and Pilger*, 1982]; subduction of young, buoyant or thickened oceanic lithosphere [*Cloos*, 1993]; and interaction between a subducting slab and a mantle hot spot (plume-modified subduction) [*Dalziel et al.*, 2000; *Murphy et al.*, 1998]. For plume-modified subduction the buoyancy of the oceanic lithosphere is increased by the interaction with a mantle hot spot [*Sleep*, 1990], particularly if oceanic plateaus, seamounts, or buoyancy swells [*Murphy et al.*, 1998] predispose the oceanic lithosphere for flat subduction (i.e., increase lithosphere buoyancy) (Figure 11a). Of all these options, the plume-modified subduction is most likely to result in the curvilinear arc geometry displayed by the St Peter Suite (Figure 12) because plume heads and hot spots increase the buoyancy along small segments of the slab and thus arc migration toward the interior of the continent is relatively local (Figures 12a and 12b).

[32] The cessation of arc magmatism at circa 1610 Ma defined the beginning of a 10–15 Ma period of amagmatism in the Gawler Craton. We interpret this hiatus to record continued flattening of the slab beneath the Gawler Craton and greater coupling between the downgoing and upper plates [*Gutscher*, 2002], forming a temporary insulating lid that refrigerated the crust and removed the asthenospheric wedge [*Haschke et al.*, 2002], inhibiting or even completely prevented further decompressive melting [*Murphy et al.*, 1998], and eventually switching off arc magmatism (Figure 11b). In a plume-modified orogenic setting this amagmatic zone may have been relatively narrow (~500–1000 km), with its size determined by the width of the slab buoyancy swell and the size of the plume head (see Figure 11b). Away from the swell and the plume head, the dip of the slab may have gradually steepened or a tear in the slab may have developed to accommodate differential buoyancy of the slab (Figure 12a). In either scenario it is possible that contemporaneous arc magmatism may have occurred on either side of the amagmatic zone in the southern Gawler Craton.

[33] The (circa 1600–1595 Ma) orogenic evolution of eastern and central Australia is interpreted to record the distal effects of extremely flat subduction and coupling between the downgoing and upper plates [*Gutscher*, 2002], which in Tertiary examples has been shown to lead to stress transfer through the overriding plate that was sufficient enough to drive orogenesis several thousand kilometers inboard of the plate margin (e.g., Laramide Orogeny [*Murphy et al.*, 1998]). Orogenesis is characterized by north directed crustal shortening associated with high-temperature, low-pressure metamorphism throughout the North Australian Craton up to 2000 km inboard of the inferred plate margin [*Betts et al.*, 2006; *Collins et al.*, 1995; *Forbes and Betts*, 2004; *Forbes et al.*, 2004; *Gibson and Nutman*, 2004; *Giles et al.*, 2006b; *MacCready et al.*, 1998, 2006; *O'Dea et al.*, 2006]. Strain was heterogeneously distributed and focused in thermally weakened regions of elevated heat flow (e.g., Mount Isa Inlier, southern Curnamona Province), possibly inherited from a previous history of back-arc lithospheric extension (Figures 11a and 11b) [*Betts et al.*, 2003; *Forbes et al.*, 2007; *Giles et al.*, 2002; *O'Dea et al.*, 2006] and/or distribution of high heat-producing granites [*Hand et al.*, 1999; *McLaren et al.*, 1999; *McLaren and Sandiford*, 2001; *McLaren et al.*, 2005]. In contrast, within the cooler and more refractory lithosphere of the Gawler Craton deformation was discrete and focused along major shear zones [*Ferris et al.*, 2002; *McLean and Betts*, 2003]; 1610–1595 Ma is interpreted as a period of incubation of the plume beneath the subducting oceanic lithosphere and the Gawler Craton continental lithosphere. Such incubations last between 20 and 40 Ma [*Oppliger et al.*, 1997] (Figure 11c), comparable to the 1610–1595 Ma magmatic gap in the Gawler Craton. Incubation of the plume may have led to thermal uplift and doming of the Gawler lithosphere, thus explaining the depositional hiatus throughout the Gawler Craton during this interval.

[34] Thermally assimilation or erosion of the subducting slab eventually resulted in the plume interacting with the Gawler Craton continental lithosphere (Figure 11c). Relatively dense portions of the subducting slab on either side of the plume head delaminated from the continental lithosphere and coupling between the slab and the overriding plate diminished. Roll-back of the subducting slab led to the resumption of arc magmatism along the plate margin. We suggest that the along strike remnants of this arc includes the 1590–1550 Ma arc-related orthogneisses preserved throughout the Musgrave Province [*Wade et al.*, 2006] (Figure 12b). Roll-back also caused a switch from a compressional to a tensional stress regime in the overriding plate (Figure 11c). The temporal overlap between age of emplacement Hiltaba Granite Suite and high-temperature metamorphism throughout the Gawler Craton have contributed to interpretations that the magmatism occurred during crustal shortening [*Direen and Lyons*, 2007; *Drummond et al.*, 2006; *Hand et al.*, 2007; *Payne et al.*, 2008]. However, there are several lines of evidence that support extension during Hiltaba Granite Suite and Gawler Range Volcanic magmatism. *McLean and Betts* [2003] used kinematics of syn-Hiltaba faults (e.g., Yerda Shear Zone) to propose an ENE-WSW extension direction (present-day coordinates) during the emplacement of the Hiltaba Granite Suite in

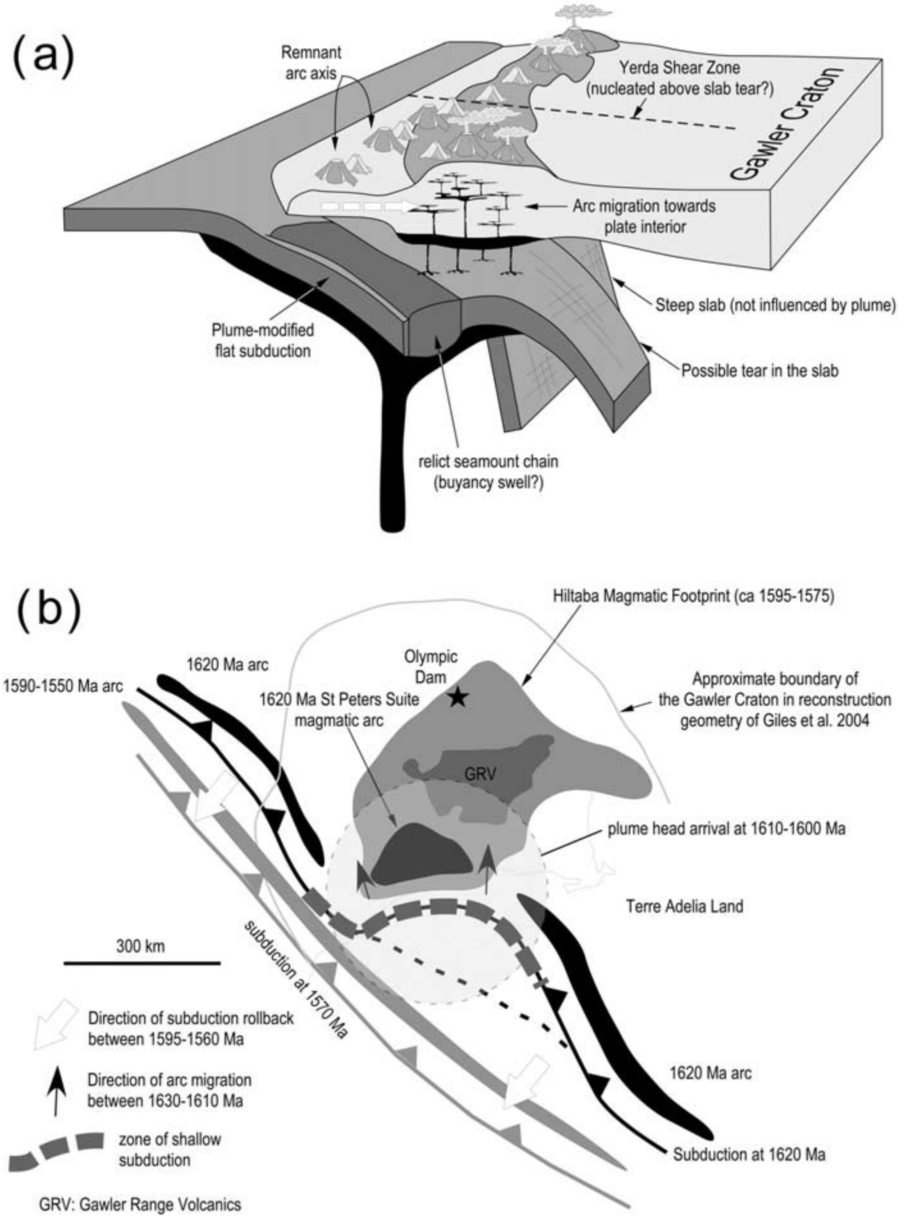

Figure 12. (a) Three-dimensional diagram showing the architecture the slab during plume modified flat subduction and the change in the architecture of the magmatic arc. (b) Schematic diagram showing the relationship between the St Peter Suite magmatism and the arc-related magmatism, which is now reworked in the Musgravian Orogeny. The preserved record of the St Peter Suite records the location of the arrival of the plume and the migration of the arc toward the plate interior as a result of slab flattening.

the central Gawler Craton. This interpretation is supported by forward modeling of the Gawler Range Volcanics [*Direen and Lyons*, 2007], which shows several kilometers of normal offset, and regional seismic data in the eastern Gawler Craton suggesting normal offset of the Moho across east dipping crustal-scale structure [*Drummond et al.*, 2006]. *Rutherford et al.* [2007] also propose an extensional tectonic regime for the Curnamona Province at circa 1585 Ma following the Olarian Orogeny. During extension the base of the Gawler Craton continental lithosphere would have been exposed to hot upwelling mantle and the switch to extension may have promoted decompressive melting of the asthenosphere, causing mafic underplating above the plume head [e.g., *Murphy et al.*, 1998]. Forward modeling of Bouguer gravity data suggests the presence of a ~5 km thick, high-density (~3.0 g/cm^3) sheet at a depth of ~35–40 km beneath the Gawler Range Volcanics [*Huynh et al.*, 2001], which may be a relict underplate associated with decompressive melting.

[35] Voluminous felsic magmatism resulted from fractionation of mantle melts and the partial melting of the lower crust [*Creaser and White*, 1991; *Daly et al.*, 1998;

Giles, 1988; K. Stewart and J. Foden, unpublished report, 2001]. A mantle component for the magmas is supported isotopically with both the uncontaminated end-member felsic and mafic parts of the system trending toward juvenile isotopic compositions as indicated by $\varepsilon_{Nd(i)}$ values of +2 to +3 (K. Stewart and J. Foden, unpublished report, 2001). The size of the magmatic system ($\sim$320,000 km^2) was enormous, with magmas emplaced and erupted over an area of and forming a large subcircular felsic igneous province $\sim$500 km in diameter (Figure 4). It is likely that large volumes were also emplaced at deeper crustal levels (J. Foden and K. P. Stewart, The South Australian Mesoproterozoic Gawler Range Volcanics-Hiltaba Granite felsic large igneous province: Reflecting a cryptic, lower crustal, flood basalt province, paper presented at Australian Earth Science Convention, Australian Society of Exploration Geophysicists, Melbourne, Victoria, Australia, 2–6 July 2006). Individual magmas systems such as the 25,000 km^3 upper Gawler Range Volcanics were erupted over a relatively short time (1–5 Ma), requiring a large melt flux from a large volume parental mafic source. The unusually elevated temperatures (950–1150°C) and the high halogen (F, Cl) content of the magmas contributed to the high melt flux by lowering the viscosity of the felsic melts.

[36] Subsequent 1580–1540 Ma orogenesis and associated high-temperature metamorphism ensued in the northern Gawler Craton [*Hand et al.*, 2007; *Payne et al.*, 2008]. Orogenesis has been interpreted to reflect the accretion of marginal terranes of the northern Gawler Craton (e.g., Coompana Block) [*Betts and Giles*, 2006], although recent work suggests that the marginal crustal domains, such as the Nawa terrane (Figure 4), have a similar circa 1740–1690 Ma orogenic evolution as the interior of the Gawler Craton [*Payne et al.*, 2006]. This relationship suggests either the mobile belts in the northern Gawler are intraplate in origin, or are ribbons of Gawler continental lithosphere reaccreted onto the Gawler Craton margin after the circa 1740–1690 Ma Kimban Orogeny [*Hoek and Schaefer*, 1998; *Tong et al.*, 2004; *Vassallo and Wilson*, 2001, 2002]. In the later scenario, accretion must predate circa 1550 Ma arc magmatism now preserved in the Musgrave Province [*Wade et al.*, 2006].

[37] Following the initial magmatic flare-up throughout the Gawler Craton, eastern Australia migrated progressively to the south resulting in A-type magma emplacement over large areas of the central and northern Curnamona Province (1575–1555 Ma) and eastern Mount Isa Inlier (circa 1550–1500 Ma). This slightly arcuate magmatic belt (in the reconstruction space of *Giles et al.* [2004]) is interpreted as a hot spot track [*Betts et al.*, 2007] (Figure 3). The central and northern segments of the circa 1600–1500 Ma hot spot track was developed on an overthickened lithosphere following orogenesis. This may have inhibited adiabatic melting of the plume, increased magma ponding in the lower crust, and enhanced crustal melting and A-type granite genesis [*Betts et al.*, 2007].

[38] Contemporaneous with the development of this hot spot track, Proterozoic terranes of eastern Australia underwent renewed orogenesis involving an approximately 90° switch in the regional shortening direction [*Betts et al.*, 2006; *Boger and Hansen*, 2004; *Cihan et al.*, 2006; *Rutherford et al.*, 2007]. *Betts and Giles* [2006] proposed that the switch in the regional shortening direction was caused by ocean closure to the east of the Australian continent and collision between Australia and Laurentia [*Betts et al.*, 2002]. The prevalence of upright folds and reverse faulting along steep faults [*Blenkinsop et al.*, 2008; *Cihan et al.*, 2006; *Giles et al.*, 2006b; *MacCready*, 2006a; *MacCready et al.*, 1998; *O'Dea et al.*, 2006; *Sayab*, 2006, 2008] suggests that the Mount Isa and Georgetown inliers were relatively distal to the plate margin and the margin did not interact with the plume.

4. Comparisons With Modern Analogs

[39] Plume-modified orogenesis is rarely documented but is more common than usually appreciated. For example, global tomography data sets in active convergent margins show hot spots rising beneath subducting slabs [*Abdelwahed and Zhao*, 2007; *Xue and Allen*, 2007; *Zhao*, 2004; *Zhao et al.*, 2007]. In the ancient geological past the crustal signature of such a setting may be cryptic as neither the subduction zone, nor the magmatic signal of the plume-lithosphere interaction, have an obvious geological response. For example, flat subduction caused by the buoyancy influence of the plume may switch-off arc magmatism. Typical magmatic responses to plumes such as continental flood basalts and radial dyke arrays may not develop because of the insulating effect of the slab lid, and because the plume is less likely to undergo adiabatic melting due to it interacting with a thickened continental lithosphere. It is therefore not surprising that modern analogs of the plume-modified tectonic setting appear rare in the geological record. Nevertheless, examples of plume-modified orogenesis have been interpreted for the voluminous outpourings of the Karoo-Ferrar large igneous province developed adjacent to the middle Jurassic convergent margin of Gondwana [*Dalziel et al.*, 2000]. The convergent plate margin of Gondwana is characterized by a gap in arc magmatism and a period of tectonic quiescence, during which time stresses at the plate margin were transmitted into the interior of the continent resulting in intraplate orogenesis (Gondwanide Orogeny [*Dalziel et al.*, 2000]) driven by flat subduction [*Lock*, 1980]. These characteristics are similar to those interpreted in the Gawler Craton. The difference lies in the style of magmatism. The Karoo-Ferrar large igneous province is dominated by outpourings of mafic igneous rocks rather than felsic rocks, which suggests that adiabatic melting of the plume head may have had a more important role at the Gondwanan margin. *Murphy et al.* [1998, 2003] proposed that the Tertiary Laramide Orogeny may have been driven by the interaction of the Yellowstone Hot spot and the subducting Kula and/or Farallon plate. Subduction of the associated buoyancy swell resulted in flat subduction associated with a hiatus in arc magmatism and the onset of the Laramide Orogeny, in which deformation propagated approximately 1200 km into the continent interior [*Murphy et al.*, 1998]. The resumption of normal angle subduction

resulted in several pulses of extension in the overriding plate and voluminous outpourings of felsic magmatism [*Gans et al.*, 1989], similar to the switch in tectonic mode and change in magmatic style that is recorded by the Hiltaba Event. Other similarities between the Gawler Craton and the Yellowstone-Laramide tectonic system is the trajectory of the hot spot track at a high angle to the plate margin, narrowing of the plume track toward the continent interior, and the preponderance of silicic magmatism to define the hot spot track, particularly as the hot spot evolved through time [*Nash et al.*, 2006].

5. Discussion

[40] The onset of the Mesoproterozoic evolution (1600–1500 Ma) of the Australian continent represents one of the most significant tectonic periods for evolution of the continent. The extent and duration makes it the largest Mesoproterozoic tectonic and thermal event, and one of the largest thermal events in the entire history of the Australian continent [*Betts et al.*, 2002]. Tectonic activity spanned more than 100 Ma and impacted on more than a third of the Precambrian continent. Sizable base metal mineral systems were created [*Betts et al.*, 2006; *Gow et al.*, 1994; *Hand et al.*, 2007; *Mark et al.*, 2006; *Skirrow et al.*, 2006], in which a belt of Iron Oxide Cu-Au mineralization extended from Gawler Craton to the Mount Isa Inlier. Despite the vast amount of research focused on understanding the Mesoproterozoic evolution of eastern and central Australia, there remains a lack of consensus of the tectonic settings operating at the time and Australia's place in a global tectonic setting. Difficulties have arisen in determining the tectonic setting because the geological history of eastern Precambrian Australia is complex, protracted, and the rock record is sparse and discontinuous. As a result, numerous tectonic models and plate tectonic geometries have been proposed, particularly between circa 1620 and 1560 Ma, to explain one or more important critical geological observations. These tectonic models involve either plate margin processes (such as subduction) or plume-related processes. These processes have very different tectonic drivers and are biased by the geological observations of specific studies (e.g., arc magmatism results in the development of a plate margin model). Neither plate margin nor plume-related processes need to be independent of one another. In this section we critically assess how the various tectonic models for eastern Mesoproterozoic Australia between circa 1620 and 1560 Ma measure against geological observations and data.

[41] Plume-related models have been suggested by *Giles* [1988], K. Stewart and J. Foden (unpublished report, 2001), and *Flint* [1993]. These models have largely been developed for the Gawler Craton and are biased by the relatively short time frame of magma emplacement and the large melt flux (K. Stewart and J. Foden, unpublished report, 2001), isotopic trends toward juvenile isotopic compositions (K. Stewart and J. Foden, unpublished report, 2001), and the size and subcircular extent of the magmatic system [*Betts et al.*, 2007]. The magmatic signature of the plume is unusual in that it is dominated by felsic melt (>90%). The absence of voluminous flood basalts and radial dyke arrays produced when a plume impinges on continental lithosphere is attributed to a lack of lithospheric extension and adiabatic melting of the plume head (Foden and Stewart, presented paper, 2006). Rather, mafic melts ponded in the lower crust, increasing interaction between mafic melts and the crust, and promoting silicic melting. *Betts et al.* [2007] expanded on the plume model and incorporated A-type granites and volcanic rocks from the Curnamona Province and the Mount Isa Inlier as part of a larger hot spot track. As a stand alone tectonic model, plume tectonics does not provide a mechanism for the crustal shortening prevalent throughout eastern Australia, nor does it consider the timing and distribution of arc magmatism.

[42] Many of the plate margin models are inadequate in their explanation of geodynamic process and timing of geological event. Two related plate margin models by *Wade et al.* [2006] and *Swain et al.* [2008] suggested plate margin architectures based on the interpreted position of arc magmatic provinces on either side of the Gawler Craton. *Wade et al.* [2006] proposed a south dipping subduction zone beneath the Gawler Craton and a circa 1590–1550 Ma intraoceanic island arc province located outboard of the northern margin of the Gawler Craton. Collision between the Gawler Craton (Mawson continent) and the North Australia Craton occurred presumably after the cessation of arc magmatism (1550 Ma). This model implies that the North Australian Craton and the Gawler Craton were disconnected until they were amalgamated at circa 1550 Ma and assumes that the present-day configuration of the Australian continent was valid at circa 1590–1550 Ma. This model most obviously explains the distribution of the arc-related rock in the Musgrave Province and the preservation of circa 1580–1540 Ma deformation and metamorphism in the northern Gawler Craton (Kararan Orogeny). However, the model provides no mechanism to drive circa 1620–1580 Ma crustal shortening throughout the North Australian Craton because this orogenesis predates the proposed Gawler-North Australia collision (circa 1550 Ma), nor is there any geological evidence for deformation in the Musgrave Province between circa 1600–1550 Ma, despite it occupying a continent-continent collision suture zone. *Swain et al.* [2008] expanded on the *Wade et al.* [2006] model and proposed an additional south dipping subduction zone separating the southern Gawler Craton from East Antarctica. In this model the St Peter Suite arc developed along the northern margin of East Antarctica and was accreted to the Gawler Craton during circa 1610 Ma collision between the East Antarctica and Gawler Craton. This models potentially explains the distribution of the St Peter Suite arc and provides a tectonic driver for north-south crustal shortening associated with circa 1610–1600 Ma orogenesis in the South Australian Craton. The model ignores evidence for geological contiguity between the southern Gawler Craton and East Antarctica between circa 2450 and 1600 Ma [*Ménot et al.*, 2005; *Oliver and Fanning*, 1997; *Peucat et al.*, 2002]. An implication of the *Swain et al.* [2008] model is a suture zone must have formed in the

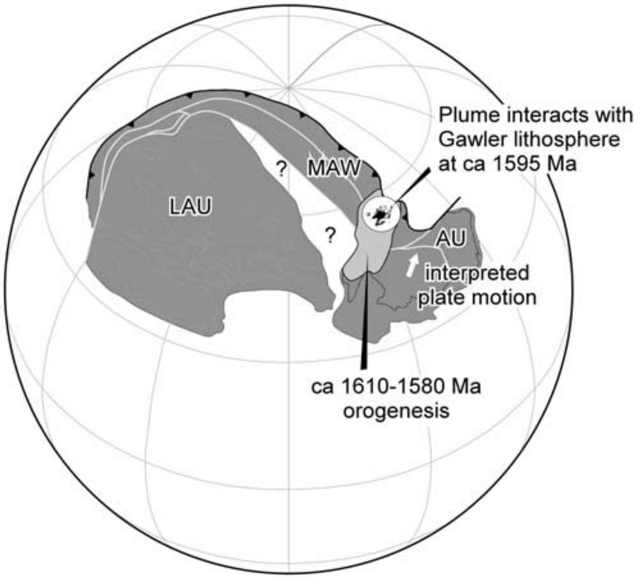

Figure 13. Modified SWEAT reconstruction showing the distribution of orogenesis associated with plume modified subduction. No requirement for orogenesis or thermal perturbation elsewhere along the plate margin is shown. MAW, Mawson continent; AU, Australia; LAU, Laurentia.

proximity to the present-day Yerda shear zone (Figure 4). There is little supporting evidence for this suture as structural analysis indicates dextral strike-slip movement during the emplacement of the circa 1595–1575 Ma Hiltaba Granite Suite [*Chalmers et al.*, 2007].

[43] *Swain et al.* [2008] and *Wade et al.* [2006] consider the circa 1595–1575 Ma intraplate A-type magmatism prevalent throughout the Gawler Craton were emplaced in response to continental back-arc extension, similar to Mesoproterozoic examples from Laurentia [*Menuge et al.*, 2002] and Baltica [*Ahäll et al.*, 2000]. In these examples, A-type granite belts formed parallel with the plate margin and are characterized by discretely aged belts parallel with the plate margin [*Ahäll et al.*, 2000], whereas eastern Australia A-type magmas form a belt at a high angle to the inferred circa 1620 Ma plate margin. The circular distribution of the Hiltaba/Gawler Range Volcanic province is more consistent with that expected from a plume interacting with continental lithosphere, whereas a linear distribution is more likely in a back-arc region. Adiabatic melting of lithospheric mantle due to continental back-arc extension could generate A-type felsic melts [*Menuge et al.*, 2002]. However, the relatively cold and refractory Gawler Craton lithosphere at circa 1600 Ma is unlikely to produce the elevated eruption temperatures for the Gawler Range Volcanics or the melt flux required for such large volume magma, although if the subducting lithosphere was relatively young (as implied in the *Wade et al.* [2006] model), heat flow beneath the Gawler Craton may have been slightly elevated [*Kukacka and Matyska*, 2008]. *Hand et al.* [2007] and *Payne et al.* [2008] used the temporal overlap between circa 1595–1575 Ma A-type magmatism throughout the Gawler Craton and circa 1600–1590 Ma orogenesis in the Curnamona Province and circa 1585–1540 Ma orogenesis in the northern Gawler Craton to propose that magmatism occurred in a back-arc setting that was experiencing bulk compression. Tectonic drivers are unknown but are speculated to be either subduction shallowing or accretion of buoyant elements at the plate margin [*Hand et al.*, 2007]. This interpretation is compelling because of the temporal overlap between crustal shortening and A-type magmatism in the Gawler Craton. It is however, difficult reconcile the large melt flux associated with the Gawler Range Volcanics and Hiltaba Granite Suite with a compressional tectonic environment without input from an external heat source (e.g., slab delamination or plume).

[44] A characteristic feature of the Proterozoic evolution of the Australian interior is the protracted extensional evolution and associated basin development between circa 1800 Ma and 1600 Ma [*Betts et al.*, 1998, 1999; *Conor and Preiss*, 2008; *Gibson and Nutman*, 2004; *Gibson et al.*, 2004; *Jackson et al.*, 2000; *Rawlings*, 1999]. These basins have been interpreted to extend from the McArthur Basin (North Australian Craton) [*Southgate et al.*, 2000] to the central Gawler Craton [*Daly et al.*, 1998]. The extensional evolution is characterized by elevated heat flow, episodic magmatism, and widespread subsidence and basin development, which may have thermally preconditioned the large areas of the Australia lithosphere leading up to high-temperature orogenic evolution [*Forbes et al.*, 2008; *O'Dea et al.*, 2006]. Basin inversion appears to focus in regions of strongest thermal imprint (e.g., southern Curnamona Province and the eastern Mount Isa Inlier). However, the simple tectonic scenario of preorogenic extension followed by basin inversion fail to explain why orogenesis is restricted to a relatively narrow belt rather than along the entire plate margin (including Laurentia), nor does it explain why orogenesis extended so far into the interior of the continent. A-type magmas do not coincide with regions of elevated geothermal gradients (e.g., southern Curnamona), suggesting that they were not necessarily generated by adiabatic melting during lithosphere extension. Moreover, A-type magmas in the Curnamona Province and Mount Isa Inlier were emplaced 40–100 Ma after circa 1620 Ma lithospheric extension.

[45] Our plume-modified orogenic model overcomes many of the spatial and temporal issues that cannot be reconciled by other tectonic models proposed for the early Mesoproterozoic evolution of eastern and central Australia. The model incorporates both the data that points to a plume as well as the geochemical, metamorphic, and structural data indicative of plate margin processes. The model requires that the St Peter Suite arc was located in the in the overriding plate of a north to northeast dipping subduction zone and that arc development occurred along the southern margin of the Gawler Craton. As the plate margin interacted with the plume by either migrating over it during trench retreat (roll-back) or as the plume arrived beneath the subducting slab, in either scenario increasing slab buoyancy. Shallowing of the slab resulted in the migration of the arc

toward the interior of the Gawler Craton forming the arcuate arc geometry defined by the present-day distribution of the slab. Continued slab flattening removed the asthenospheric wedge, switching off arc magmatism (circa 1610–1600 Ma). Increased coupling of the downgoing slab and the overriding plate as a result of flat subduction drove orogenesis up to 2000 km into the continent interior (1600–1590 Ma) (e.g., Laramide Orogeny [*Murphy et al.*, 1998]). Emplacement of the Hiltaba Granite Suite and Gawler Range Volcanics (circa 1595–1575 Ma) record the interaction of the plume with the continental lithosphere following thermal assimilation with the subducting slab. The dense components of the slab on either side of the plume head delaminated, decoupling the slab from the overriding plate (Figure 11) and triggering renewed trench retreat and extension in the overriding plate. This promoted adiabatic melting of the plume head and lower crustal melting and switched-off orogenesis in continent interior. For this model to work, circa 1580–1540 Ma orogenesis in the Gawler Craton must be considered a separate orogenic event with a different tectonic driver than the Olarian, Jana, and Isan orogenies. Overprinting relationships in the northern Gawler Craton show that northwest trending faults active at circa 1590 Ma are overprinted by the leading edge of the Kararan Orogen [*Betts*, 2000]. The model also requires that the circa 1590–1550 Ma arc-related rocks preserved in the Musgrave Block [*Wade et al.*, 2006] were emplaced further along strike to the St Peter Suite and may have been part of the same evolving arc (Figure 12b). To be feasible this interpretation requires the *Giles et al.* [2004] reconstruction of the South Australian Craton (Figure 12b). Australia continued to drift to the south resulting in the development of the hot spot track in eastern Australia. Renewed orogenesis in eastern Australia probably was influenced by collision between Australian and possibly Laurentia at circa 1550–1500 Ma, resulting in a 90° shift in the regional shortening direction. During this period the plume interacted with overthickened crust continental lithosphere distal to interpreted plate margins and this contributed to the propensity of A-type magmas.

6. Laurentian Correlations

[46] Numerous plate reconstructions have been proposed for an Australia-Antarctica-Laurentia connection throughout the Paleoproterozoic [*Betts et al.*, 2008; *Giles et al.*, 2004; *Zhao et al.*, 2004] and the Late Mesoproterozoic [*Burrett and Berry*, 2000, 2002; *Karlstrom et al.*, 2001; *Wingate et al.*, 2002]. In all of these reconstructions the eastern margin of Australia is located against the western margin of Laurentia and they share a southern convergent margin. The implication of many of these reconstructions is that Australia and Laurentia should have a shared tectonic evolution and therefore the circa 1600–1500 Ma orogenesis and magmatism so prevalent throughout eastern Australia "should" be recorded in Laurentia. Correlations between the temporally poorly constrained Racklan Orogeny (preserved in the Yukon Territories of northern Canada) and the Isan Orogeny have been suggested [*Thorkelson et al.*, 2001a, 2001b], and metamorphic mineral growth and fault reactivation, dated between circa 1620 Ma and 1590 Ma, has been recognized along the southern margin of the Wyoming Craton [*Duebendorfer et al.*, 2006]. The period 1600–1500 Ma also represents a significant magmatic gap in the evolution of Laurentia [*Goodge and Vervoort*, 2006] with the onset of widespread A-type magmatism occurring at circa 1480 Ma [*Nyman et al.*, 1994]. It has been speculated that Australia and Laurentia were not connected at circa 1600 Ma [*Betts et al.*, 2003] and they collided at circa 1550 Ma [*Betts and Giles*, 2006]. Such a collision explains circa 1550–1500 Ma orogenesis in eastern Australia, and Australia's detrital zircon input into the Belt-Purcell Supergroup [*Ross et al.*, 1992; *Ross and Villeneuve*, 2003]. However, if Australia and Laurentia remained connected at the beginning of the Mesoproterozoic then a plume-modified tectonic setting for eastern Australia may explain the dearth of 1600–1500 Ma deformation and magmatism in Laurentia because stress propagation and magmatism is restricted to a relatively local segment of the convergent plate margin (in a global tectonic sense) (Figure 13). The influence of a plume on melt generation within continental lithosphere is also relatively narrow compared with the length of a plate margin in which it has interacted with. Given the local plume-related driver for orogenesis and magmatism in eastern Australia there is no requirement for global correlation of this event.

7. Conclusions

[47] The circa 1620–1500 Ma tectonic evolution of Australia involved arc-related magmatism, multiple cycles of orogenesis that switched between extensional and shortening regimes, high-temperature/low-pressure metamorphism and voluminous magmatism. It is one of the most significant periods of thermal activity in the geological evolution of Australia. The architecture and sequence of geological events for eastern Australia (circa 1620–1550 Ma) are suggested to be the result of plume-modified orogenesis, where the north subducting slab along the southern Australian plate margin interacted with an impinging plume. This was the major tectonic driver for orogenesis, and was ultimately responsible for plume related magmatism and the development of a north trending hot spot track, which is defined by the distribution of A-type magmas from the Gawler, through the Curnamona and into the Mount Isa Inlier. A plume-modified orogenic model most effectively reconciles the spatial and temporal distribution of magmatism and the timing and extent of major orogenic events. The circa 1550–1500 Ma evolution of Australia was dominantly influenced by subduction-related tectonism along the eastern plate margin. The Yellowstone Hot spot represents a modern analog to the tectonic setting proposed for the first 100 Ma evolution of Mesoproterozoic Australia.

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