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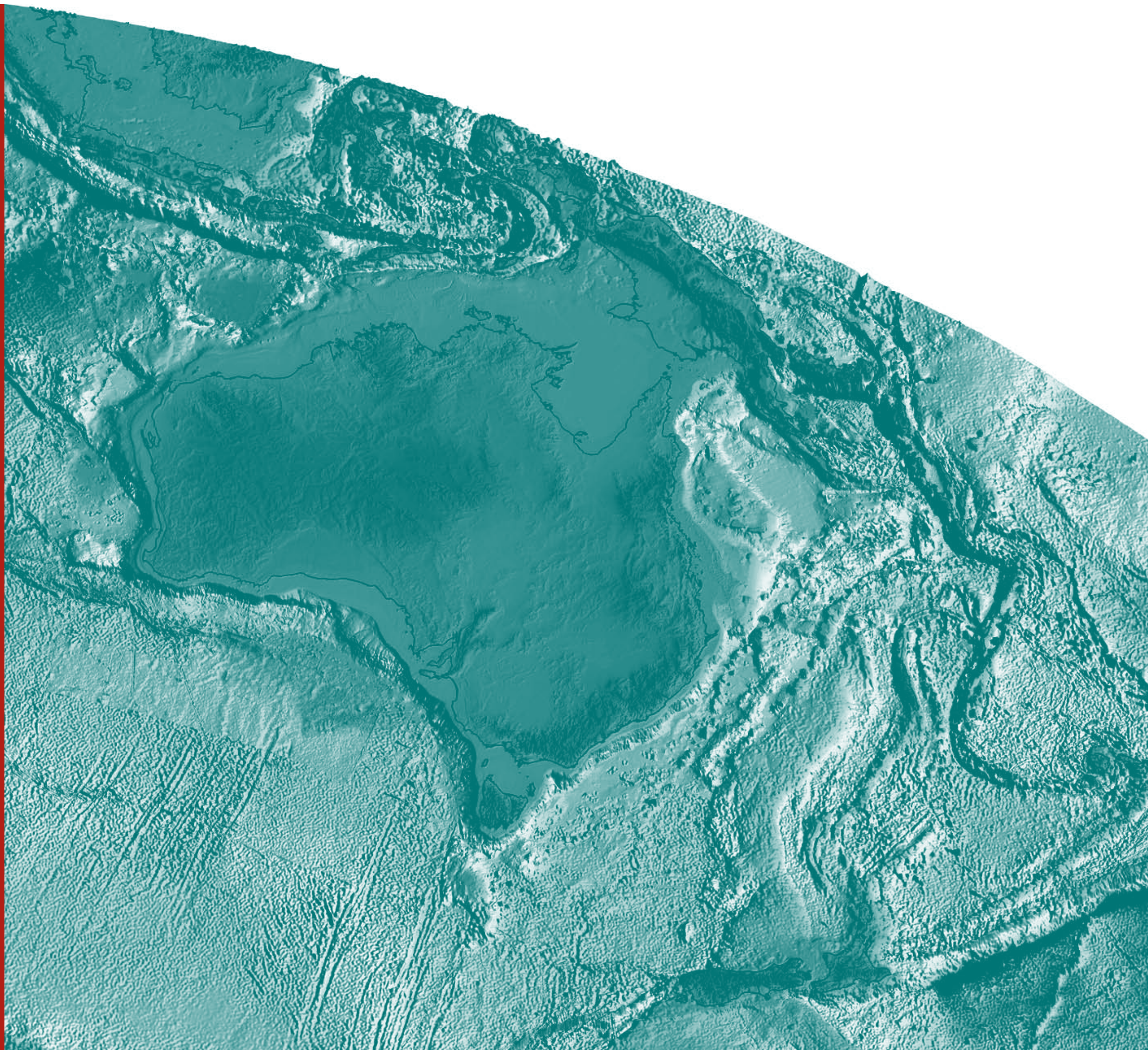

SPATIAL INFORMATION FOR THE NATION

Geodynamic and Metallogenic Evolution of Proterozoic Australia from 1870 – 1550 Ma: a discussion

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by

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Introduction

In this report, the primary motivation for considering the geodynamic evolution of Australian Proterozoic terranes arises from the premise that an understanding of geodynamic setting provides a useful guide to mineral systems that are likely to have been operative in particular regions at particular times. Our understanding of the link between mineral systems and geodynamic setting is based on the generalised syntheses of Groves et al. (2005), Kerrich et al. (2005) and Groves and Bierlein (2007) and on our understanding of mineral systems of Proterozoic Australia gained during our own studies, particularly in the North and South Australian Cratons.

This report is set out in three parts:
Part I is a review of ideas and geodynamic reconstructions for Proterozoic Australia, with discussion of the evidence underpinning these,
Part II is a summary of the metallogeny of Proterozoic mineral systems of Australia, subdivided into age intervals,
Part III presents two alternative geodynamic models at the continental scale depicting the shifting locus of geological activity across Australia through the period ~1870 – 1550 Ma, with explanatory notes. Also shown on these geodynamic models is the distribution of known mineral commodities and commodities that may be predicted on the basis of the interpreted geodynamic setting.

Much of the geological and geochronological information underpinning the construction of the geodynamic models presented in Part III below is contained in a companion report (Neumann and Fraser, in press), in which Time-Space plots are presented for each of the Proterozoic Inliers of Australia.

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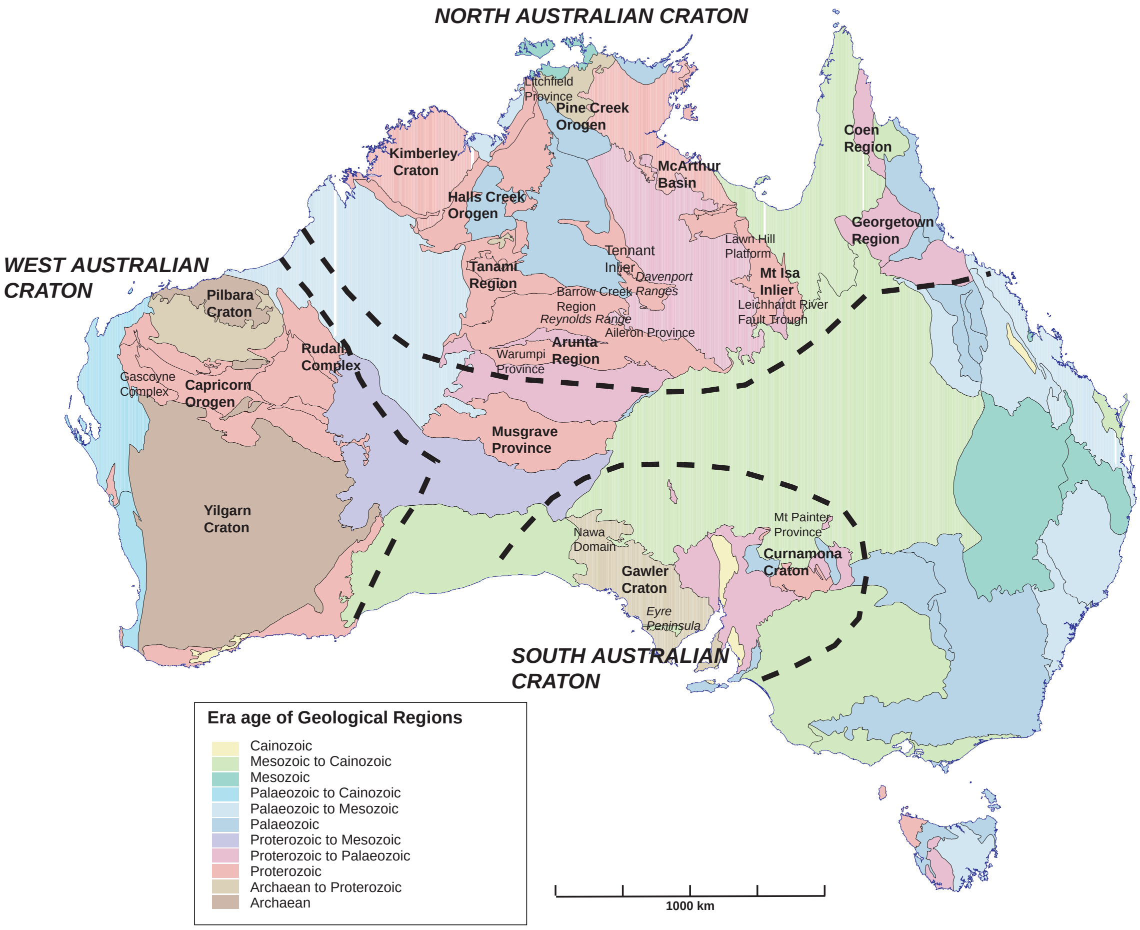
We acknowledge constructive reviews from Andy Barnicoat, Russell Korsch and James Johnson.

Figure 1. Map of Australia showing the broad subdivision into three major cratonic elements (after Myers et al., 1996); the North Australian Craton, West Australian Craton and South Australian Craton. Also shown are geological provinces and regions referred to in the text.



Part I: A Review of Tectonic Reconstructions of Proterozoic Australia

INTRODUCTION

The present day geology of central and western Australia, west of the Tasman Line, is characterised by large cratonic inliers of Archaean and Proterozoic basement rocks separated by equally large regions of Phanerozoic sedimentary cover (Figure 1). Due to the isolated nature of these inliers, considerable uncertainty continues to surround the extent of geological continuity between them, allowing for radically different interpretations of their former spatial relationships. Here we review the development of ideas over the past ~20 years regarding the Proterozoic evolution of Australia.

Twenty years ago Etheridge et al. (1987) appraised the Proterozoic geology of northern Australia, and developed an 'ensialic' tectonic model to explain their observations. Their model has significant differences compared with modern-style, plate-margin tectonics. In contrast, Myers et al. (1996) interpreted the same geological record as a consequence of modern-style plate tectonics, in which various continental fragments were amalgamated via oceanic subduction followed by continental collision. Following Myers et al. (1996), the past decade has seen the development of numerous tectonic reconstructions for Proterozoic Australia involving subduction tectonics (Scott et al., 2000; Sheppard et al., 2001a; Giles et al., 2002; Betts et al., 2002; Giles et al., 2004; Betts and Giles, 2006; Wade et al; 2006). Most recently, Gibson et al. (in press) have proposed a Basin-and-Range-style model, based largely on their experience in the Mt Isa Inlier in which crustal evolution was dominated by extension. In this interpretation, the relative positions of the North Australian and South Australian Cratons have not changed significantly through the palaeo– to mesoproterozoic. Given the radically different models that have been applied to explain the same geology, it is worthwhile to review the evidence on which these contrasting models are based.

TECTONIC MODELS FOR PROTEROZOIC AUSTRALIA

The Ensialic Model

In developing the 'ensialic' tectonic model for northern Australia, Etheridge et al. (1987) emphasised the following observations:

- The absence of ophiolitic rocks
- The presence of older crystalline 'ensialic' basement
- The paucity of andesitic volcanic rocks
- The presence of broad basins with dominantly shallow water sequences
- The lack of significant vertical exhumation, evidenced by the lack of high-pressure metamorphic rocks at the surface
- The absence of palaeomagnetic evidence for significant relative motion between continental fragments or 'inliers'.

Etheridge et al. (1987) interpreted these observations as inconsistent with modern-style tectonics dominated by lateral accretion, and instead developed an ensialic model that involves predominantly vertical accretion to the continental crust via underplating.

Etheridge et al. (1987) proposed a working hypothesis in which small-scale mantle convection resulted in "widespread, contemporaneous underplating and continental extension in linear belts". This model was influenced by the work of McKenzie and Weiss (1975), who appealed to small-scale mantle convection cells developed under a slow-moving or stationary continental mass to explain the polygonal array of topographic and geological features of modern-day Africa. In this model extension and basin-development are driven by mantle upwelling and underplating which, in turn, lead to gravitational spreading. Subsequent basin inversion, or "orogeny", was envisaged to have occurred in response to either (i) horizontal stresses induced by a sudden increase in plate velocity, or (ii) delamination of the mantle lithosphere into the asthenosphere, resulting in high geothermal gradients, crustal melting and high T-low P metamorphism. Of these two processes, Etheridge et al. (1987) favoured the latter.

Ensialic versus modern-style plate-tectonics

As noted by Etheridge et al. (1987), the ensialic model for Proterozoic tectonics of northern Australia is similar to the A-subduction model of Kroner (1981, 1984), and primarily involves vertical accretion of material to the continental lithosphere via widespread underplating. This model contrasts with modern-style (B-subduction) tectonics in which continental accretion occurs in relatively narrow arcs that are accreted horizontally onto the margins of pre-existing continental masses. The ensialic tectonic model for northern Australia (Etheridge et al., 1987) engendered considerable debate that was polarised between those who advocated a uniformitarian view of tectonics (e.g. Myers et al., 1996), and therefore interpreted Proterozoic geology in terms of modern-style tectonic processes, and the non-uniformitarian, "ensialic" proponents. Polarisation of the debate led to considerable criticism of the A-subduction model on theoretical grounds, rather than on a detailed evaluation of the geological evidence in particular Australian terranes. For example, Ellis (1992) presented a detailed critique of the ensialic orogenic model on the basis of petrological, chemical and physical arguments. In particular, Ellis (1992) presented density calculations to argue that depleted lithospheric mantle is more buoyant than the underlying asthenosphere and is, therefore, unlikely to spontaneously sink or delaminate from the crust, thereby undermining the envisaged driving force for ensialic orogeny. Instead, Ellis (1992) argued for modern-style Wilson-cycle tectonics throughout Earth's history, and that the driving force for Proterozoic orogenesis was stresses transferred from subduction of oceanic crust at active plate boundaries. Ellis (1992) acknowledged the possibility of intracratonic orogenesis far from an active subduction front, citing the modern example of the Tien Shan mountains, but regarded this phenomenon as a consequence of stress transfer from active margins rather than a consequence of intracratonic lithospheric delamination.

Over the past decade, the model of ensialic orogenesis has been largely dismissed, and modern-style plate tectonic models have been widely applied to Proterozoic terranes worldwide, as well as within Australia. In general, debate has moved on from a consideration of possible alternative driving mechanisms towards resolving details of how and when Proterozoic Australia was assembled, with most workers interpreting the geological evidence in a modern-style plate tectonic context. While the debate regarding tectonic driving forces appears to be largely over, many of the observations underpinning the Ensialic Model remain valid, and the tectonic evolution of Proterozoic Australia is still not well understood. A plethora of models has been published in recent years invoking subduction and accretion in the Australian Proterozoic, and these models vary widely in the proposed location, timing and polarity of convergent margins. Several of these models are briefly reviewed below.

Modern-style plate-tectonic models

Myers et al. (1996) presented a model for Proterozoic Australia that considered all the Proterozoic inliers as well as the older Archaean cratons. They envisaged a dynamic tectonic evolution similar to modern-style accretionary processes, citing modern-style tectonic interpretations of the Proterozoic geology of North America, Europe and Africa in support of this view (e.g. Windley, 1993). A feature of the model of Myers et al. (1996) is the subdivision of Precambrian Australia into three large cratonic elements; the West Australian Craton (WAC), the North Australian Craton (NAC) and the South Australian Craton (SAC). Myers et al. (1996) envisaged these three cratonic elements to have each been separately assembled from Archaean fragments by ~1830 Ma, and then amalgamated into their present relative positions in the period 1300 – 1000 Ma, with the Albany-Fraser and Musgrave Orogens recording this amalgamation.

Following Myers et al. (1996) an increasing number of tectonic reconstructions for Proterozoic Australia involving accretionary and subduction-driven tectonics have appeared in the literature (Scott et al., 2000; Sheppard et al., 2001a; Giles et al., 2002; Betts et al., 2004; Betts and Giles, (2006); Wade et al., 2006).

Sheppard et al. (2001a) proposed that the Halls Creek orogen represents a Palaeoproterozoic convergent margin, with subduction being terminated at ~1830 Ma due to collision between the Kimberley Craton and NAC.

Both Scott et al. (2000) and Giles et al. (2002) interpreted the evolution of Proterozoic sedimentary basins in the Mt Isa and Georgetown Inliers, and the McArthur Basin, as a consequence of forces transmitted from an evolving north-dipping, subduction margin along the southern edge of the North Australian Craton (NAC). This idea is based, at least partly, on the studies of Zhao (1994) and Zhao and McCulloch (1995), who interpreted the geochemistry of mafic and some felsic rocks in the southeast Arunta region as having a subduction origin at ~1780 Ma. Giles et al. (2002) also proposed that the Curnamona Craton was originally part of the eastern NAC, and that the Gawler Craton collided with the NAC along its southern margin at ~1730 Ma, resulting in the combined Strangways-Kimban Orogen. This model is further-developed on a continental scale by Betts et al. (2002), Giles et al. (2004), and Betts and Giles (2006). Betts et al. (2002) extended the proposed north dipping subduction margin along the southern margin of the NAC westwards through the Rudall Complex. Consequently, this model involves a long-lived accretionary margin south of the NAC that is the locus for collision of the WAC with the NAC at ~1800 Ma, collision of the Gawler Craton with the NAC at ~1730 Ma, and accretion of the Ifould terrane to the western Gawler Craton (present coordinates) at ~1670 Ma.

Based on the geochemistry of felsic gneisses, interpreted as being derived from a magmatic arc, Wade et al. (2006) proposed a south-dipping subduction zone between the NAC and SAC at ~1590 Ma. This contrasts with north-dipping subduction under the NAC proposed by the models of Scott et al. (2000), Giles et al. (2002), Betts et al. (2002), Giles et al. (2004) and Betts and Giles (2006).

Although these models differ in detail, all are based on the geochemistry of igneous rocks and/or the characteristics of basins to infer tectonic environments. With the exception of the Halls Creek Orogen model (Sheppard et al., 2001a), all these models imply the presence of a long-lived, east-west-trending convergent margin along the southern flank of the NAC, during the Palaeo- to Mesoproterozoic.

The Basin-and-Range model

Based on a review of basin development along the eastern margin of Proterozoic Australia, including the Mt Isa Inlier and Broken Hill region, Gibson et al. (in press) propose that ENE- to NE-directed crustal extension occurred almost continuously from ~1800 Ma to ~1640 Ma. This extension produced stacked sedimentary basins controlled by growth faults, and exhumed mid-crustal, syn-extensional igneous rocks along extensional shear zones, creating an inferred Basin-and-Range-style crustal architecture. This model, in which parts of the NAC (Mt Isa region) and SAC (Broken Hill region) form a continuous east-facing continental margin through the period ~1800 – 1640 Ma, differs significantly from the models outlined above, in which this same period is characterised by a south-facing convergent margin south of the NAC. The model of Gibson et al. (in press) does not invoke, and may be incompatible with, a convergent margin along the southern flank of the NAC. Rather it requires the NAC and SAC to have been in essentially their current configuration, while allowing for significant intracratonic rifting and basin inversion. Although Gibson et al. (in press) do not extend their model before ~1800 Ma, geologic data may in fact allow this, as discussed below. In some respects this model is similar to the ensialic model of ~20 years ago (Etheridge et al., 1987), inasmuch as Palaeoproterozoic ocean closure is not invoked between Australian crustal elements, yet there are significant differences. Gibson et al. (in press) do not question the operation of modern-style plate tectonics, but interpret the geological record of eastern Proterozoic Australia in a largely extensional setting. In this interpretation, the Mt Isa and Broken Hill regions are situated in a back-arc position with respect to a west-dipping subduction zone located east of the present-day Australian Proterozoic margin. This model attempts to reconcile the geology of Proterozoic eastern Australia with Rodinia reconstructions in which eastern Australia is correlated with Laurentia.

LINES OF EVIDENCE

The discussion presented above illustrates the wide diversity of tectonic models that have been proposed for Proterozoic Australia. This diversity includes contrasts in tectonic styles (i.e. ensialic, convergent margin and Basin-and-Range models) as well as contrasts in the location and polarity of proposed convergent margins. Each of the models that have been proposed is based on specific geological, geochemical and/or geophysical observations and makes predictions about the distribution of, and relationship between, geological elements in the Australian Proterozoic. In the following section we assess the evidence upon which the various models are based.

Palaeomagnetic evidence

Various published tectonic models, as reviewed above, invoke widely varying spatial arrangements of Australian Proterozoic crustal elements. For example, the interpretation of Sheppard et al. (2001a) proposes that the Kimberley Craton (KC) collided with the proto-NAC at ~1830 Ma, following a period of subduction and consumption of oceanic crust. Similarly, collision of the largely Archaean WAC with the NAC is envisaged to have occurred at ~1790 to 1750 Ma after subduction-closure of an intervening ocean (Betts and Giles, 2006), and subduction is inferred to have occurred at various times between 1810 and 1550 Ma between the present locations of the NAC and SAC, mostly along the southern margin of the NAC (e.g. Scott et al., 2000; Giles et al., 2002; Betts et al., 2002; Giles et al., 2004; Betts and Giles, 2006; Wade et al., 2006). Hence, these various subduction models would predict major differences in palaeopoles between the proto-NAC and Kimberly Cratons prior to 1830 Ma, between the "consolidated" NAC and WAC prior to ~1750 Ma, and between the "consolidated" NAC and SAC prior to ~1550 Ma. In contrast, the Basin-and-Range-style model of Gibson et al. (in press) proposes that the NAC and SAC were in relatively close proximity throughout the period ~1800 - 1600 Ma. Palaeomagnetism provides a potentially definitive test between these models.

Wingate and Evans (2003) conclude that “most intracratonic deformation, including formation or destruction of small ocean basins, will not be detectable within typical uncertainties of 5 – 15° in palaeopole determination.” (Wingate and Evans, 2003). Consequently palaeomagnetism cannot provide tests for the presence of intracratonic deformation or the closure of small ocean basins, but should be able to test models that invoke amalgamation of continental masses after closure of wide oceans.

Wingate and Evans (2003) conclude that the available palaeomagnetic evidence “permit the North and West Australian cratonic assemblages to have occupied their present relative positions since at least c. 1.7 Ga, and to have been joined to the South Australian cratonic assemblage since at least c. 1.5 Ga.” In detail, poles from the KC, McArthur Basin (NAC) and Pilbara (WAC) indicate that the

NAC and WAC were in their present relative positions since at least 1.7 Ga. The Kimberley and McArthur Basin poles indicate that these regions were amalgamated by ~1.79 Ga. These palaeomagnetic constraints, while useful, do not extend far enough back in time to test the models involving collision of the Kimberley and NAC at ~1830 Ma, and collision of the WAC and NAC at ~1790 Ma.

Poles for the Gawler Range Volcanics in the Gawler Craton (SAC) and from the upper Balbirini Dolomite in the McArthur Basin (NAC) are 60° apart. As both rock units have an age of ~1590 Ma, and Wingate and Evans (2003) tentatively interpret poles from both these units as primary, this suggests that the NAC and SAC were separated by at least 6000 km at ~1590 Ma. Other available poles suggest the NAC and SAC were amalgamated by ~1550 to 1500 Ma, which is broadly consistent with the model of Wade et al. (2006) in which the Musgrave Province records the convergence and suturing of the SAC and NAC in the period ~1590 to 1550 Ma. The comparison of poles from the Gawler Range Volcanics and Balbirini Dolomite is extremely important because if these poles are indeed primary, models such as that of Gibson et al. (in press), that imply the NAC and SAC were effectively conjoined since ~1800 Ma, become untenable. Much depends upon the interpretation of the two ~1590 Ma poles as primary, and Wingate and Evans (2003) suggest further confirmation is required.

In contrast with the findings of Wingate and Evans (2003), Schmidt et al. (2006) have argued that poles at ~1070 Ma within the WAC, NAC, and SAC are not consistent with these crustal blocks being in their current relative positions at that time. Rather they suggest an anticlockwise rotation of ~70° of the WAC relative to the combined NAC-SAC since ~1070 Ma. This requires a zone of deformation between the WAC and NAC-SAC that was active after ~1070 Ma, in sharp contrast to most recently-published continental reconstructions. The Grenvillian-age deformation events in the Albany-Fraser and Musgrave regions are older than ~1070 Ma, and cannot account for the apparent mismatch of poles at ~1070 Ma presented by Schmidt et al. (2006). A possible explanation for this mismatch lies in the Miles Orogeny (~800 Ma) in the northern WAC. This suggestion would also predict the presence of a post-1070 Ma deformation zone somewhere between the western Gawler Craton and the eastern WAC. This is a very poorly understood region (the Coompana Domain) under the cover of younger sediments of the Officer Basin.

These uncertainties and data gaps, combined with the inability of existing palaeomagnetic data to resolve the possibility of intra-cratonic element translation limit the use of these data to critically test the alternative models for the geodynamic evolution of Proterozoic Australia. Resolution of these limitations requires expansion of the palaeomagnetic dataset to include reliable Proterozoic poles from different continental fragments at equivalent ages. Consequently, most published tectonic models are based on geological evidence other than palaeomagnetism.

Evidence from Igneous Geochemistry

The geochemistry of igneous rocks has been used by many workers to make inferences regarding tectonic setting in the Australian Proterozoic. In initially proposing that the evolution of the Proterozoic of Australia differed from modern-style plate tectonics, Etheridge et al. (1987) pointed out that two key rock assemblages, ophiolites and intermediate (andesitic) igneous rock, which are present in many modern convergent settings, are generally absent in Proterozoic Australia. This observation remains valid. With the possible exception of the Wangi Basics in the Litchfield Province (Glass, 2007, see discussion below), no ophiolitic rocks have been recognised in any Australian Proterozoic terranes, and as pointed out by Wyborn et al. (1987, 1992), intermediate composition igneous rocks are uncommon.

Wyborn et al., (1992; see also McLaren et al., 2005) divide Australian Proterozoic granites into several types that can be most simply classified into two groups: (a) predominant and temporally widespread Sr-depleted and Y-undepleted granites, and (b) uncommon Sr-undepleted and Y-depleted ("adakitic") granites. Depletion of Sr in group (a) implies granite generation at relatively shallow crustal levels, where plagioclase is stable rather than garnet. These granites are not typical of granites in modern convergent settings. Group (b) granites, which are akin to Phanerozoic adakitic granites, are typical of subduction zones within modern convergent margins, however these are relatively uncommon in the Australian Proterozoic (3.8% of Australian Proterozoic felsic igneous rocks; McLaren et al., 2005). It is also worth noting that adakitic rocks, while usually regarded as evidence of slab melting, can also form from melting of a mafic lower crust, and thus are not definitive indicators of subduction (Castillo, 2006).

Some authors (e.g. Zhao and McCulloch, 1995; Sheppard et al., 2001a; Giles et al., 2002) have used the presence of group (b) granites to infer subduction in local (both temporal and spatial) areas of the North Australian Craton, whereas other authors (e.g. Etheridge et al., 1987; Wyborn et al., 1992) have used the low abundance of group (b) granites to infer that subduction was not a significant process through large parts of the Proterozoic in Australia. Sheppard et al. (2001a) have used the presence of group (b) granites in the Halls Creek Orogen, where they are more abundant than in any other Australian Proterozoic terrain, to argue for subduction processes in the period ~1850 to ~1820 Ma during convergence between the NAC and KC. Similarly, in the Aileron Province, Giles et al. (2002) have used the presence of group (b) granites (the CAT granites of Zhao and McCulloch, 1995) as evidence for north dipping subduction under the southern margin of the NAC. However, it must be noted that these granites, which are restricted to the southeastern Aileron Province, constitute only a small fraction of all granites along the southern margin of the NAC.

Evidence from Nd isotopes

Another line of evidence used by some workers to infer tectonic setting is ε_{Nd}, as calculated at the time of granite emplacement. Positive ε_{Nd} values (to +7 in the Proterozoic) are generally considered to indicate derivation from largely juvenile sources (i.e. directly derived from the mantle), whereas large negative values (e.g. ~ -5 to –7 for average Gawler Craton crust at ~1600 Ma; Wade et al., 2006) are interpreted to indicate derivation from an evolved source (i.e. long prior crustal residence). Intermediate values are interpreted to represent mixing between the end-member sources. Subduction-derived igneous rocks would tend to have high (positive) ε_{Nd} values whereas intracontinental remelting of pre-existing crust would tend to have low (negative) ε_{Nd} values. Juvenile ε_{Nd} values, while consistent with a subduction origin, are not definitive of such a setting, but simply indicate a source component that has been relatively-recently extracted from the depleted mantle. It must also be stressed that because of the high abundance of Nd in crustal rocks relative to mantle rocks, granitic ε_{Nd} values are highly sensitive to the incorporation of small amounts of crustal material in granitic melts.

Evidence from metamorphic rocks

The observation of Etheridge et al. (1987) that metamorphic style in Australian Proterozoic terranes is dominated by relatively low-pressure conditions, and relatively isobaric or anticlockwise *P-T-t* paths remains true today. The outstanding exception is the Rudall Complex where metamorphic pressures reached ~12 kbar (Smithies and Bagas, 1997), and the *P-T*-t path appears to have been clockwise, involving a period of near-isothermal decompression. Medium pressure metamorphic conditions have been documented from the Strangways Range where pressures reached 8 – 9 kbar (Goscombe, 1992), and from the poorly understood Nawa Domain in the western Gawler Craton where peak metamorphic pressure reached ~10 kbar (Teasdale, 1997). However, both the

Strangways Range and Nawa Domain rocks exhibit petrological evidence for anticlockwise *P-T-t* paths and relatively isobaric cooling (Goscombe, 1992; Teasdale, 1997). In general, high T- low P metamorphism is not characteristic of collisional settings, and the predominance of this style of metamorphism in the Australian Proterozoic record was used by Etheridge et al. (1987) to argue against subduction tectonics. The general paucity of medium- to high-pressure metamorphic rocks, and particularly the absence of blueschists and eclogites remains a problem in applying modern-style accretionary models to the Australian Proterozoic. An explanation for the high geothermal gradients expressed in Australian Proterozoic metamorphic rocks may lie in the enrichment of radioactive heat-producing elements that appears to be characteristic of the Australian Proterozoic (e.g. McLaren et al., 2005). It is possible that elevated crustal heat production in the Proterozoic modified the metamorphic response compared with that of modern accretionary orogens.

GEOLOGICAL EVIDENCE FOR SUBDUCTION AND TERRANE ACCRETION IN THE AUSTRALIAN PROTEROZOIC

As outlined above, several Australian Proterozoic orogens have been proposed to represent subduction-driven convergent margins. The most thoroughly-documented of these is the Halls Creek Orogen. In this section we review the evidence for subduction in the Halls Creek Orogen, then go on to consider evidence from the southern margin of the North Australian Craton, and from the Musgrave region, both of which have also been proposed to represent sites of Palaeo- to Mesoproterozoic subduction.

The Halls Creek Orogen

The geology, geochronology and geochemistry of the Halls Creek Orogen has been thoroughly documented in a series of relatively recent publications (Blake et al., 2000; Griffin et al., 2000; Sheppard et al., 1999; Sheppard et al., 2001a). Considerable emphasis has been placed on the geochemistry of igneous rocks in developing a model involving NW-trending convergence during the period ~1850 – 1820 Ma. Sheppard et al. (2001a) divide igneous rocks of the Halls Creek Orogen into several suites and supersuites based on their age and geochemical characteristics, as reviewed below.

Paperbark Supersuite

The Paperbark Supersuite (~1865 – 1850 Ma) is bimodal, consisting of gabbros, granites and felsic volcanics with a distinct silica gap between the mafic and felsic components (Griffin et al., 2000). Spatially, the Paperbark Supersuite granites are restricted to the western parts of the Halls Creek Orogen. The gabbros show trace-element similarities to continental tholeiites, and are interpreted by Sun and Hoatson (2000) to be consistent with an intraplate environment. The granites and felsic volcanics of the Paperbark Supersuite have chemistry typical of the high-K, Sr-depleted granites that are widespread in northern Australia (e.g. Wyborn et al., 1992), and are regarded as a product of crustal melting at relatively high temperature (>900°C) and moderate pressure (~8 – 10 kbar) (Griffin et al., 2000). The chemistry of these granites is not consistent with that of granites from modern convergent plate margins.

Dougalls Suite

The Paperbark Supersuite was closely followed by intrusion of the Dougalls Suite at ~1850 Ma (Sheppard et al., 2001a). The Dougalls Suite is largely composed of tonalitic sheets, with lesser amounts of more mafic rocks i.e. gabbros. There is a compositional gap between the tonalitic and gabbroic compositions, indicating that these are distinct magma types rather than being the products of fractional crystallisation from a mafic parent magma. The Dougalls Suite is significantly different from the Paperbark Supersuite and other high-K, Sr-depleted granites of northern Australia. Geochemical evidence from the Dougalls Suite suggests they are "crustally-derived adakites"

(Sheppard et al., 2001a). The Dougalls Suite is interpreted to represent melting of a mafic source in the deep crust, (>40 km) (Sheppard et al., 2001a), implying significant crustal thickening prior to ~1850 Ma. These rocks show some geochemical similarities to Cretaceous and Tertiary igneous rocks from active continental margins. Sheppard et al. (2001a) argue for a subduction-origin for the Dougalls Suite adakites because they regard the timing at ~1850 Ma to predate the "collision and stitching" of the Kimberley and NAC at ~1820 Ma. Sheppard et al. (2001a) also acknowledge that crustally-derived adakites may form in settings other than subduction zones. Essentially, these rocks may have formed in any environment in which relatively deep-crustal mafic sources melt.

Sally Downs Supersuite

The Sally Downs Supersuite (~1835 – 1805 Ma) consists of granite and gabbro plutons, and is divided by Sheppard et al., (2001a) into the Mabel Downs, Syenite Camp and Kevins Dam suites, each interpreted to derive from melting at different crustal levels. All three suites in the Sally Downs Supersuite are regarded by Sheppard et al. (2001a) as primary, crustally-derived melts, and not derived by crystal fractionation or assimilation and fractional crystallisation (AFC) from a parent mafic magma. This would suggest that these rocks do not represent either slab melting or melting of a mantle wedge above a subducting slab.

The Mabel Downs Suite has major and trace element chemistry similar to Archaean high-Al TTG suites and Phanerozoic adakites. This suite is distinguished from other suites in the Sally Downs Supersuite by having a positive Eu anomaly, and is interpreted by Sheppard et al. (2001a) to be a product of melting of a deep crustal source (~10 – 15 kbar i.e. ~35 – 50 km depth) of metabasaltic composition, leaving a garnet-amphibolite residue.

The Syenite Camp Suite is regarded as a product of melting of an amphibolite source at pressures of less than 10 – 12 kbar (i.e. depths of less than ~35 km). Sheppard et al. (2001a) regard the Syenite Camp Suite as chemically similar to granites from the Coastal Batholith in Peru, and the Coast Batholith in Alaska.

The Kevins Dam Suite consists of high-K granites with similar major and trace element abundances to the Paperbark Supersuite. Melts of this composition are regarded as the product of dehydration melting of tonalite or quartz-diorite compositions at 5 – 10 kbar and >850°C, leaving a residue dominated by plagioclase, orthopyroxene and augite, and not amphibole or garnet, and have low Sr and high Y contents (Sheppard et al., 2001a). These melts are relatively shallow crustal, and require relatively high geothermal gradients.

In summary, the Paperbark Supersuite and Kevins Dam Suite rocks are relatively shallow-crustal, and imply high-geothermal gradients and have chemistries not typical of modern convergent margins. The Dougalls Suite, Mabel Downs Suite and Syenite Camp Suite indicate relatively deep crustal melting and have compositions more analogous to modern subduction settings. None of these igneous rocks can be definitively interpreted as subduction-related. So, while the subduction model of Sheppard et al. (2001a) may be correct, the geochemical evidence for it is not compelling and other models are worthy of consideration; for example, extension followed by oblique contraction.

It may be significant that the igneous rocks regarded as most indicative of subduction processes (the Dougalls Suite, Mabel Downs Suite and Syenite Camp Suite) are either synchronous with, or closely bracketed by, igneous rocks not typical of subduction origin (Paperbark Supersuite and Kevins Dam Suite). This apparent paradox is recognised by Sheppard et al. (2001a) who acknowledge that the "subduction" chemistry of some of the granites could have been inherited from their source, and may not necessarily indicate subduction at the time of granite intrusion. In defence of the subduction model, Sheppard et al. (2001a) point to discrete tectonostratigraphic terranes within the Halls Creek Orogen, with distinct geological histories up until ~1820 Ma. They argue that this is consistent with horizontal movement and favour a subduction setting to accomplish this.

Independent support for a subduction setting for parts of the Halls Creek Orogen comes from Glass (2007), who reports geochemistry from the Wangi Basics, a suite of mafic rocks in the Litchfield Province, in the northwestern NAC. This region has previously been speculated to represent a northeasterly extension of the Halls Creek Orogen. Glass (2007) subdivides the Wangi Basics into six suites, several of which are regarded as geochemically arc-like. Glass (2007) suggests that these rocks may represent part of a Palaeoproterozoic ophiolite complex. If this interpretation is correct, it would represent the first identification of ophiolitic rocks in the Australian Proterozoic, and lend strong support to models proposing a Palaeoproterozoic convergent margin setting between the Kimberley Craton and NAC. The age of the Wangi Basics has not been precisely determined, but is thought to be ~1865 – 1850 Ma (Chris Carson, pers. comm. 2007), broadly consistent with the timing of proposed subduction and accretion across the Halls Creek Orogen. The spatial distribution of the Wangi Basics, and their relationship with the Halls Creek Orogen, remain to be further documented.

The southern margin of the North Australian Craton

North-dipping subduction along the southern margin of the Palaeoproterozoic NAC is incorporated into the models of Scott et al. (2000), Giles et al. (2002), Betts et al. (2002), Giles et al. (2004) and Betts and Giles (2006). Much of the evidence used in these models comes from geochemical studies of igneous rocks in the Arunta region by Zhao (1994) and Zhao and McCulloch (1995). Zhao (1994) documented the geochemical characteristics of amphibolites from the SE Arunta, which he regarded to have an igneous age of ~1770 Ma. He divides these into two groups according to REE patterns and ε_{Nd} values. The two groups are characterised by:
(1) flat to LREE-depleted with high positive ε_{Nd} values (+4 to +5; approximately equivalent to depleted mantle values at ~1770 Ma); and
(2) LREE-enriched with negative Nb anomalies and lower ε_{Nd} values (-1.0 to –2.8).
The first group crops out mostly in the SE Aileron Province, in association with Inkamulla granites, whereas group (2) crops out mainly in the north. Lower ε_{Nd} values from the more northerly samples are broadly consistent with more crustal contamination within the craton interior. Both groups are depleted in HFS (Ti, Zr, Nb) elements, and selectively enriched in LIL (Rb, Sr, Ba, K) elements. Zhao (1994) suggests that the presence of negative Nb anomalies in his group 2 amphibolites precludes a rift- or plume-related underplate as a source for these rocks, and instead argues for a subduction origin. Both group 1 and group 2 amphibolites are interpreted by Zhao (1994) as partial melts of a variably metasomatised mantle wedge in an island arc or back-arc basin setting. The geochemistry of mafic-ultramafic intrusions at ~1810 Ma and ~1780 Ma in the southern Arunta region is interpreted by Hoatson et al. (2005) to most likely reflect a subduction-related back arc setting, in accord with the conclusions of Zhao (1994).

Granites from the southern Arunta region are subdivided by Zhao and McCulloch (1995) into three groups. Of these, the most volumetrically significant are K-rich and Sr-depleted, similar to those described by Wyborn et al. (1992) as typical of northern Australian granites. As noted previously, the chemistry of these granites is unlike that of Phanerozoic convergent margin granites, and has been interpreted by Wyborn et al. (1992) to indicate crustal melting at relatively shallow levels. In contrast, Zhao and McCulloch (1995) note the presence of negative Nb anomalies in these granites, and argue that although these granites may not have formed in subduction settings, they represent melts of a source-region that was originally derived from subduction-processes. Zhao and

McCulloch (1995) also recognise a volumetrically more limited group of granites, restricted to the south-eastern Arunta, which they term the Calcalkaline-trondhjemitic (CAT) Group. These are interpreted as melts of a mafic source that was derived via partial melting of a metasomatised mantle wedge in a subduction setting. Granites of the CAT Group have ages of ~1770 – 1750 Ma, and thus if the petrogenetic interpretation of Zhao and McCulloch (1995) is correct, imply subduction prior to this time.

Sun et al. (1995) also considered geochemical and Nd-isotopic evidence from granites in the Arunta region, concluding that although subduction is a "convenient and plausible mechanism", it "is not the only tectonic process which can achieve the observed Nd isotopic and geochemical features". These authors do, however, suggest that "petrological, chemical and Nd-isotopic data support the concept of back-arc opening and formation of the Harts Range Metamorphic Igneous Complex" in the southeast Arunta region at ~1780 to 1750 Ma.

In summary, most studies focussing on igneous geochemistry of the Arunta region tend to favour subduction processes, at least in the southeast, at ~1780 to 1750 Ma or some time prior to this. Other geological features of the region are less-clearly subduction-related. For example, Collins and Shaw (1995) regard "the lack of melange and typical accretionary prism rock-types, including ophiolites, cherts and immature greywackes, and the paucity of typical subduction-related granitoids" as inconsistent with a convergent margin setting on the southern margin of the NAC.

The Warumpi Province – an accreted terrane?

Based on the presence of ~1680 Ma and ~1650 Ma intercalated chemical sediments and volcanics, which have no known correlatives in the Aileron Province to the north, the Warumpi Province has been interpreted as an accreted terrane along the southern margin of the NAC (Close et al., 2004). This interpretation is consistent with the model that the southern NAC margin was a convergent margin through much of the Proterozoic. Rocks of the Warumpi Province are thought to have formed as distinct terranes outboard of the NAC, and been accreted to the NAC during the Leibig Orogeny at ~1640 Ma (Close et al., 2004). The Leibig Orogeny resulted in granulite-facies metamorphism at relatively deep crustal levels (~30 km depth), together with voluminous felsic and mafic magmatism (Scrimgeour et al., 2002; Hoatson et al., 2005). Coeval with the Leibig Orogeny, the southwestern NAC was intruded by layered mafic igneous rocks of the Andrew Young Hills, interpreted by Hoatson et al. (2005) as indicative of an extensional environment, relatively distant from a collision zone. The Andrew Young Hills complex could be interpreted as forming in a back-arc setting relative to an accretionary margin further south.

Close et al. (2004) also cite Nd-isotopic evidence to support their interpretation that the Warumpi Province represents crust that is distinct from the NAC. Granitic rocks in the Warumpi Province yield ε_{Nd} values of –2.3, compared with granites in the SW of the NAC with typical ε_{Nd} values of –5.7. Mafic rocks at ~1640 Ma from the Warumpi Province have ε_{Nd} values of ~0.01 compared with mafic rocks of the same age from the southwest NAC with ε_{Nd} values of –5.1. These data indicate a more juvenile average composition for the Warumpi Province compared with the NAC, although they do do not necessarily require the Warumpi Province to be exotic to the NAC prior to ~1640 Ma.

The Musgrave Province

Based on geochemical and ε_{Nd} data from felsic gneisses in the northern Musgrave Province, Wade et al. (2006) proposed that this region was the site of early Mesoproterozoic (~1.60 Ga) subduction. In this model, protoliths to the Musgraves formed as an island arc above a south-dipping subduction zone situated to the north of the Gawler Craton. This convergent margin culminated in collision of the NAC with the SAC, and the accretion of intervening arcs.

This model is based on geochemical and Nd-isotopic arguments from felsic gneisses from the northern part of the Musgrave region. The geochemical arguments are based on Pearce et al. (1984) tectonic discrimination diagrams and trace and rare-earth element spidergrams showing LREE enrichment and prominent Nb and Ti depletion. However, as noted by Wade et al. (2006), the discrimination diagrams of Pearce et al. (1984) may not be appropriate for Proterozoic rocks, and LREE enrichment and Nb and Ti depletion are typical of continental crust in general (D. Champion, pers. comm.).

In addition to geochemistry, the other line of evidence used by Wade et al. (2006) is the Nd isotopic signature of these rocks. $\varepsilon_{Nd(1550)}$ values for the Musgrave felsic gneisses range between –1.2 and +0.9, a range more juvenile than average ε_{Nd} values for adjacent crust in either the Aileron Province or Gawler Craton. Although Wade et al. (2006) argue that this Nd isotopic evidence is consistent with an arc origin, this interpretation is not unique. The Nd isotopic evidence simply indicates the presence of a slightly more isotopically juvenile source for these rocks. Any process or tectonic setting that extracts some mantle melt and mixes it with small amounts of crustal material (e.g. 10 – 20 %) could account for the Nd isotopic evidence.

In addition to the uncertainties based on the geochemistry, uncertainties in age and origin of the rocks studied by Wade et al. (2006) also add ambiguity to the interpreted tectonic setting. The rocks studied by Wade et al. (2006) are migmatitic felsic gneisses that were highly deformed and metamorphosed during the Musgravian Orogeny (~1200 – 1160 Ma), and the age and original rock-types that these gneisses represent are somewhat uncertain. The evidence for a Mesoproterozoic age of these rocks comes from U-Pb ages of zircon cores in the gneisses. These zircons, however, could represent inheritance and may not record the magmatic age of the gneiss protolith. In addition, distinguishing ortho- from paragneisses is notoriously difficult. Although the samples are from large bodies of relatively homogeneous gneiss, local metapelitic rocks are present, indicating a possible sedimentary protolith. Irrespective of age and protolith uncertainty, the fact that these rocks have been through high-grade metamorphism and migmatisation raises questions regarding to what extent their original chemistry may have be modified.

SUMMARY AND DISCUSSION

As described above, a number of authors have relied upon the geochemistry of granites and, to a lesser extent, mafic rocks to infer a subduction origin to some belts of rocks in Proterozoic Australia. Others have focussed more on evidence from the sedimentary record (e.g. Gibson et al., in press) and favour an extensional setting for much of the Australian Proterozoic. Geochemical evidence supposedly diagnostic of subduction processes is restricted to certain granites in the Halls Creek Orogen and the Inkamulla granites in the southeastern Aileron Province. Outside these areas, the geochemistry of most granitic rocks is indicative of an overwhelming crustal component in their source, and is not diagnostic of a particular tectonic setting. Given the relatively low volumes of "arc-like" granitic rocks, and their non-unique derivation from subduction settings, the geochemical evidence for subduction is not conclusive. In each of the regions where subduction models have been invoked, alternative explanations remain plausible.

The subduction model for the Halls Creek Orogen (Sheppard et al., 2001a), in which subduction is terminated by collision of the Kimberley and North Australian cratons at ~1830 Ma, appears to be the most thoroughly documented and convincing case for subduction in the Australian Proterozoic. On the southern margin of the NAC, most recent interpretations invoke a south-facing accretionary margin south of the Aileron Province through much of the period ~1800 to 1600 Ma. An accretionary margin of this longevity tends to imply a major ocean south of the NAC throughout the late Palaeoproterozoic, separating the NAC and SAC. Wide separation of the NAC and SAC is not consistent with studies that have emphasised geological commonalities between the eastern NAC (Mt Isa) and eastern SAC (Curnamona) through the same Palaeoproterozoic period (e.g. Gibson et al., in press). The models of Giles et al. (2002), Betts et al. (2004), and Betts and Giles (2006), have attempted to resolve this paradox by translating and rotating parts of the SAC northwards, and regarding them as easterly extensions of the NAC in the Palaeoproterozoic. Such models clearly imply subsequent translation of the SAC south into its present position. Structures with the appropriate kinematics and timing to accommodate this southwards translation have yet to be identified.

It is clear from the foregoing discussion that studies of particular geological regions have led to widely disparate and divergent tectonic models at the continental-scale. This is highlighted by the recent model of Gibson et al. (in press), developed to explain observations from the Mt Isa and Curnamona regions, in which a long-lived accretionary margin south of the NAC is difficult to accommodate. Essentially we are left with two end member models: one invoking long-lived accretionary tectonics on the southern margin of the NAC though the period ~1800 – 1600 Ma, and the other in which the same period is dominanted by extensional processes, and in particular, by a long-lived east facing extensional margin. Clearly, further studies are needed involving specific tests designed to discriminate between these end-member scenarios. Some of these tests are listed below. In the meantime, for the purposes of predicting mineral prospectivity on the basis of tectonic setting, we consider both these end member models (see Part III below).

Major Outstanding Questions

The timing of juxtaposition of the WAC, NAC and SAC remains highly uncertain. High pressure (~12 kbar) metamorphism within the Rudall Complex has been interpreted as a consequence of collision between the WAC and NAC (Smithies and Bagas, 1997), yet direct age constraints on this episode of metamorphism are lacking.

A major point of difference between contrasting sets of models concerns the nature of the southern NAC margin during the Palaeoproterozoic. Models based on the geology of the southern NAC tend to favour a south-facing accretionary margin (e.g. Zhao, 1994; Zhao and McCulloch, 1995; Close et al., 2004), whereas studies of the eastern Australian Proterozoic terranes of the Mount Isa Inlier and Curnamona Province tend to favour geological continuity between the NAC and SAC during the same period (Giles et al., 2002, 2004; Gibson et al., in press).

Numerous studies support a southern NAC subduction-accretion margin that was active for some or all of the period ~1880 – 1590 Ma. For example, Zhao (1994) and Zhao and McCulloch (1995) interpret a subduction margin from ~1880 to ~1750 Ma, and tentatively suggest this margin may have remained active through to ~1600 Ma, terminated by accretion of the Musgrave Province. Terranes proposed to have accreted to this margin include, from north to south, the Atnarpa Complex in the SE Arunta region (Zhao, 1994; Zhao and McCulloch, 1995), the Warumpi Province at ~1640 Ma (Close et al., 2004), and the Musgrave Province at ~1590 Ma (Wade et al., 2006), although we note that Wade et al., (2006) propose south dipping subduction under the SAC in contrast to models for earlier accretionary events that generally invoke north dipping subduction under the NAC.

In combination, these models appear to indicate the presence of a long-lived subduction-accretion margin between the NAC and SAC, that was active at least episodically for ~200 Ma from ~1800 to

~1600 Ma. Based on our understanding of tectonics on the modern earth, such a long-lived active margin probably implies the presence of a major ocean south of the NAC that progressively closed during the late Palaeoproterozoic. At face value, such models would predict that the SAC was not contiguous with the NAC in the period ~1800 to 1600 Ma. This clearly contrasts with geological correlations between the Mount Isa and Curnamona Regions (Giles et al., 2002, 2004; Gibson et al., in press). Giles et al. (2002) have proposed a solution to this apparent contradiction that involves rotating and translating the SAC anticlockwise and northeast, such that the SAC is in fact an eastern extension of the NAC during the period of accretionary tectonics between ~1800 and 1600 Ma.

Tests of the Tectonic Models

As is clear from the discussion above, evidence from specific geological disciplines is rarely, if ever, definitive in identifying tectonic settings for Proterozoic terranes. Consequently, tectonic interpretation requires integration of a variety of geological and geophysical evidence. Having said this, several lines of enquiry are outlined below that we suggest may help to resolve some of the major points of difference between contrasting Proterozoic tectonic reconstructions.

Presence or Absence of Subduction-related Sutures

Several of the models described above invoke subduction followed by accretion of distinct crustal blocks e.g. between Kimberley and NAC, between NAC and Warumpi Province, between Musgrave Province and SAC. New deep seismic datasets, in combination with existing deep seismic and magnetotelluric transects, are likely to provide some level of testing for these models. The rigour of tests using seismic and/or magnetotellurics depends upon the extent to which current geometries imaged by such methods can be uniquely interpreted as a record of ancient dynamics. For example, can a particular geometry seen in a seismic section be confidently attributed to convergent/accretionary tectonics as opposed to extensional or strike-slip movement? In regions where the current geometry is a consequence of multiple periods of tectonism, geodynamic interpretation of geophysical images is often non-unique.

Timing and tectonic interpretation of the Hutchison Group sedimentary rocks

The Hutchison Group metasedimentary rocks, on the south-eastern margin of the Gawler Craton, have been interpreted by some workers as a passive margin sequence, deposited shortly before intrusion of the Donington Suite magmas at ~1850 Ma. The provenance of these sediments, and particularly whether they exhibit any commonalities with Palaeoproteroic sediments in the NAC, is relevant to the question of whether the SAC and NAC were in close proximity at the time of sedimentation. We note that Vassallo and Wilson (2002) suggested that the Hutchison Group contains significant structural repetition and that part or all of the Hutchison Group may in fact be younger than the ~1850 Ma Donington Suite. In addition, unpublished isotopic data from the Hutchison Group (Szpunar et al., 2007) suggest distinctly different sediment sources in different parts of the sequence, consistent with the presence of a previously-unrecognised structural or sedimentological boundary. It is clear that the timing and origin of the Hutchison Group is poorly constrained.

Correlation of ~1850 Ma magmatism in NAC and SAC

Volumetrically significant magmatism at ~1850 Ma occurs in broadly linear belts along the eastern margin of the Gawler Craton (Donington Suite) and NAC (Kalkadoon-Leichhardt Suite). It is possible to speculate that these rocks form part of a previously-continuous magmatic belt along the eastern margin of Proterozoic Australia. This hypothesis requires testing via more detailed comparison of the geochemistry, Nd isotopic signature and inherited zircon populations of the Donington Suite versus Kalkadoon-Leichhardt Suite. Such a comparison will help answer the question of whether the NAC and SAC were in close proximity at ~1850 Ma.

Correlation of ~1760 – 1730 Ma sediments in NAC and SAC

Sedimentation between ~1760 and 1730 Ma occurred in the SAC in the eastern Gawler Craton (Wallaroo Group) and in the Nawa Domain of the northern Gawler Craton. In the NAC, the Ledan Package metasedimentary rocks were deposited at broadly the same time. A comparison of these metasedimentary rocks in the SAC and NAC, via detrital zircon, Nd and Hf isotopes may help address the question of proximity of the SAC and NAC in the Palaeoproterozoic.

Comparison of ~1760 – 1720 Ma magmatism in NAC and SAC

Inkamulla igneous rocks (~1760 Ma) have been interpreted as indicative of subduction processes (Zhao, 1994; Zhao and McCulloch, 1995; Champion, pers. comm.) on the southern margin of the NAC. The studies of Zhao (1994) and Zhao and McCulloch (1995) were based primarily on geochemical classification of igneous rocks. Further studies of these rocks with the benefit of modern geochronology may help assess to what extent the geochemical groupings identified by Zhao (1994) and Zhao and McCulloch (1995) are spatially and temporally distinct.

Very limited geochemical data from mafic igneous rocks in the Fowler Belt on the western margin of the Gawler Craton have been tentatively interpreted to indicate an east dipping subduction zone on the western margin of the Gawler Craton from ~1740 Ma (Teasdale, 1997). This suggestion requires testing via additional geochronology and geochemistry, although future studies will be hampered by the lack of outcrop and would benefit from new diamond drill holes.

Provenance of sediments in the Warumpi Province

Sediments were deposited between ~1690 and 1640 Ma in the Warumpi Province (Madderns Yard Metamorphic Complex, YaYa Metamorphic Complex). The provenance of these sediments, and particularly whether any source can be identified from within other Australian Proterozoic terranes, is critical to test the interpretation that these rocks represent an exotic terrane accreted to the NAC at ~1640 Ma (Close et al., 2004).

Nd-isotopic comparison of NAC and SAC

A comparison of the Nd-isotopic signatures of Palaeoproterozoic igneous rocks from the NAC and Gawler Craton may provide some indication of the commonality or otherwise of these two large crustal blocks, and therefore help test models that invoke Palaeoproterozoic continuity between NAC and SAC.

Improved Palaeomagnetic constraints

Palaeomagnetic constraints potentially provide the most definitive test of models that invoke large separation between crustal blocks. As discussed above, the currently available palaeomagnetic dataset is not sufficient to provide these tests.

Part II: Metallogenic Events in Proterozoic Australia

In this section, descriptions of known Proterozoic mineralising events in Australia are grouped according to the following time intervals:

- > 1870 Ma
- 1870 – 1810 Ma
- 1810 – 1750 Ma
- 1730 – 1670 Ma
- 1660 – 1630 Ma
- 1620 – 1550 Ma
- 1520 – 1000 Ma.

This information comes from data in Geoscience Australia's OZMIN database as well as the authors' knowledge of deposits that have been recently discovered or described. The timing of mineralization is either based on measured ages or inferred from geological relationships and/or similar nearby deposits.

SPATIAL AND TEMPORAL DISTRIBUTION OF MINERALISING EVENTS

> 1870 Ma

In this time interval, the most active mineral system was the iron-ore mineral system, in which iron accumulations, originally deposited in banded iron-formation, were upgraded by hydrothermal and/or supergene fluid flow to form iron-ore deposits. The upgrading process resulted in the dissolution of deleterious minerals such as phosphates, silicates and carbonates along with the oxidation of magnetite to hematite (Clout and Simonson, 2005). Initial deposition of iron-rich sedimentary rocks and/or upgrading of the accumulations to form iron-ore deposits ocurred in Proterozoic Australia in the Hamersley Group that overlies the Pilbara Craton, the Middleback Subgroup in the Cleve Domain of the Gawler Craton and in the Wildman Siltstone in the Pine Creek Orogen of the NAC.

In the Hamersley Basin, which hosts one of the largest global accumulations of iron-ore (3.5 Gt: Clout and Simonson, 2005), banded-iron formations were deposited at ca. 2597 Ma and ca. 2479 Ma (c.f. Nelson et al., 1999). These accumulations are interpreted to have been upgraded at ca. 2008 Ma by moderate temperature (150-250°C), oxidised saline brines expelled during continental extension between 2050 and 2000 Ma (Barley et al., 1999; Müller et al., 2005). Although strictly speaking not Proterozoic deposits, Proterozoic iron accumulations were also the source of Cainozoic riverine or channel iron-ore deposits.

Hematite iron-ore deposits in the Middleback Ranges of the Gawler Craton have produced over 200 Mt with a remaining reserve of 26 Mt. In addition, significant resources (370 Mt) of magnetite-rich iron ore has been established in the region. Although the age of the host Middleback Subgroup is not well constrained, intrusion of ca. 1850 Ma granites of the Donington Suite and an age of ca. 1870 Ma for a volcanic unit correlated with the upper Middleback Subgroup (Fanning et al., 2007; Fraser and Reid, 2007) suggests deposition of the carbonate and oxide facies banded iron-formation, which formed the proto-ore to the iron-ore deposits, occurred before ca. 1870 Ma. Note, however, that recent work by Szpunar et al. (2007) has suggested that parts of the Middleback Subgroup may have been deposited after ~1790 Ma. Yeates (1990) interpreted that the iron ores formed by supergene upgrading of the proto-ore via dissolution of gangue material.

Ironstones within the Frances Creek district of the Pine Creek Orogen historically have produced 5.8 Mt of iron ore with a JORC-compliant resource of an additional 3.4 Mt (http://www.territoryiron.com.au). These deposits occur within carbonaceous phyllite and siltstone near the base of the ca. 2020 Ma Wildman Siltstone (Worden et al., in press), and are interpreted to have formed during early thrusting (Stuart-Smith et al., 1993).

Other than these iron-ore deposits, the Challenger lode gold deposit in the northwestern Gawler Craton is the only well dated deposit formed in Proterozoic Australia prior to 1870 Ma. The deposit was formed in two stages: pre-metamorphic primary deposition and remobilisation during peak metamorphism between 2454 Ma and 2414 Ma (McFarlane, 2006).

The Browns deposit in the Pine Creek Orogen (JORC compliant resource of 84 Mt @ 2.70% Pb, 0.78% Cu, 0.12% Co and 0.11% Ni: http://www.compassnl.com.au) is hosted by the Whites Formation, which underlies the Wildman Siltstone. McCready et al. (2004) interpreted this deposit to be syn-diagenetic, which would imply an age of ~2020 Ma. Alternatively, lead isotope model ages imply an epigenetic origin at ca. 1630 Ma (calculated from data in McCready et al., 2004, using the CSIRO-AGSO lead evolution model).

1870-1810 Ma

Mineralisation between 1870 and 1810 Ma was restricted to the NAC, where a large variety of mineral deposits of this age are present in the Halls Creek Orogen and its extension into the Litchfield Province of the Pine Creek Orogen. The most significant deposits, however, are located in the Tennant Creek goldfield.

In the Halls Creek and Pine Creek Orogens, mineralisation spanned the period between ca. 1862 Ma and ca. 1840 Ma. The earliest deposits are small (0.8 Mt @ 10% Zn) volcanic associated massive sulphide (VAMS) deposits within the Daly River mineral field in the Litchfield Province that are associated with ca. 1862 Ma submarine felsic volcanic rocks (Ferenczi, 2004). In the Halls Creek Orogen, ca. 1855 Ma to ca. 1846 Ma (Page and Hoatson, 2000) layered mafic-ultramafic intrusions in the Central and Western Zones contain platinum group elements (**Panton: 14.3 Mt @ 5.2 g/t 7E [2.2 g/t Pt, 2.4 g/t Pd and 0.3 g/t Au], 0.3% Ni and 0.08% [http://www.platinumaus.com]**) and nickel-copper deposits (Sally Malay: 3.74Mt @ 1.74% Ni, 0.72% Cu and 0.09% Co [http://www.sallymalay.com]).

Felsic volcanic rocks, which form part of the ca. 1843 Ma (Page et al., 1994) Koongie Park Formation in the Central Zone of the Halls Creek Orogen host two VAMS deposits, Sandiego and Onedin, which have a combined JORC-compliant resource of 4.65 Mt @5.2% Zn, 1.2% Cu, 0.8% Pb and 29.6 g/t Ag (http://www.anglo.com.au). The Angelo Microgranite, which was intruded along the contact between the Koongie Park Formation in the Central Zone and the Olympio Formation in the Central Zone, is associated with the Mount Angelo deposit, which is interpreted as a porphyry Cu-Mo deposit with a non-JORC-compliant resource of 144 Mt grading 0.2% Cu (Sewell, 1999; Sanders, 1999). The Angelo Microgranite is interpreted to be a subvolcanic intrusion related to the Koongie Park Formation (Sheppard et al., 1995).

Outside of the Halls Creek-Pine Creek orogenic belt, the only significant mineralising event between 1870 Ma and 1810 Ma is the Tennant Creek iron-oxide copper-gold event. The Tennant Creek goldfield is the third largest gold producer in the Northern Territory, producing of 5 MOz of gold and 345,000 tonnes of copper. Geochronological data (Compston, 1995; Compston and McDougall, 1994; Fraser et al., submitted; Maidment et al., 2006) and geological relationships (Wedekind et al., 1989; Huston et al., 1993; Huston and Cozens, 1994; Skirrow and Walshe, 2002) constrain this mineralising event to between 1850 Ma and 1845 Ma, contemporaneous with basin inversion associated with east-west-trending folds and the intrusion of granites and porphyritic dikes of the Tennant Creek Suite. Ore deposits in the Tennant Creek and nearby Rover fields, which are closely associated with ironstones, are dominated by a Au-Cu assemblage, with many deposits also containing significant bismuth and selenium. Some deposits, such as Juno, locally contain in excess of 80 ppm uranium (Large, 1975). Recent exploration in the Rover field has highlighted the presence of Zn-Pb-rich systems (http://www.westgold.com.au).

1810-1750 Ma

The period between 1810 and 1750 Ma contains the most significant known lode gold mineral systems of Proterozoic Australia as well as less important volcanic-associated massive sulphide and iron-oxide copper-gold mineral systems. In the northern and central parts of the NAC, lode gold deposits are known in the Tanami and Pine Creek Orogens. The Tanami and Pine Creek Orogens are the two largest gold provinces in Proterozoic Australia, with global resources of 12 MOz (Huston et al., 2007) and 12 MOz (Partington and Williams, 2000), respectively.

In the Pine Creek Orogen, recent dating of xenotime associated with gold indicates an age of 1780 ± 10 Ma (Rasmussen et al., 2006), whereas in the Tanami Orogen xenotime ages suggest gold deposition at 1801 ± 19 Ma (Cross et al., 2005; Bagas et al., 2007). Although within uncertainty of each other, the geographical distribution of the ages may suggest younging of lode gold deposits toward the northeast. This suggestion requires testing with improved geochronological constraints.

At the same time as lode gold mineralisation in the Tanami Orogen, small Zn-Cu-Pb VAMS deposits (e.g. Edwards Creek and Harry Creek) formed in felsic-dominated volcaniclastic rocks in the Strangways Metamorphic Complex along the southern margin of the NAC (Warren and Shaw, 1985; Hussey et al., 2005). Dating of the host rocks suggest that these inferred syngenetic deposits formed at ca. 1810 Ma to ca. 1800 Ma (Hussey et al., 2005). Tin-Cu veins in the Mount Wells area in the Pine Creek Orogen at ca. 1805 Ma (Wyborn et al., 1998) pre-date local lode gold deposits, but overlap the age of gold mineralisation in the Tanami Orogen.

In addition to VAMS deposits, the Strangways Metamorphic Complex and rocks in the Jervois area contain Cu-Au (Bellbird) and Zn-Pb-Ag deposits that were initially interpreted as syngenetic deposits (Warren and Shaw, 1985), but more recently interpreted as IOCG deposits (Hussey et al., 2005). Hussey et al. (2005) made this interpretation based on metal assemblages (e.g. the presence of significant REEs), metal ratios (i.e. Zn/Pb) and more radiogenic lead isotopes relative to the Strangways VAMS deposits. Based on lead isotope model ages Hussey et al. (2005) interpreted IOCG mineralisation to have occurred at ca. 1790 Ma.

The Oonagalabi Zn-Cu deposit in the eastern Arunta region is hosted by a younger succession dominated by felsic volcaniclastic rocks with an age of ca. 1765 Ma (Hussey et al., 2005). Although deposit-scale observations suggest mineralisation occurred as replacement of a carbonate lens, lead isotope model ages are consistent with replacement during or shortly after sedimentation (Hussey et al., 2005; D. Huston, unpub. data).

1740-1670 Ma

The period between 1740 Ma and 1670 Ma was characterised three broad pulses of mineralisation. The oldest event is constrained to between 1740 Ma and 1730 Ma and includes spatially and metallogenically diverse mineral systems. Lode gold deposits in the Mt Olympus district of the Ashburton Province in Western Australia, which have global resources totalling nearly 1 MOz, are interpreted to have ages of ca. 1738 Ma (Rasmussen et al., 2006). A similar age is inferred for the Tick Hill deposit **(**0.5 MOz: Partington and Williams, 2000**)** in the Mount Isa Inlier based on the inferred age of the Wonga Event with which it has been associated (Neumann, in press). In addition to these gold deposits, this event is also manifested at the ca. 1740 Ma Ranger unconformity uranium deposit and ca. 1730 Ma Bynoe tin-tantalum pegmatites in the Pine Creek Orogen (Kinny, P. D. and Wartho, J., unpublished data).

In contrast, the second mineralising pulse is more constrained both in space and metallogeny. This event includes vein tungsten deposits (e.g. Hatches Creek district) and skarn W±Mo deposits located within and south of the Davenport Province in the NAC. These deposits have ages between ca. 1720 and ca. 1710 Ma (G. Fraser et al., submitted).

The period between 1695 Ma and 1670 Ma is characterised by uranium and base metal systems related to basinal fluid flow with or without active magmatism, including unconformity uranium deposits in the northern NAC and Broken Hill-type (BHT) Zn-Pb-Ag deposits in the eastern Curnamona Province, the Eastern Succession of the Mt Isa Inlier and the Georgetown region. Deposits in the eastern Curnamona Province, which include the giant Broken Hill deposit (280 Mt @ 8.5% Zn, 10.0% Pb and 148 g/t Ag: Huston et al., 2006) that has a likely age of ca. 1686 Ma (Page et al., 2005; assumes deposition during or closely after sedimentation), are the oldest, and apparently ~10 million years older than deposits in the Eastern Succession of the Mt Isa Inlier (e.g. Cannington [43.8 Mt @4.4% Pb, 11.6% Zn and 538 g/t Ag: Huston et al., 2006] at ca. 1675 Ma (Carr et al., 2001). This age relationship requires testing with detailed geochronological comparisons. Broken Hill-type deposits appear to be restricted to the eastern margin of Proterozoic Australia. The range in age of BHT Zn-Pb-Ag deposits appears to overlap with that of unconformity uranium deposits (e.g. the Jabiluka deposit, 52 Mt @ 0.39% U_3O_8; Ozmin database).

1660-1630 Ma

The period between 1660 Ma and 1630 Ma is marked by two mineralising events that involve similar types of mineral systems but occur in spatially discrete parts of the NAC. Both of these events are marked by major Mount Isa-type (MIT) deposits and smaller unconformity uranium deposits. The older event, which affected the eastern NAC between 1655 Ma and 1650 Ma, includes the giant Mt Isa (150 Mt @ 7.0% Zn, 6.0% Pb and 150 g/t Ag: Huston et al., 2006) and Hilton-George Fisher (228 Mt @ 10.8% Zn, 5.5% Pb and 99 g/t Ag: Huston et al., 2006) MIT deposits and the small Redtree sandstone uranium deposit. The younger event, which affected the northern NAC between 1640 Ma and 1630 Ma, includes the giant HYC (227 Mt @ 9.2% Zn, 4.1% Pb and 40 g/t Ag: Huston et al., 2006) MIT deposit and the Nabarlek (0.6 Mt @ 1.81% U_3O_8, Ozmin database) unconformity uranium deposit, and some sandstone-hosted uranium deposits (e.g. Junnaguna, Westmoreland field) in the northern and eastern parts of the NAC (Polito et al., 2006). Vallini et al. (2007) report an age of unconformity uranium-type mineralisation of ca. 1632 Ma for the Killi Killi Hills prospect in the western Tanami region. The enigmatic Browns Pb-Cu-Ni-Co deposit, which is also associated with significant uranium has a lead isotope model age consistent with formation during this latter event. Outside of the northern NAC, enigmatic deposits at Abra and Mt Misery (possibly BHT) appear to have formed at this time in the Ashburton region in Western Australia and in the Georgetown region, respectively.

1620-1550 Ma

Several mineralising events affected the SAC between 1620 Ma and 1550 Ma. In the central and western Curnamona Province IOCG systems formed between 1624 Ma and 1612 Ma. These were followed by a major IOCG event at ca. 1595 Ma that resulted in the giant Olympic Dam deposit (Johnson and Cross, 1995; 4500 Mt @ 1.08% Cu, 0.5 g/t Au, 0.04% U_3O_8; Ozmin database) and, possibly, other important deposits such as Prominent Hill and Carrapeteena in the eastern Gawler Craton. This IOCG event appears to be similar in age to a lode gold event in the Central Gawler goldfield, including the Tarcoola, Tunkillia and Weednanna deposits and prospects (Budd and Fraser, 2004; Fraser et al, in press). Some IOCG deposits in the Eastern Mt Isa inlier (Osborne) are similar in age to the Olympic Dam deposit, as are uranium deposits (e.g. Radium Hill and Crockers Well) in the Curnamona Province. Deposition of the Century MIT deposit (105 Mt @ 12.1 % Zn, 1.8% Pb and 46 g/t Ag: Huston et al., 2006) in the northeastern part of the NAC occurred at ca. 1575 Ma.

Between 1560 and 1550 Ma in the eastern NAC, lode gold deposits in the Croydon area (e.g. Croydon: 4.0 Mt @ 7.7 g/t Au: Ozmin database) and uranium (skarn and albitite) deposits (e.g. Valhalla: 16.3 Mt @ 1.13 kg/t U_3O_8 [JORC-compliant]: http://www.valhallauranium.com.au) in the Mt Isa Inlier were formed.

1520-1000 Ma

The Eastern Succession of the Mt Isa Inlier hosts a number of IOCG deposits, including the Ernest Henry deposit (total resources of 2.7 MOz Au and 1.83 Mt Cu: Partington and Williams, 2000), dated between 1530 and 1515 Ma (Mark et al., 2006) and the Selwyn deposit (1.1 MOz Au and 0.345 Mt Cu: Partington and Williams, 2000), dated at ca. 1500 Ma (Mark et al., 2006). In addition, the copper orebody at Mt Isa (648 Mt @ 2.2% Cu: Ozmin database) has been dated at ca. 1525 Ma (Perkins et al., 1999). However, as these dates are based on $^{40}Ar/^{39}Ar$ analyses of ore-related biotite/phlogopite, they must be regarded as minimum ages given the relatively low closure temperature of biotite (~300°C) in the K-Ar system. A molybdenite Re-Os age from the Osborne deposit, which is in the same belt that hosts the Ernest Henry and Selwyn deposits, yielded a much older age of ca. 1595 Ma (Gauthier et al., 2001).

Australia's largest diamond deposit, Argyle (681 Mcrts recovered to end of 2006) in the Halls Creek Orogen, has been dated at ca. 1178 Ma (Pidgeon et al., 1986), and the recently discovered Nebo-Babel Ni-Cu deposit in the western Musgrave Province (300 Mt @ 0.3% Ni and3% Cu: Ozmin database:) has an inferred age of ca. 1080 Ma based on the age of the associated suite of layered mafic intrusions (Seat et al., 2007). In addition to these deposits, the Tropicana and Havana gold deposits in the Biranup Complex of Albany-Fraser Orogen are hosted by felsic gneisses (http://www.independencegroup.com.au) that, based on regional data, underwent high-grade metamorphism at ca. 1200 Ma (Spaggiari et al., 2007), although the timing of gold mineralization relative to high-grade metamorphism is not well established.

Part III: Geodynamic Models for Proterozoic Australia – 1870 to 1550 Ma

INTRODUCTION

The discussion in Part I above highlights many of the ambiguities in particular lines of geological evidence often used to infer geodynamic setting. In response to these uncertainties, and to encourage consideration of alternative geodynamic scenarios, here we present two alternative scenarios of the geodynamic evolution of Proterozoic Australia for the time interval 1870 to 1550 Ma.

These two geodynamic scenarios are presented as continental-scale models for five time intervals, as follows:

- 1870 – 1810 Ma
- 1810 – 1750 Ma
- 1730 – 1670 Ma
- 1660 – 1630 Ma
- 1620 – 1550 Ma

For each time interval, we present a list of geological elements followed by two alternative geodynamic scenarios, labelled Model A and Model B. Model A is dominated by subduction and accretion processes, in part based on the work of Giles et al. (2002), Betts et al. (2004), Betts and Giles (2006), Close et al. (2004), and Wade et al. (2006). Model B is an extensional-dominated scenario, based on the work of Gibson et al. (in press). Each of these two models is presented in two figures; the first with the geological elements and geodynamic setting, and the second with a coloured overlay showing known and predicted commodities (see below). The two models A and B can be viewed as end members, highlighting the contrasting geodynamic interpretations that can be drawn from the available geological evidence. Much of the information, particularly the time constraints, used to generate the lists of geological elements for particular time intervals is derived from Neumann and Fraser (in press).

PREDICTIVE METALLOGENESIS

A feature of this work is the explicit motivation to use geodynamic reconstructions to predict the potential for particular mineral systems at a continental-scale., Many authors have related metallogeny to geodynamic environment, with some authors (e.g. Sawkins, 1984; Groves et al., 2005; Kerrich et al., 2005) inferring geodynamic environment from mineral deposit assemblages. The understanding of the setting of many classes of mineral deposits has advanced over the last three decades to the point that knowledge of geodynamic setting can be used as a predictor of the potential for mineral deposits in space and time. In Table 1 (Appendix) we present a classification system that links geodynamic environment with mineral system groups and subgroups, and with deposit types and commodities. We have used the mineral system understanding encapsulated in Table 1 (Appendix) to predict regions of prospectivity for particular commodities on the basis of geodynamic setting and the mineral systems likely to have operated in that setting. Predicted mineral systems include extensions of known mineral systems under cover, as well as mineral systems that are, as yet, unknown in an area but may be predicted on the basis of the interpreted geodynamic setting. The results of this approach are depicted as coloured overlays on each of the geodynamic scenarios, in which we display known and predicted mineral commodities. The distribution of known commodities follows the discussion outlined in Part II above. Predicted commodities are divided into eight commodity groupings as listed below.

U
Unconformity-style, roll-front and paleochanel-style U deposits are predicted in intraplate settings, particularly where basinal fluid flow may be triggered by distal tectonic activity.

Au
Settings predicted as prospective for lode-Au include collisional orogens and strike-slip pop-up deformation. Intrusion-related gold is predicted in continental back-arc and fore-arc basin settings.

Pb-Zn-Cu-Ag±Au
Geodynamic settings associated with developing basins that may have experienced large-scale fluid-flow are predicted to be prospective for base metals. This prediction includes various deposit types, including Broken Hill-type (BHT) Zn-Pb-Ag-Cu, Kuroko-type VAMS Zn-Cu-Pb-Ag-Au, Cyprus-style VAMS Cu-Zn-Co-Ag-Au, MVT-style Zn-Ag-An and Salton Sea-type Zn-Pb-Cu deposits. Geodynamic settings potentially prospective for base metals include, therefore, backarc and forearc basins, continental rifts, rifted arcs, passive margins, mid-oceanic ridges, and strike-slip pull-apart basins.

Cu
Porphyry-Cu is predicted in continental-arc and island-arc settings and Mt Isa-type Cu is predicted in collisional orogenic settings.

Cu-Au
Iron-oxide Cu-Au (IOCG) deposits, including Olympic Dam-type, Concurry-type, Candelaria-type and Tennant Creek-type are predicted in continental arc and backarc settings, and in collisional orogens.

Fe
Algoma-type BIFs are predicted in back-arc settings whereas Hammersley-type BIFs are predicted in passive margin settings.

Ni-Cu-PGE
Orthomagmatic Ni-Cu-PGE deposits are predicted in association with episodes of known or predicted mafic magmatism in continental arc and island arc settings, as well as continental rifts and mid-ocean ridges. These deposits may also be associated with continental hotspot-related magmatism.

Sn-W-Mo
Pegmatite and fractionated granite-related Sn-W-Mo deposits are predicted in regions of continental reworking. Skarn-related Sn-W-Mo deposits may be formed in magmatic-hydrothermal systems in arc settings.

The semi-transparent coloured overlays on the continental-scale geodynamic scenarios (Figures 2 to 21) illustrate regions predicted to be prospective for particular commodities based on these conceptual links between geodynamic setting and mineral systems. While recognising the inevitable uncertainties, we hope that the ideas set out here may encourage interest in further geological activity across the spectrum of the geological community, including the mineral industry, government surveys and academia. The addition of fundamental geological observations, particularly in regions obscured by younger cover, will be critical to providing tests for the ideas presented here, both with respect to geodynamics and mineral prospectivity, and thus to developing and refining new resource-exploration strategies.

GEODYNAMIC AND METALLOGENIC MODELS FOR THE INTERVAL 1870 – 1810 Ma

Geological Elements

The following geological elements are depicted on the continental-scale tectonic diagrams, and require consideration in any tectonic models:

- Granitic magmatism of the ~1865 – 1850 Ma Paperbark Supersuite and Dougalls Suite in the Halls Creek Orogen, together with broadly coeval mafic magmatism (e.g. Sally Malay, Panton), followed by tight folding and metamorphism to migmatite-grade during the Halls Creek Orogeny at ~1840 Ma,
- Felsic magmatism of the Sally Downs Supersuite (~1835 – 1805 Ma) following the Halls Creek Orogeny (Sheppard et al., 2001a),
- Arc-like mafic magmatism of the Wangi Basics in the Litchfield Province, western Pine Creek Orogen, probably in the time interval ~1865 – 1850 Ma (Glass, 2007),
- Sedimentation of the turbiditic Finniss River Group in the Litchfield Province, at ~1860 Ma (Worden et al., in press),
- Metamorphism of the Fog Bay and Hermit Creek metamorphics in the Pine Creek Orogen at ~1855 Ma (Carson et al., in press),
- Sedimentation of the Edith River and El Sherana groups in the Pine Creek Orogen at ~1830 Ma (Worden, in press),
- Sedimentation of the ~1860 Ma Stubbins Formation in the Tanami region of the western NAC, followed by deposition of Tanami Group sediments including the turbiditic Killi Killi Formation at ~1840 Ma (Crispe et al., 2007),
- Granitic magmatism of the ~1825 – 1810 Ma Birthday Suite, in the Tanami region (Crispe et al., 2007),
- Deposition of the turbidites of the Lander Rock Beds in the Aileron Province at ~1840 Ma, correlating with the Killi Killi Formation in the Tanami region (Claoue-Long, in press),
- Sedimentation of the ~1860 Ma Warramunga Formation, followed by the Flynn and Ooradidgee groups in the interior of the NAC, in the Tennant Inlier. Deposition of the Warramunga Formation was closely followed by intrusion of the Tennant Suite granites at ~1850 Ma, upright folding about east-west trending fold axes, and accompanying Cu-Au-Bi-mineralisation (Claoue-Long, in press; Fraser et al., submitted),
- Intrusion of the Kalkadoon-Leichhardt Suite granites (~1850 Ma) on the eastern margin of the NAC, in the Mt Isa Inlier (Neumann, in press),
- Sedimentation of at least parts of the Hutchison Group on the eastern side of the Gawler Craton (Fraser and Reid, in press),
- Intrusion of the Donington Suite granites at ~1850 Ma on the eastern side of the Gawler Craton (Fraser and Reid, in press),
- Deposition of black shales together with mafic volcanics of the Maraloou Formation at ~1840 Ma in the upper Yerrida Basin, along the southern margin of the Capricorn Orogen (Kositcin in press),
- Intrusion of early phases of the Moorarie Supersuite granites from ~1830 Ma in the Capricorn Orogen (Kositcin, in press).

Continent-Scale Geodynamic Scenarios

Model A: Subduction/accretion-dominated

Note that in this model the Western Australian (WAC), North Australian (NAC) and South Australian (SAC) cratons were probably widely-separated during this time interval, and the tectonic development in these three cratons is, therefore, envisaged as independent.

Subduction is envisaged between the Kimberley Craton and NAC, terminated by continental collision at ~1840 Ma, followed by intrusion of stitching granites of the Kevins Dam Suite (Griffin et al., 2000; Sheppard et al., 2001a). Subduction between the Kimberley and NAC is regarded to have been predominantly northwest-dipping, with a possible short-lived switch to southwest dipping at ~1860 Ma, shortly before continental collision (Griffin et al., 2000). This collisional margin is represented by rocks of the Halls Creek Orogen, and possibly the Litchfield Province of the western Pine Creek Orogen. Evidence for a subduction margin includes adakitic granitoids of the Dougalls Suite (~1850 Ma) and parts of the Sally Downs Supersuite (~1830 – 1805 Ma) (Sheppard et al., 2001a), and possible arc-like geochemistry of the Wangi Basics in the Litchfield Province (Glass, 2007).

Another convergent margin to the south can tentatively be proposed, responsible for suturing of the Aileron Province with the northern NAC prior to ~1840 Ma. This convergent margin is considerably more speculative than the convergent margin proposed for the Halls Creek Orogen. Evidence for this suture comes from reflection-seismic data in the Tanami region, from which a crustal-scale suture is interpreted to pre-date deposition of Tanami Group sediments at ~1840 Ma (Huston, 2006). More specific timing constraints do not exist for such a suture, and no subduction-related igneous rocks have been identified of appropriate age in the appropriate location. However, north-south directed compression at ~1850 Ma would provide an explanation for east-west trending fold axes in the Warramunga Formation, in the Tennant Creek Inlier. In this scenario, sedimentation of the Warrumunga (Tennant Inlier) and Stubbins (Tanami region) formations at ~ 1860 Ma, and the overlying Ooradidgee (Tennant Inlier) and Tanami (Tanami region) groups, was broadly syn-collisional, and could, therefore, be interpreted as occurring in a foreland basin setting.

Felsic intrusive and extrusive rocks of the ~1850 Ma Kalkadoon-Leichhardt Suite form a north-south trending linear belt along the inferred eastern margin of the NAC. In keeping with the subduction-dominated theme of this model, the Kalkadoon-Leichhardt Suite is depicted above a west-dipping subduction zone. This is largely on the basis of the geometry of a broadly linear magmatic belt parallel with a continental margin. We note, however, that the Kalkadoon-Leichhardt Suite is S-depleted, Y-undepleted, indicating plagioclase-residual crustal melting at relatively shallow-levels, and not characteristic of Phanerozoic arc magmas (Wyborn et al., 1987, 1992). Consequently, the presence of a west-dipping subduction zone at ~1850 Ma under the eastern margin of the NAC is speculative.

East-dipping subduction at ~1850 Ma on the eastern margin of the Gawler Craton has been tentatively proposed by Ferris et al. (2002). These authors intepret the Hutchison Group to have been deposited on a passive margin, with the Donington Suite granites (~1850 Ma) forming as an outboard island arc.

In the WAC, collision of the Yilgarn and Pilbara Cratons is envisaged by Sheppard et al. (2001b) to have occurred during the ~2000 – 1960 Ma Glenburgh Orogeny, significantly prior to the 1870 – 1810 Ma interval of interest here. Consequently, the WAC is regarded as already amalgamated by ~1870 Ma, with intracratonic extension accounting for sedimentary deposition in the upper Yerrida Basin at ~1840 Ma (Cawood and Tyler, 2004).

Model B: Extension-dominated

This scenario is based on apparent geological similarities between the eastern margins of the North Australian (NAC) and South Australian (SAC) cratons in subsequent time periods (Gibson et al., in press), and therefore places the NAC and SAC broadly in their current relative positions.

An east-facing ocean-margin is proposed, with deposition of the Hutchison Group sediments on the eastern margin of the Gawler Craton occurring in a continental extensional margin setting. Magmatism occurred along, or outboard of, this margin at ~1850 Ma, represented by the Donington Suite in the south and by the Kalkadoon-Leichhardt Suite in the north, possibly in a back-arc position relative to a subduction-zone located further east.

The NAC is interpreted to have been under extension for much of this period, explaining the relatively continuous and widespread sedimentary record across the NAC, but punctuated by short intervals of basin inversion. The Halls Creek Orogen is interpreted as the locus of more focussed lithospheric extension, possibly as a failed rift.

As in Model A above, deposition of the upper succession in the Yerrida Basin is envisaged as intracratonic, in response to continental extension between the Yilgarn and Pilbara Cratons.

Known mineral systems

Mineral systems known to have been operative in this time period include:

- Cu-Au±Bi in the Tennant Inlier, hosted in the Warramunga Formation (Tennant Creek goldfield),
- Ni-Cu-PGE in the Halls Creek Orogen (Panton, Sally Malay),
- Porphyry-Cu in the Halls Creek Orogen (Mount Angelo),
- VAMS in the the Halls Creek and Pine Creek orogens (Saniego, Onedin),
- Iron-ore in the Middleback Ranges in the eastern Gawler Craton,
- Orogenic-Au was deposited in the Sandpiper and Kookaburra deposits in the western Tanami region (Bagas et al., 2007), although it is uncertain whether the timing of this mineralization fits within the 1870 – 1810 Ma interval or the 1810 – 1750 Ma interval. For the purposes of this exercise, orogenic-Au in the Tanami region has been depicted only in the time interval 1810 – 1750 Ma, consistent with the available time-constraints from The Granites and Dead Bullock Soak goldfields (Huston et al., 2007).

Predicted mineral systems

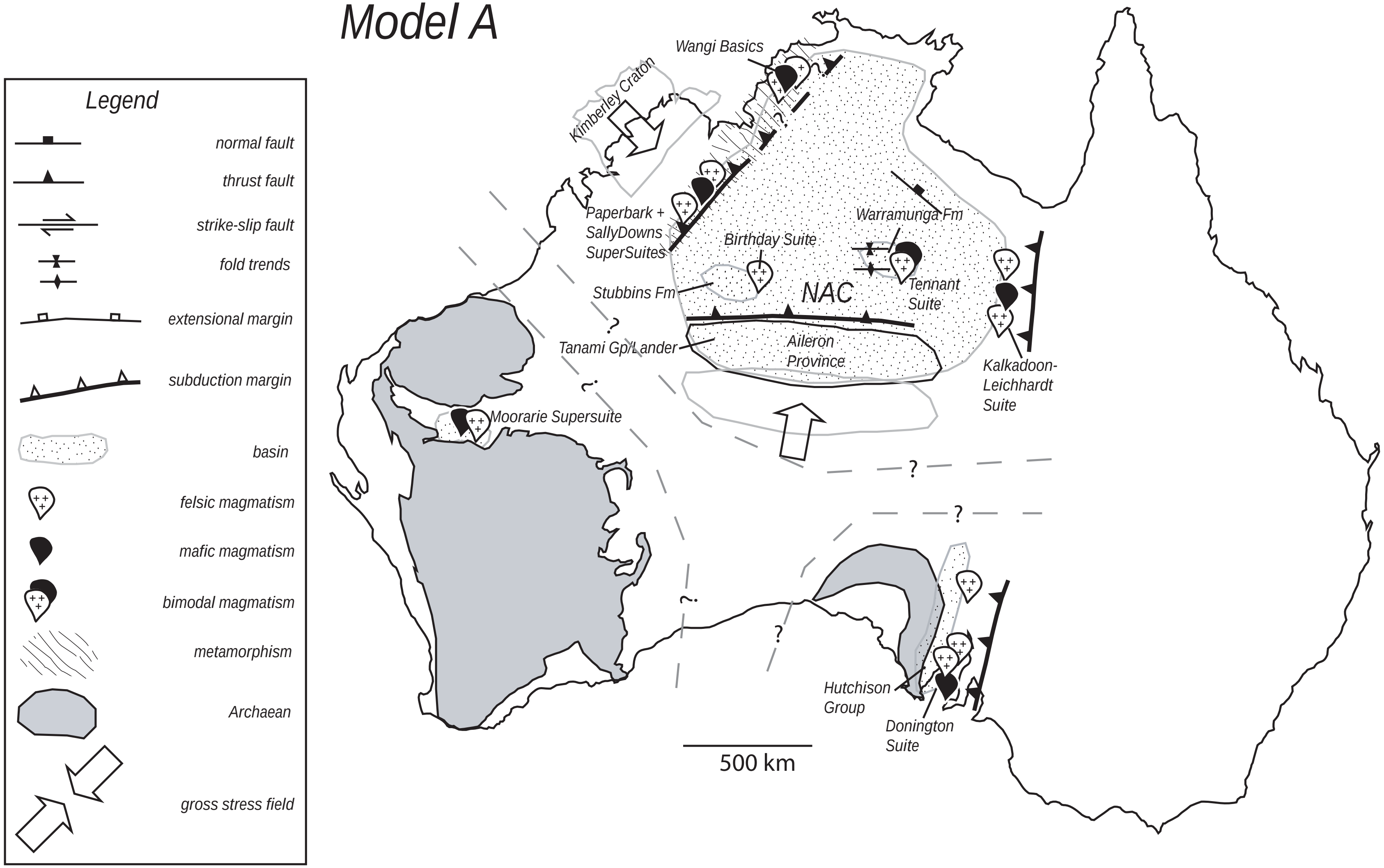
Model A: Subduction/accretion-dominated

- Lode-Au in an east-west-trending belt north of the inferred suture between the Aileron Province and NAC,
- Arc-related porphyry-Cu and back-arc VAMS in the Mt Isa region, associated with the Kalkadoon-Leichhardt Suite, predicted on the basis that the Kalkadoon-Leichhardt Suite represents a former magmatic arc,
- Arc-related porphyry-Cu and back-arc VAMS on the eastern Gawler Craton, associated with the Donington Suite, predicted on the basis that the Donington Suite represents a former magmatic arc,
- Extension of known porphyry-Cu from Halls Creek northeastwards into the Pine Creek region, in a linear belt associated with a former accretionary margin.

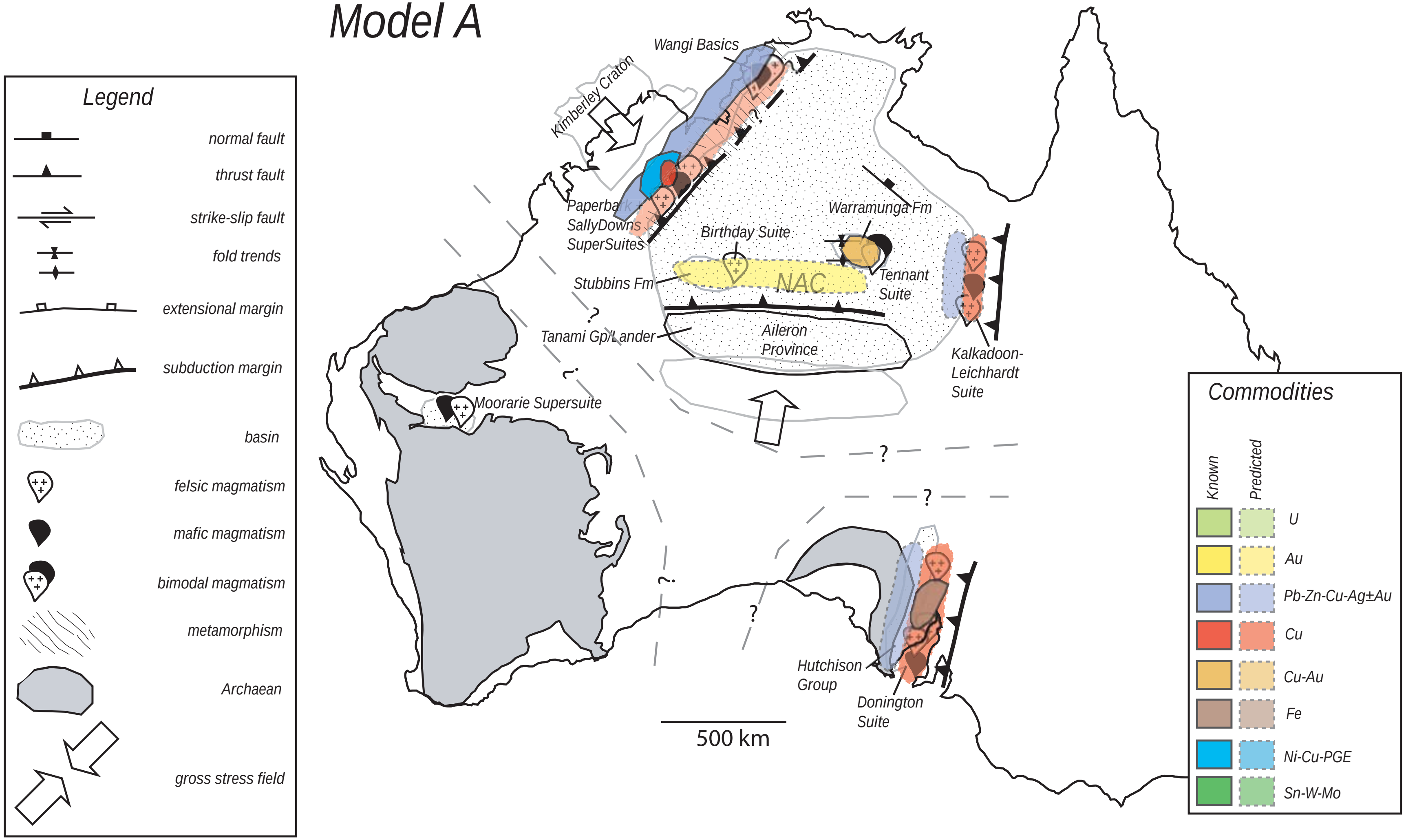
Model B: Extension-dominated

- Extension-related VAMS in a broadly north-south-trending belt along the eastern margin, from the Hutchison Group in the Gawler Craton northwards to the Mt Isa area.

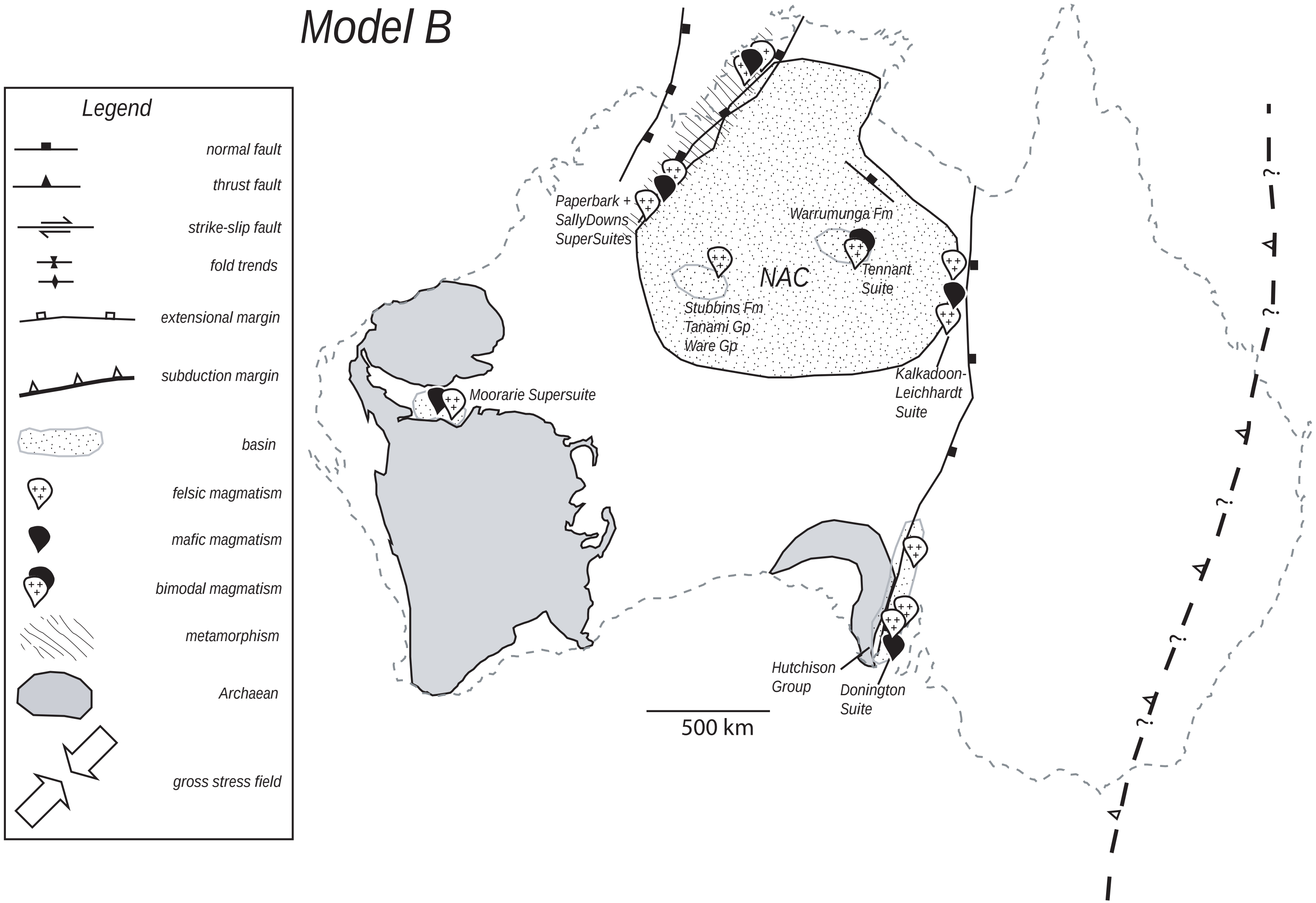
1870 - 1810 Ma
Model A



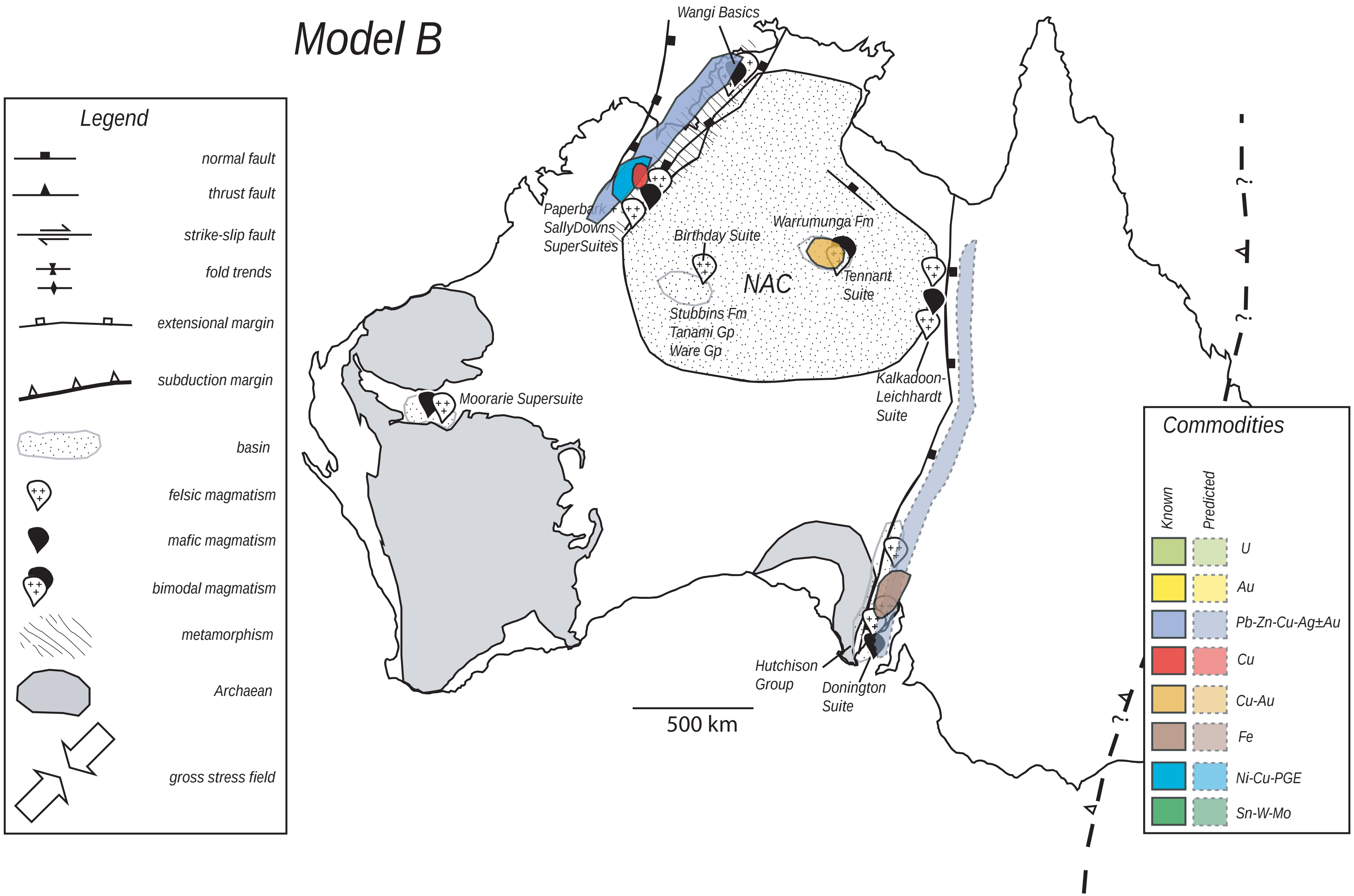
1870 - 1810 Ma
Model A



1870 - 1810 Ma
Model B



1870 - 1810 Ma
Model B



GEODYNAMIC AND METALLOGENIC MODELS FOR THE INTERVAL 1810 – 1750 Ma

Geological Elements

The following geological elements are depicted on the continental-scale tectonic diagrams, and require consideration in any tectonic models:

- Intrusion of the widespread, flat-lying Hart Dolerite at ~1790 Ma in Kimberley region (Carson, in press),
- Widespread sedimentation across the NAC including the Kimberley Group in the Kimberley Craton and Halls Creek Orogen, the Katherine River Group in the Pine Creek Orogen, the Pargee Sandstone in the Tanami region, the Hatches Creek Group in the Davenport Ranges, and the Reynolds Range Group and Ongeva Package in the Aileron Province (Carson, in press; Claoue-Long, in press),
- Widespread magmatism across the NAC, including the Frederick and Grimwade suites in the Tanami region, the Stafford Event (~1810 – 1800 Ma) and Yambah Event(~1780 – 1760 Ma) granites in the Aileron Province, and the Kudinga Basalt in the Davenport Ranges (Crispe et al., 2007; Claoue-Long, in press),
- Sedimentation and volcanism in the Leichhardt Superbasin on the eastern margin of the NAC (Neumann, in press),
- Mafic magmatism in Gawler Craton including the Tournefort dykes on southern Eyre Peninsula and the Bills Lookout Gabbro in the northeastern Gawler Craton (Fraser and Reid, in press),
- Sedimentation of the lower part of the Wallaroo Group along eastern margin of Gawler Craton may have begun towards the end of this time interval (1810 – 1750 Ma), and extended into the following time interval (~1730 – 1670 Ma) (Fraser and Reid, in press),
- Sedimentation in the Nawa Domain of the northwest Gawler Craton may have commenced late in this time interval (~1750 Ma), or early in the following time interval (Payne et al., 2006),
- Sedimentation in the Ashburton, Blair and Earaheedy basins, and intrusion of late-stage phases of Moorarie Supersuite granites in the Capricorn Orogen, broadly synchronous with the Capricorn Orogeny between ~1830 and 1780 Ma (Kositcin, in press),
- Deformation, medium- to high-grade metamorphism and granite intrusion associated with the ~1830 – 1780 Ma Capricorn Orogeny,
- Felsic magmatism of the Bridget Suite at ~1800 – 1790 Ma on the northern margin of the Pilbara Craton. Bridget Suite granites are Sr-undepleted, Y-depleted, which is unusual in comparison with most Australian Proterozoic granites (Budd et al., 2001),
- Thrusting, high-grade metamorphism and granite intrusion during the ~1790 – 1760 Ma Yapungku Orogeny in the Rudall Complex along the northeastern margin of the WAC (Maidment and Kositcin, in press).

Continent-scale Geodynamic Scenarios

Model A: Subduction/accretion-dominated

In this time period the locus of convergent tectonics shifted away from the collision between the Kimberley Craton and NAC, and towards the southern margin of the NAC. North-dipping subduction under the NAC is inferred, based on arc-like mafic and felsic intrusives in the southeastern NAC (Zhao, 1994; Zhao and McCulloch, 1995). The NAC is, therefore, in a back-arc position with respect to the convergent margin to the south. Continental back-arc extension across the NAC may explain the widespread sedimentary record, including the Leichhardt Basin (Scott et al., 2000; Giles et al., 2002).

In the northwest of the NAC, the Kimberley Group sediments are deposited over the Kimberley Craton, and across the Halls Creek Orogen, implying that any elevated topography generated during earlier collisional tectonics had been destroyed by this time. The sheet-like Hart Dolerite is intruded into these sediments, consistent with an extensional setting in the vicinity of the Halls Creek Orogen by ~1790 Ma.

The models of Giles et al. (2002) and Betts and Giles (2006) propose that the SAC was rotated and translated anticlockwise northeastwards such that the Wallaroo Group formed in a back-arc setting relative to an easterly extension of the subduction zone along the southern margin of the NAC. This is illustrated on the geodynamic model in pale grey. In this model, the remainder of the Gawler Craton lies south of this subduction zone and is not juxtaposed with the Wallaroo Group until collision during the Kimban Orogeny between ~1730 and 1700 Ma.

Convergent tectonics in the region of the Rudall Complex, on the northeastern margin of the WAC, is inferred to account for the effects of the Yapungku Orogeny (Bagas, 2004). In this model, we depict southwest-dipping subduction in order to explain the presence of contemporaneous magmatism of the Bridget Suite on the northern margin of the Pilbara Craton. Note, however, that other authors have suggested northwest-dipping subduction in this region at this time (Smithies and Bagas, 1997). Following Bagas (2004), the Yapungku Orogeny can be interpreted as recording the collision of the WAC and NAC. This is consistent with palaeomagnetic studies suggesting that the WAC and NAC were in close proximity by ~1800 Ma (Li, 2000; Williams et al. 2004). We note, however, that geochronological constraints from the Rudall Complex are relatively sparse, and it is possible that significant metamorphic and deformation features attributed to collisional tectonics occurred much later (e.g. 1590 – 1550 Ma) than depicted here (Maidment and Kositcin, in press).

In the Capricorn Orogen, sedimentation in the upper Ashurton and Blair Basins is interpreted as occurring in a foreland basin setting, associated with an orogenic front advancing from the southeast (Cawood and Tyler, 2004). The Capricorn Orogeny resulted in amphibolite-facies metamorphism and intrusion of the Moorarie Supersuite granites between ~1830 and 1780 Ma within the Gascoyne Complex and Ashburton Basin, as well as within the northern margin of the Yilgarn Craton.

Model B: Extension-dominated

This model envisages broadly east-west extension across much of the continent during this time interval, with sedimentation focused mainly along the eastern margin, resulting in the Leichhardt Basin in the north, and deposition of the Wallaroo Group in the south, but with widespread platform sedimentation across much of the NAC (e.g. Kimberley Group, Katherine River Group, Hatches Creek Group, Reynolds Range Group). Intrusion of granites in the Tanami Region and southeastern Arunta Province, and mafic magmatism in the Kimberley-Halls Creek region (Hart Dolerite), Davenport region (Kudinga Basalt) and Gawler Craton (Tournefort dykes and Bills Lookout Gabbro) is interpreted as a consequence of extension.

Exceptions to extension in this time interval occur in the WAC, as expressed by the Capricorn and Yapungku Orogenies. The Capricorn Orogeny is interpreted as an episode of intracontinental reworking involving convergent deformation between the Yilgarn and Pilbara Cratons (Cawood and Tyler, 2004). The Yapungku Orogeny in the Rudall Complex is relatively poorly understood with respect to timing and tectonic setting. Bagas (2004) reports thrusts dipping NNE, broadly consistent in orientation with the strike of the Capricorn Orogen to the south, and suggesting a possible linked evolution within a NNE-SSW compressional regime within the WAC. Such a stress direction is not inconsistent with broadly eastwest directed extension envisaged for the combined NAC-SAC in this model.

Known mineral systems

Mineral systems known to have been active in this time interval include:

- Lode-Au in the Pine Creek and Tanami regions,
- IOCG in the southeast Arunta region (Johnnies Reward and Jervois prospects),
- VAMS in the southeast Arunta (Edwards Creek prospect).

Predicted mineral systems

Both Model A and Model B allow prediction of:

- Lode-Au under cover linking the known goldfields in the Pine Creek and Tanami regions,
- Ni-Cu-PGE potential in the Kimberley region associated with the Hart Dolerite,
- Shale-hosted Cu (Zambian-type) in the Kimberley region, hosted in shales overlying the Hart Dolerite,
- Broken Hill-type VAMS in the Wallaroo Group, eastern Gawler Craton, associated with continental extension,
- Possible Ni-Cu-PGE potential associated with mafic magmatism as represented by the Bills Lookout Gabbro in the northern Gawler Craton,
- Sn-W mineralization in the Capricorn Orogen associated with continental reworking during the Capricorn Orogeny,
- Lode-Au in the Rudall Complex associated with the Yapungku Orogeny.

Model A: Subduction/accretion-dominated

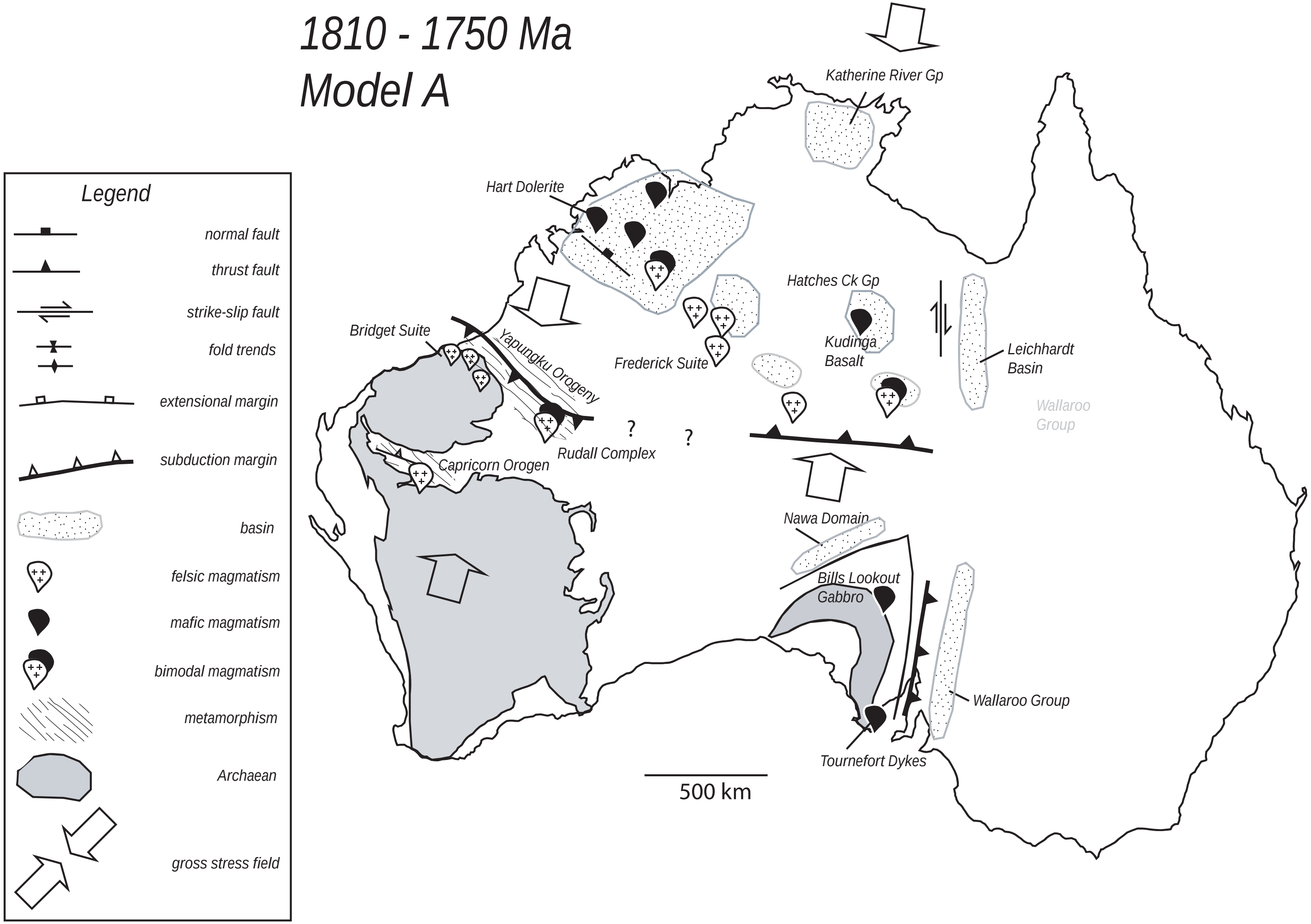
Mineral system predictions specific to Model A for this time interval include:

- Parallel east-west trending belts of porphyry-Cu and VAMS near the southern margin of the NAC, associated with an inferred convergent margin to the south,
- Parallel belts of porphyry-Cu and VAMS along the northeastern margin of the Pilbara Craton, associated with an inferred southwest-dipping subduction margin

Model B: Extension-dominated

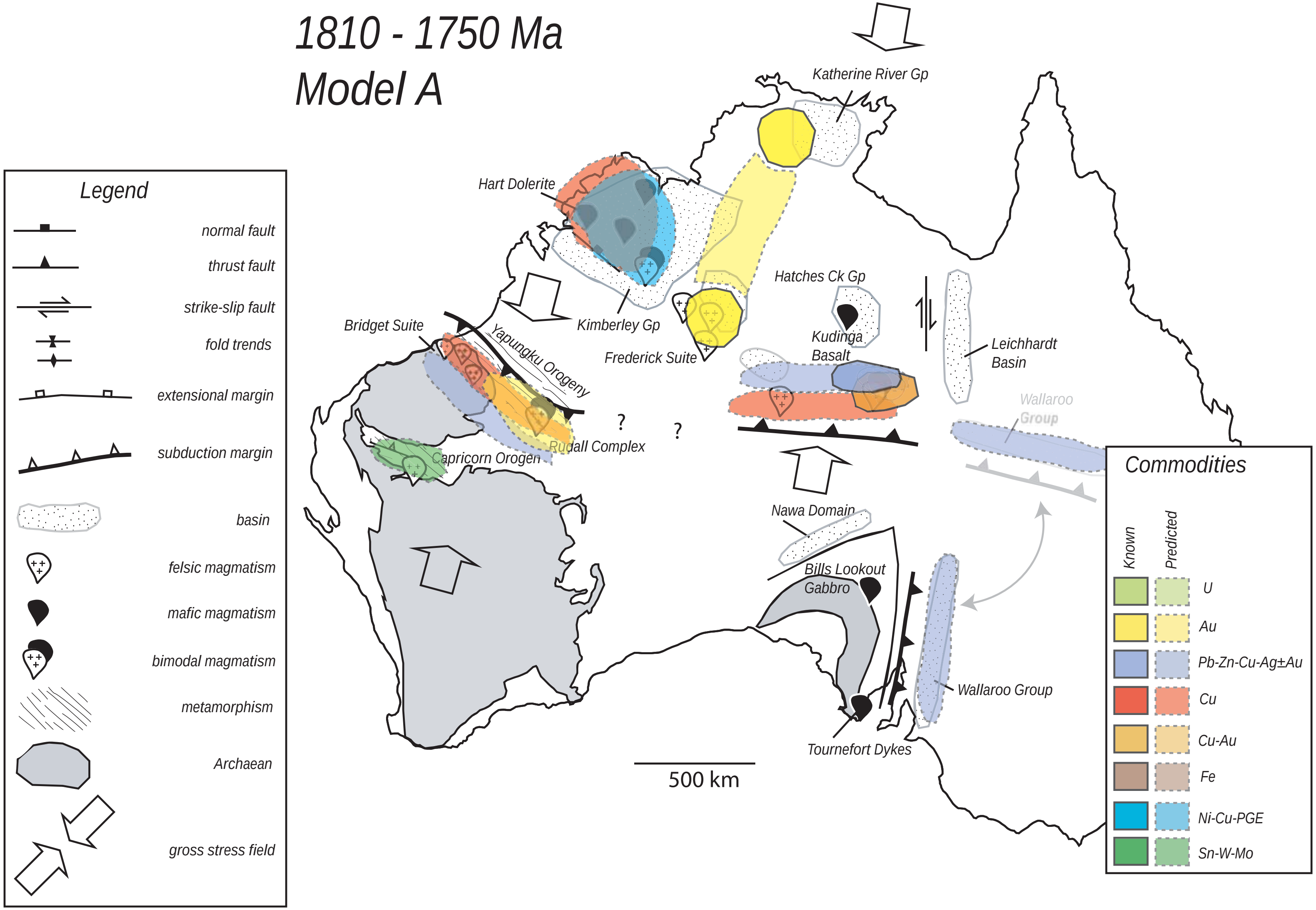
Mineral system predictions specific to Model B for this time interval include

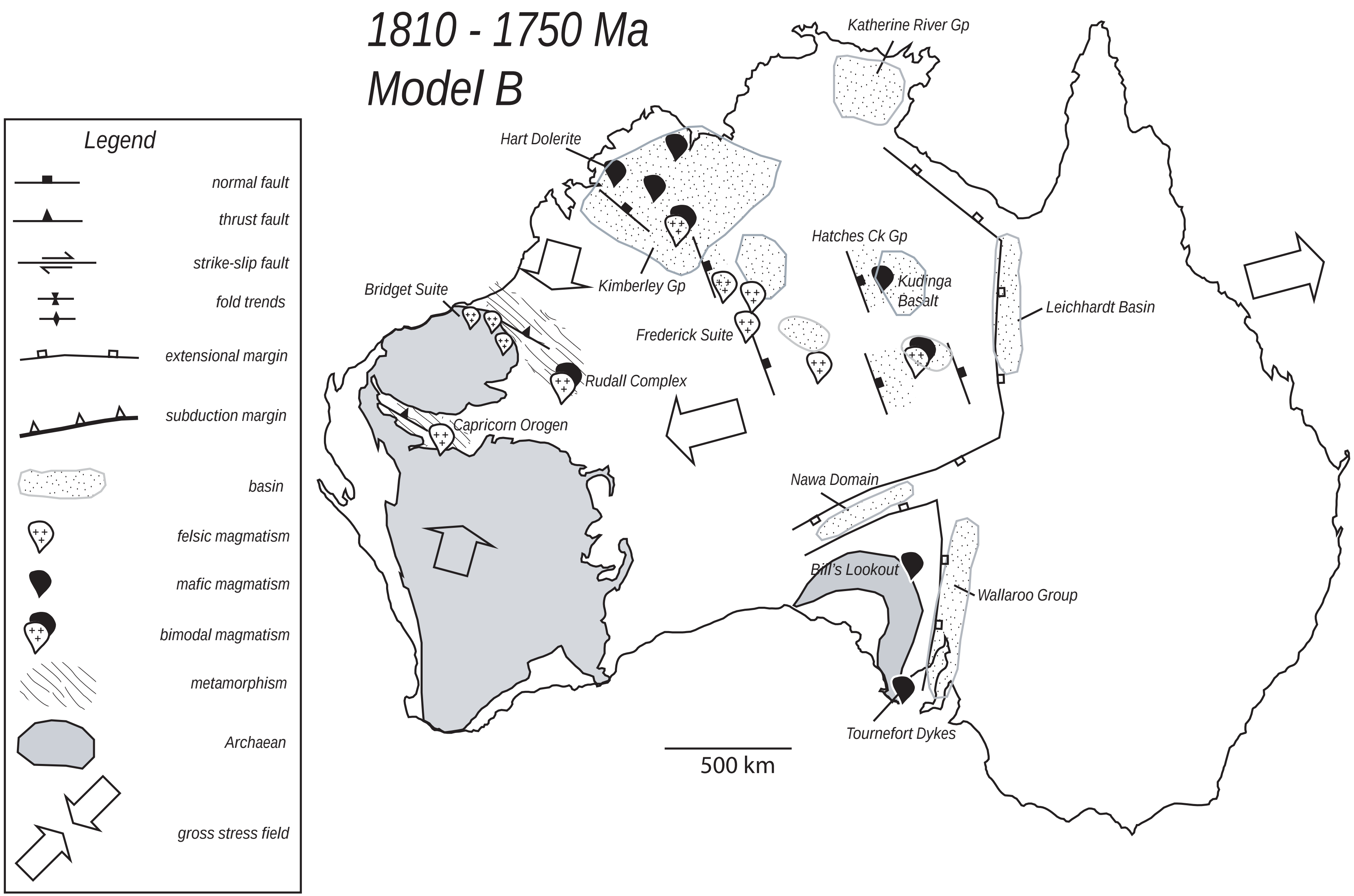
- a laterally extensive belt of VAMS prospectivity oriented north-south along the entire eastern margin, associated with continental extension-related volcanism.

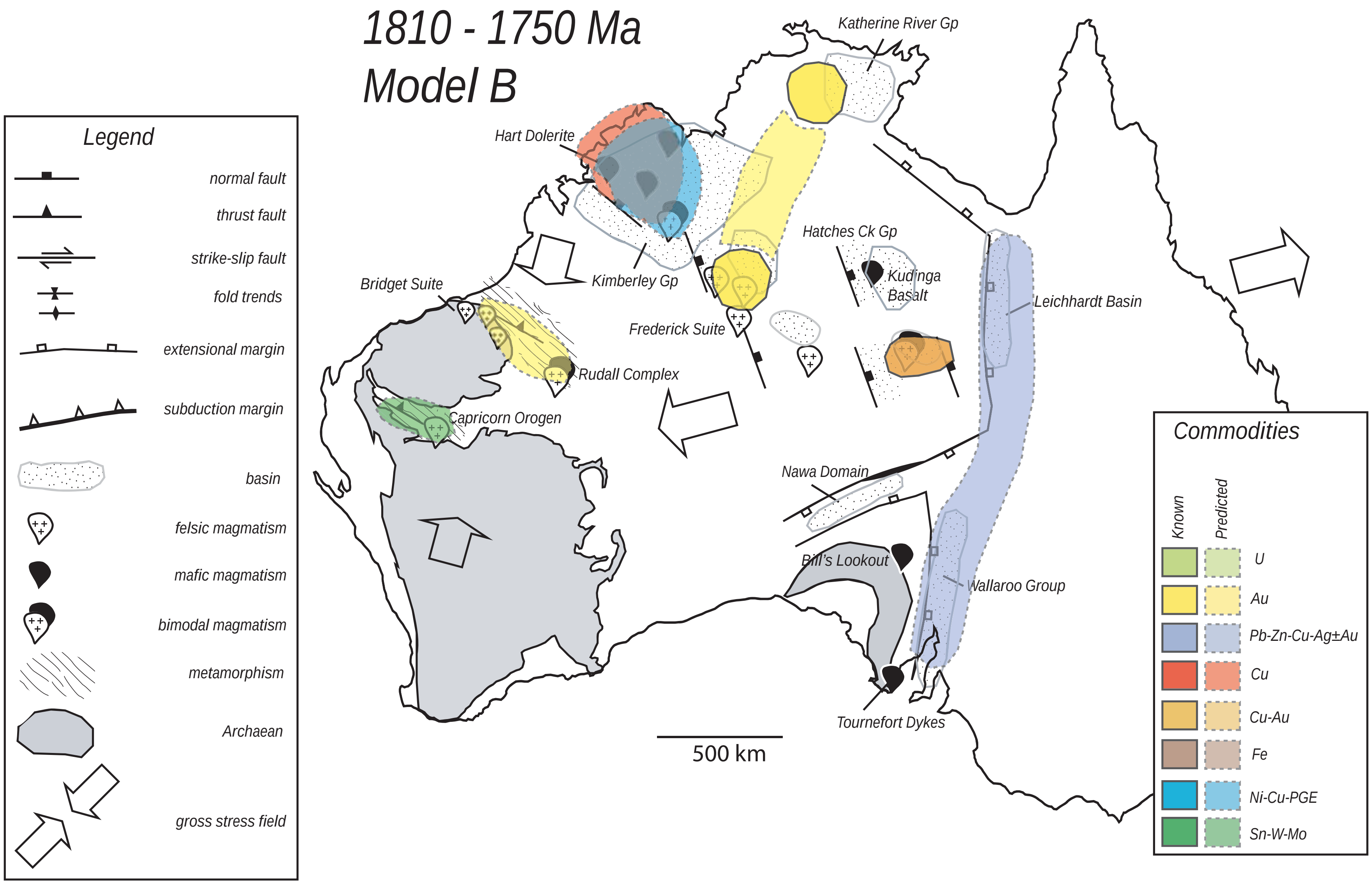


1810 - 1750 Ma
Model A
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Katherine River Gp
Hart Dolerite
Hatches Ck Gp
Kudinga Basalt
Leichhardt Basin
Bridget Suite
Yapungku Orogeny
Frederick Suite
Wallaroo Group
?
?
Rudall Complex
Capricorn Orogen
Nawa Domain
Bills Lookout Gabbro
Wallaroo Group
Tournefort Dykes
500 km

1810 - 1750 Ma
Model A




1810 - 1750 Ma
Model B
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Katherine River Gp
Hart Dolerite
Hatches Ck Gp
Kudinga Basalt
Kimberley Gp
Bridget Suite
Frederick Suite
Leichhardt Basin
Rudall Complex
Capricorn Orogen
Nawa Domain
Bill's Lookout
Wallaroo Group
Tournefort Dykes
500 km


1810 - 1750 Ma
Model B
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Katherine River Gp
Hart Dolerite
Kimberley Gp
Hatches Ck Gp
Kudinga Basalt
Leichhardt Basin
Bridget Suite
Frederick Suite
Rudall Complex
Capricorn Orogen
Nawa Domain
Bill's Lookout
Wallaroo Group
Tournefort Dykes
500 km
Commodities
Known
Predicted
U
Au
Pb-Zn-Cu-Ag±Au
Cu
Cu-Au
Fe
Ni-Cu-PGE
Sn-W-Mo

GEODYNAMIC AND METALLOGENIC MODELS FOR THE INTERVAL 1730 – 1670 Ma

Geological Elements

The following geological elements are depicted on the continental-scale tectonic diagrams, and require consideration in any tectonic models:

- Very widespread sedimentation across the NAC including within the Calvert Superbasin on the eastern margin, the McArthur Basin on the northeastern margin and across much of the Pine Creek Orogen, and the Birrindudu Group in the Tanami region (Neumann, in press; Crispe et al., 2007),
- Mafic magmatism within sedimentary basins in the northeastern NAC, including intrusion of the Oenpelli Dolerite into the Katherine River Group (Worden, in press), the Fiery Creek Volcanics in the Calvert Superbasin (Neumann, in press), and the Dead Horse Metabasalt in the Etheridge Group in the Georgetown region,
- Deformation and metamorphism up to granulite-facies in the southern NAC during the Strangways Orogeny (Claoue-Long et al., in press),
- Felsic magmatism in the NAC, including in the Strangways Range, and the Devils Suite in Tennant Inlier (Claoue-Long, in press),
- Pegmatites of the Bynoe field in the southern Pine Creek Orogen (Kinny, P. D. and Wartho, J., unpublished data),
- Felsic magmatism in the Haasts Bluff Domain of the Warumpi Province, in the southern NAC (Close et al., 2006),
- Mafic and felsic magmatism within the Calvert Superbasin culminating in intrusion of the Sybella Batholith at ~1675 – 1660 Ma (Neumann, in press),
- Sedimentation of the Etheridge Group and protoliths to the Einsleigh Metamorphics in the Georgetown Region (Black et al., 1998),
- Sedimentation of the Lower Willyama Supergroup in the Curnamona Province (Conor et al., 2006),
- Sedimentation of the Wallaroo Group in the eastern Gawler Craton, closely followed by metamorphism during the Kimban Orogeny between ~1730 and 1700 Ma (Fraser and Reid, in press),
- Sedimentation of protoliths to high-grade paragneisses in the Nawa Domain of the northwest Gawler Craton, closely followed by upper-amphibolite to granulite-facies metamorphism (Payne et al., 2006),
- Deformation and upper-amphibolite to granulite-facies metamorphism at ~1730-1700 Ma associated with the Kimban Orogeny in the Gawler Craton. Metamorphic and deformational effects of this event appear to be concentrated in the southeastern part of the Gawler Craton, on either side of the Kalinjala Shear Zone, and in the western part of the craton, in the Fowler and Nawa domains (Fraser and Reid, in press),
- Widespread felsic magmatism across the Gawler Craton throughout this period. This includes the ~1740 – 1730 Ma Middlecamp Granite and McGregor volcanics, ~1715 Ma Paxton Suite granites, ~1710 – 1700 Ma Moody Suite granites, and the ~1690 – 1670 Ma Tunkillia Suite and Ifould Suite granites (Fraser and Reid, in press).
- Intrusion of the granitic Biranup Supersuite (~1700 – 1670 Ma) along the southeastern margin of the Yilgarn Craton,
- Greenschist- to amphibolite-facies high T – low P metamorphism in the Gascoyne Complex of the Capricorn Orogen, known as the Mangaroon Orogeny (~1680 – 1620 Ma), began late in this time interval and extended into the following time interval (Kositcin, in press),
- Intrusion of early phases of the predominantly felsic Durlacher Supersuite (~1680 – 1620 Ma) in the Gascoyne Complex, associated with the Mangaroon Orogeny.

Continent-scale Geodynamic Scenarios

Model A: Subduction/accretion-dominated

Continued convergence is envisaged along the southern margin of the NAC, associated with high-grade metamorphism of the Strangways Orogeny. Further north, in the interior of the NAC, sedimentation within the Calvert, McArthur and Birrindudu basins can be interpreted as a response to continental back-arc extension with respect to the convergent margin to the south (Giles et al., 2002).

Protoliths to the Warumpi Province are envisaged to be forming at this time as felsic intrusions in an oceanic-arc setting south of the NAC (Close et al., 2006).

In the Gawler Craton, contractional deformation and high-grade metamorphism during the Kimban Orogeny may have been in response to collision and accretion of the Donington Suite from the east, terminating. This period sees the earliest rock record in the Curnamona Province, with deposition of the Willyama Supergroup. Note that the model of Giles et al. (2002) interprets the Curnamona Province to have been an eastern extension of the NAC at this time. If this is correct, deposition of the Willyama Supergroup could be regarded as occurring in essentially the same setting as the Calvert Superbasin of the Mt Isa region.

Development of a new subduction zone on the southwestern side (current co-ordinates) of the Gawler Craton is envisaged in some models (e.g. Ferris et al., 2002), associated with intrusion of the ~1690 – 1670 Ma Tunkillia Suite and Ifould Suite granites. If the model of Giles et al. (2002) is correct, in which the SAC is regarded as an easterly extension of the NAC at this time, the subduction zone southwest of the Gawler Craton (current coordinates) proposed by Ferris et al. (2002) could, in fact, form part of the same long-lived subduction system that is envisaged along the southern margin of the NAC. However, the locus of subduction in this time interval appears to have stepped south-westwards across the Archaean core of the Gawler Craton as compared with the previous time interval. In the model of Betts and Giles (2006), this southwestward stepping of the subduction margin is attributed to collision of the Gawler Craton with the NAC. This is illustrated on the geodynamic diagram in pale grey. In this scenario, the ~1690 - 1670 Ma Tunkillia and Ifould Suite in the Gawler Craton, and the broadly synchronous felsic intrusions in the Haasts Bluff Domain of the Warumpi Province, may be genetically linked to the same subduction system.

In the WAC, the Mangaroon Orogeny began late in this time interval and extended from ~1680 – 1620 Ma, resulting in greenschist- to amphibolite-facies metamorphism, reactivation of faults and shear-zones and intrusion of peraluminous Durlacher Supersuite granites. This is regarded as a consequence of intracontinental reworking.

In the southern WAC, granites of the Biranup Supersuite were intruded along the southeastern margin of the Yilgarn Craton between ~1700 and 1670 Ma. These rocks were subsequently intensely deformed and metamorphosed to granulite-facies at ~1200 – 1150 Ma during the Albany-Fraser Orogen and their tectonic setting at ~1700 Ma is highly uncertain. It is possible that magmatism of the Biranup Supersuite could be related to a northeasterly trending subduction zone linked to the inferred convergent margin south of the NAC, although this is highly speculative.

Model B: Extension-dominated

This model, instead of invoking an accretionary margin south of the NAC, envisages ongoing ENE-WSW extension across the combined NAC-SAC. In the NAC, this extension results in sedimentary deposition in the Calvert and McArthur Basins on the northeastern margin. In the SAC, sedimentary deposition shifts eastwards, from the Gawler Craton margin where the Wallaroo Group was deposited in the previous time interval, to the Curnamona region where the Willyama Supergroup is deposited.

A relatively short-lived rift arm can be envisaged in the Nawa Domain of the northwest Gawler Craton, in which sediments are deposited and then metamorphosed within approximately 10 to 20 Ma of deposition (Payne et al., 2006). Renewed extension within this same rift arm may be invoked to explain addition to the crust of more juvenile material that becomes the protolith to the Warumpi Province.

Felsic magmatism is relatively widespread in this period, and in this model is attributed to crustal melting associated with lithospheric extension and consequent increased geothermal gradients.

Although depicted as a period dominated by crustal extension, this interval also includes periods of significant contractional deformation, basin inversion and high-grade metamorphism in both the NAC (Strangways Orogeny) and in the Gawler Craton (Kimban Orogeny). Contraction in both the Strangways and Kimban Orogenies appears to be east over west directed (in current co-ordinates). The duration and driving-force for such contractional deformation is an unresolved problem within this broadly extensional model, particularly as contractional deformation in the Strangways and Kimban orogens appears to have been synchronous with ongoing sedimentation in the Calvert Superbasin and Willyama Supergroup, respectively.

In the WAC, effects of the Mangaroon Orogeny can be envisaged as a consequence of intracontinental transtension or transpression.

Known mineral systems

Active mineral systems in this time period include:

- W-Sn-Ta mineralization in the northern Aileron Province (Moly Hill prospect), in the Davenport Ranges and Barrow Creek regions associated with the Devils Suite granites, and in the Pine Creek region associated with pegmatites of the Bynoe pegmatite field,
- Broken Hill-type Pb-Zn in the eastern succession of the Mt Isa region and in the Broken Hill Domain,
- Uranium in the Pine Creek Region (Ranger, Jabiluka),
- Lode-Au in Ashburton Basin of the Capricorn Orogen, and at Tick Hill in the Mt Isa region.

Predicted mineral systems

Model A: Subduction/accretion-dominated

Mineral system predictions associated with Model A for this time interval include:

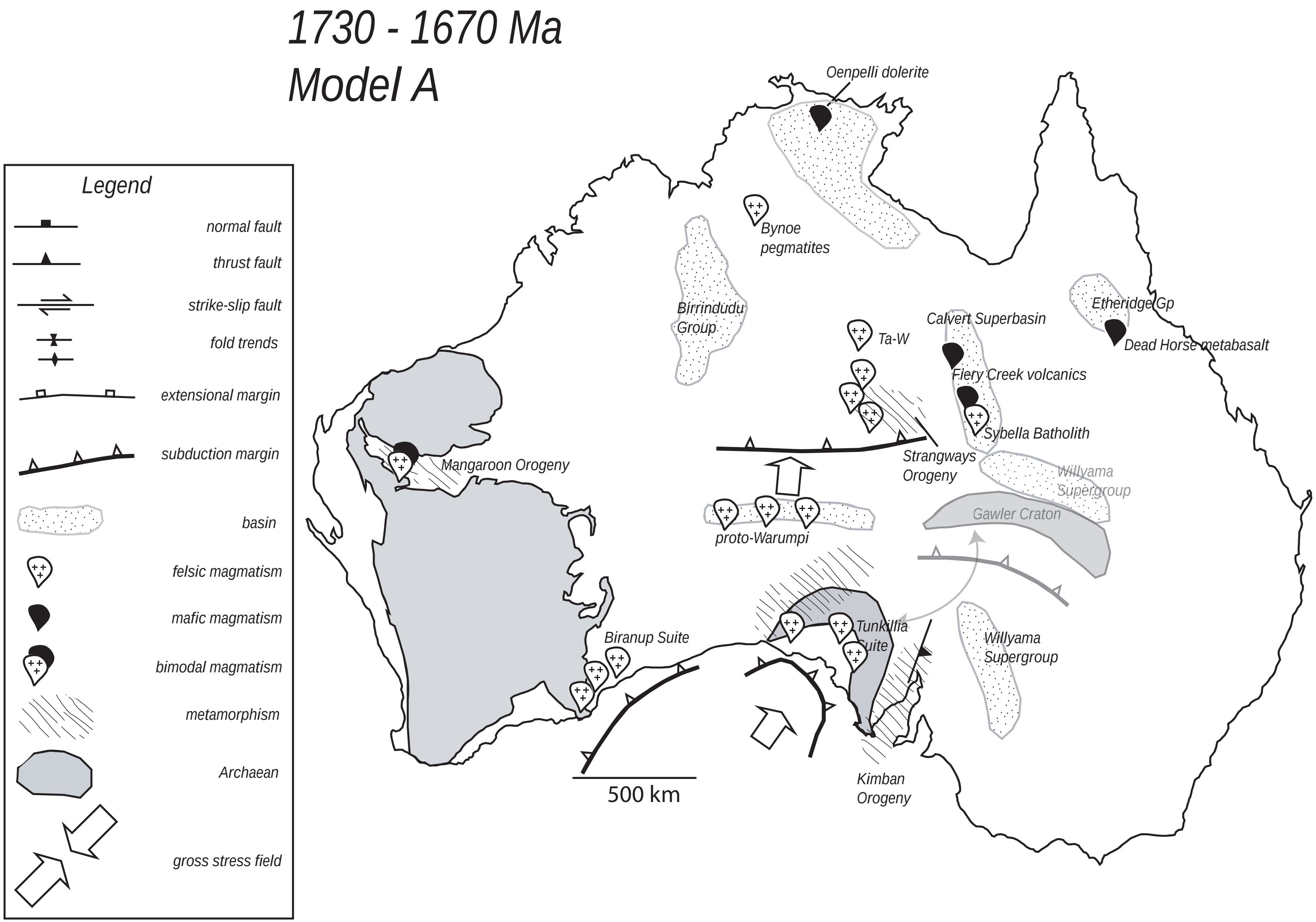
- Porphyry-Cu in the Warumpi Province associated with an inferred magmatic arc forming outboard of the NAC. Note that due to the exposure of mid-crustal levels through much of the Warumpi Province this mineral system, if ever present, may not have been preserved,
- Lode-Au in the southeastern Gawler Craton, and possibly in the Fowler and Nawa Domains of the northwestern Gawler Craton, associated with the Kimban Orogeny,
- Porphyry-Cu on the southeastern margin of Yilgarn Craton associated with the Biranup Suite granites, following the interpretation of a subduction margin and arc magmatism,
- Sn-W mineralization is predicted in the WAC associated with continental reworking of the Mangaroon Orogeny.
- Sn-W mineralization is predicted in the NAC in a belt linking known deposits and prospects.

- Uranium is predicted extending beyond known deposits in the Pine Creek Region, and within the broadly contemporaneous Birrindudu Group.

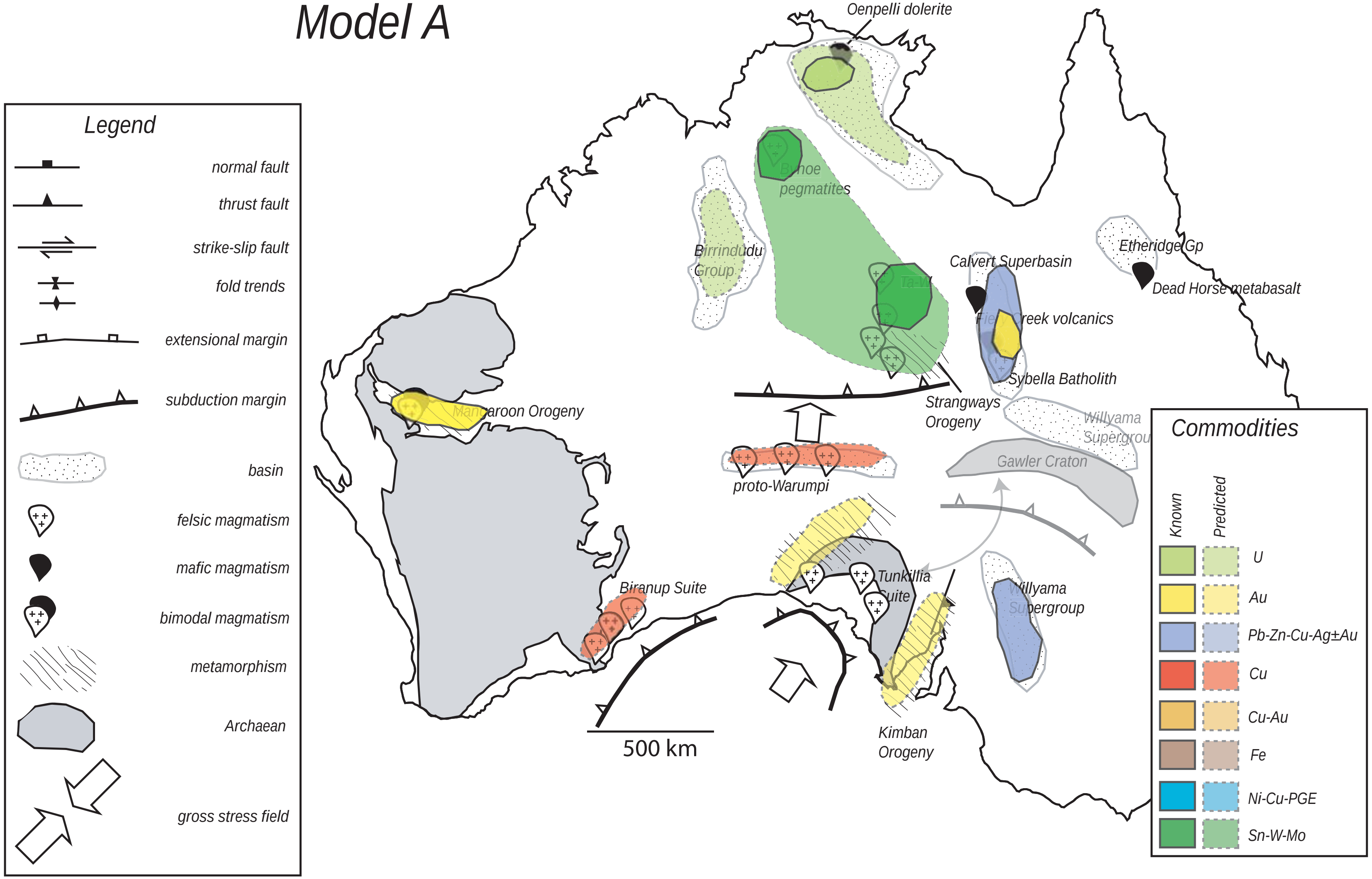
Model B: Extension-dominated

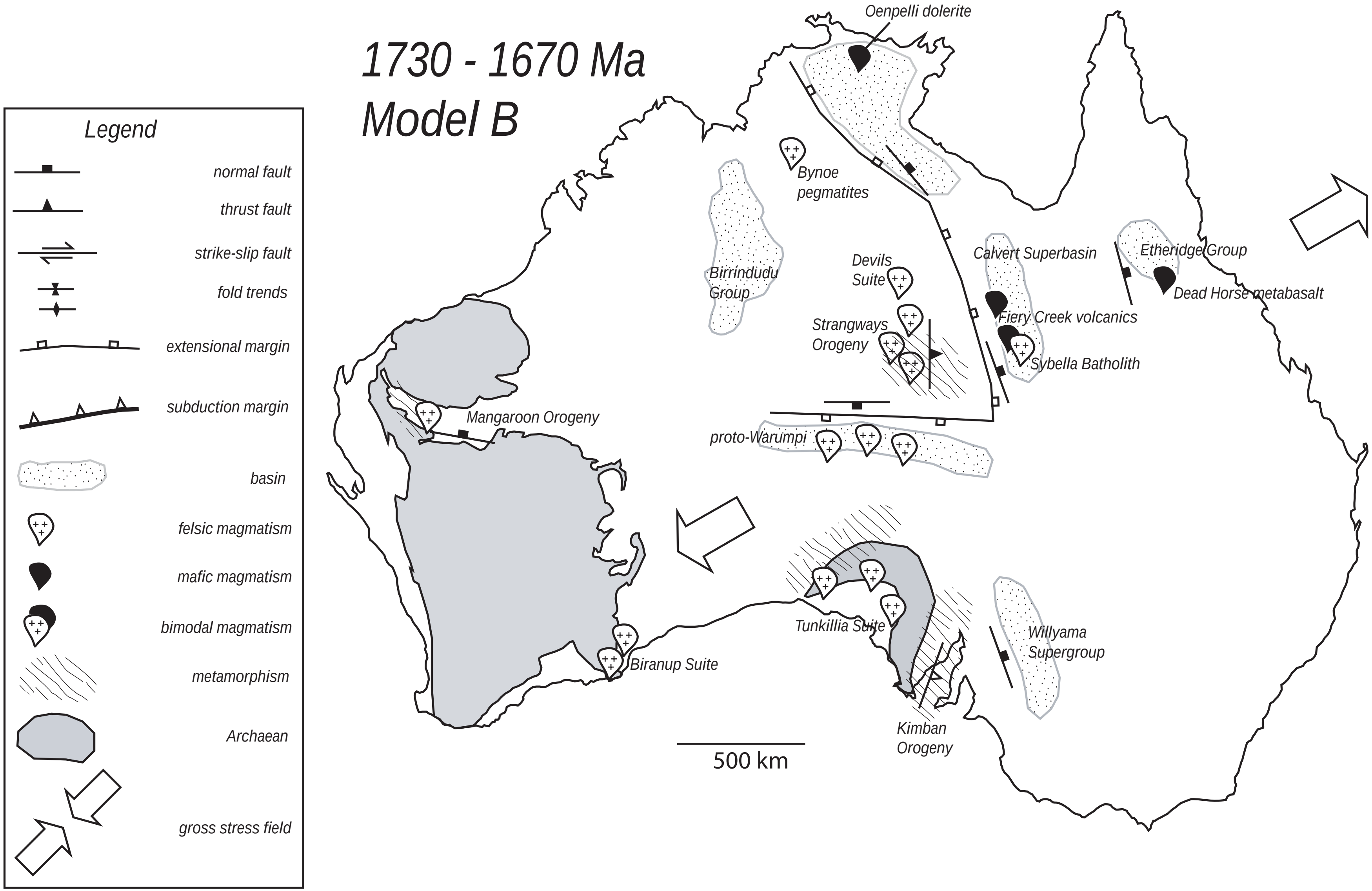
Mineral system predictions associated with Model B for this time interval include:

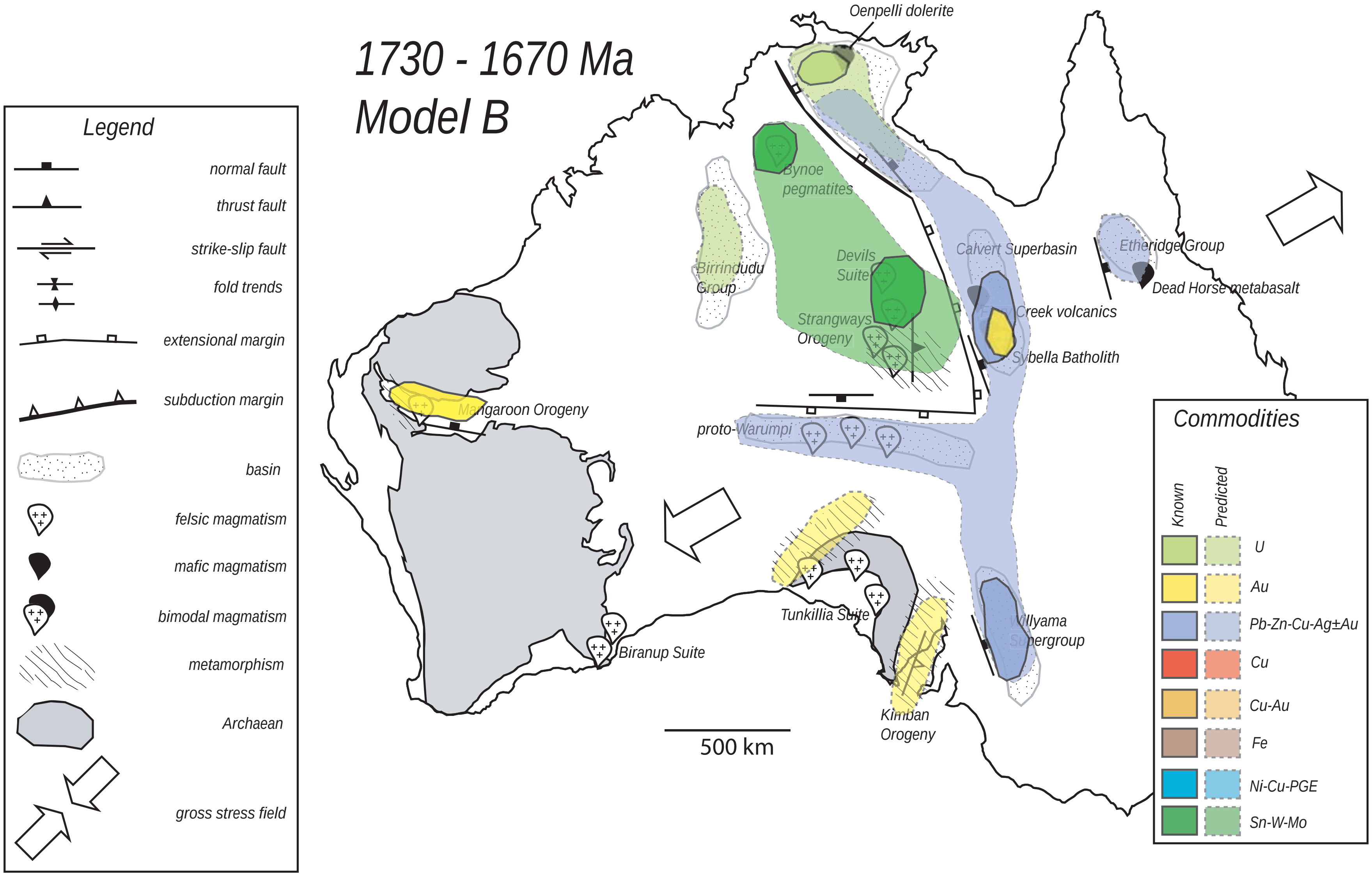
- An extensive VAMS system along the eastern margin associated with extension, linking the known VAMS systems in the Calvert Basin and Willyama Supergroup, and extending eastwards into the Georgetown Inlier. A proposed rift arm containing metasedimentary protoliths of the Warumpi Province can also be predicted as a site of potential VAMS mineralization,
- Lode-Au in deformed and metamorphosed sediments of the Wallaroo Group and Nawa Domain,
- Sn-W mineralization is predicted in the WAC associated with continental reworking of the Mangaroon Orogeny,
- Sn-W mineralization is predicted in the NAC in a belt linking known deposits and prospects.
- Uranium is predicted extending beyond known deposits in the Pine Creek Region, and within the broadly contemporaneous Birrindudu Group.


1730 - 1670 Ma
Model A
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Oenpelli dolerite
Bynoe pegmatites
Birrindudu Group
Ta-W
Calvert Superbasin
Etheridge Gp
Dead Horse metabasalt
Fiery Creek volcanics
Sybella Batholith
Strangways Orogeny
Willyama Supergroup
Gawler Craton
Mangaroon Orogeny
proto-Warumpi
Tunkillia Suite
Biranup Suite
Willyama Supergroup
Kimban Orogeny
500 km

1730 - 1670 Ma
Model A




1730 - 1670 Ma
Model B
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Oenpelli dolerite
Bynoe pegmatites
Birrindudu Group
Devils Suite
Strangways Orogeny
Calvert Superbasin
Etheridge Group
Dead Horse metabasalt
Fiery Creek volcanics
Sybella Batholith
Mangaroon Orogeny
proto-Warumpi
Biranup Suite
Tunkillia Suite
Kimban Orogeny
Willyama Supergroup
500 km


1730 - 1670 Ma
Model B
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Oenpelli dolerite
Bynoe pegmatites
Birrindudu Group
Devils Suite
Strangways Orogeny
Calvert Superbasin
Etheridge Group
Dead Horse metabasalt
Creek volcanics
Sybella Batholith
Mangaroon Orogeny
proto-Warumpi
Tunkillia Suite
Biranup Suite
Willyama Supergroup
Kimban Orogeny
500 km
Commodities
Known
Predicted
U
Au
Pb-Zn-Cu-Ag±Au
Cu
Cu-Au
Fe
Ni-Cu-PGE
Sn-W-Mo

GEODYNAMIC AND METALLOGENIC MODELS FOR THE INTERVAL 1660 – 1630 Ma

Geological Elements

The following geological elements are depicted on the continental-scale tectonic diagrams, and require consideration in any tectonic models:

- Sedimentation in the Birrindudu Basin, including the Birrindudu Group and Limbunya Group, in the northwest NAC (Crispe et al., 2007),
- Sedimentation in the Isa Superbasin (~1670 – 1575 Ma) throughout the McArthur region, Lawn Hill Platform and Leichhardt River Fault Trough (Neumann, in press),
- High-grade metamorphism in the Warumpi Province of the southern NAC, together with felsic and mafic intrusions, associated with the Leibig Orogeny (Close et al., 2006),
- Mafic intrusions of the Andrew Young Igneous Complex in the southern Aileron Province (Claoue-Long and Hoatson, 2005),
- Sedimentation of the Sundown and Paragon Groups forming the upper part of the Willyama Supergroup in the Curnamona Province, with sedimentation apparently ceasing at ~1640 Ma (Gibson et al., in press),
- Sedimentation of the ~1660 Ma Tarcoola Formation in the central Gawler Craton, and possible sedimentation in the Mt Woods Domain of the northern Gawler Craton (Fraser and Reid, in press),
- High-grade metamorphism in the Moondrah Gneiss at ~1660 Ma, in the western Gawler Craton (Fanning et al., 2007),
- Intrusion of the ~1680 – 1620 Ma Durlacher Supersuite, and high T- low P metamorphism of the Mangaroon Orogeny, in the Capricorn Orogen (Kositcin, in press).

Continent-scale Geodynamic Scenarios

Model A: Subduction/accretion-dominated

The Leibig Orogeny in the southern NAC is proposed to have occurred in response to the Warumpi Province colliding with the NAC at ~1640 Ma, along a long-lived convergent margin as also shown in the previous two time intervals. For consistency with interpretations for previous time intervals, we depict the Warumpi Province colliding with the NAC across a north-dipping subduction zone. We note, however, that Scrimgeour (2006) suggests that formation and accretion of the Warumpi Province occurred in a south-dipping subduction setting between ~1690 and 1610 Ma, implying a switch in subduction polarity between ~1750 and 1700 Ma.

On the eastern and northern margin of the NAC, this period marks a change from extensional to sag-phase basin development (Betts and Giles, 2006).

On the western margin of the Gawler Craton, ultrahigh temperature metamorphism of the Moondrah Gneiss occurred at ~1660 Ma (Fanning et al., 2007). In the models of Giles et al. (2002) and Betts and Giles (2006), in which the SAC is regarded as an easterly extension of the NAC at this time, high-grade metamorphism of the Moondrah Gneiss at ~1660 Ma can be attributed to accretionary tectonics along the subduction margin south of the combined NAC-SAC.

Model B: Extension-dominated

The overall extension depicted in the previous two time slices is interpreted to cease during this time interval, at ~1640 Ma, as evidenced by an apparent cessation of sedimentation in the Curnamona Craton, and an interpreted change from syn-rift to post-rift or sag-phase sedimentation in the Isa Superbasin (Gibson et al., in press). This change in stress may have occurred response to major changes in plate motion, as suggested by a hairpin bend in the apparent polar wander path (APWP) at ~1640 Ma (Idnurm, 2000).

In the southern NAC this is the time of the Leibig Orogeny, during which the Warumpi Province converged with the Aileron Province via sinistral transpression (Close et al., 2006), producing granulite-facies metamorphism and lower-crustal melting (Close et al., 2006). At approximately the same time, slightly further north, in the Aileron Province, the Andrew Young Hills mafic intrusions were emplaced. In this model, transpressional deformation during the Warumpi Province is interpreted as essentially intracratonic, perhaps involving inversion and closure of a former rift basin, but not involving significant subduction and major ocean closure.

In the northern NAC, significant fluid-flow within basins resulted in unconformity-related U-mineralisation (Narbalek, Ranger), consistent with a change in stress driving fluid-movement.

In the SAC, deposition of the Tarcoola Formation can be interpreted as occurring in a localised intracontinental basin, prior to transpressional deformation in central Australia.

Known mineral systems

Active mineral systems in this time period include:

- Unconformity-related U-mineralization in the Pine Creek region, and also in the southernmost Birrindudu Basin (Vallini et al., 2007),
- U-mineralization in the Mt Isa Inlier (Redtree and Westmoreland deposits),
- Mt Isa type Pb-Zn-Ag at HYC in the McArthur Basin and in the Mt Isa Inlier.

Predicted mineral systems

Both Model A and Model B predict the following mineral systems:

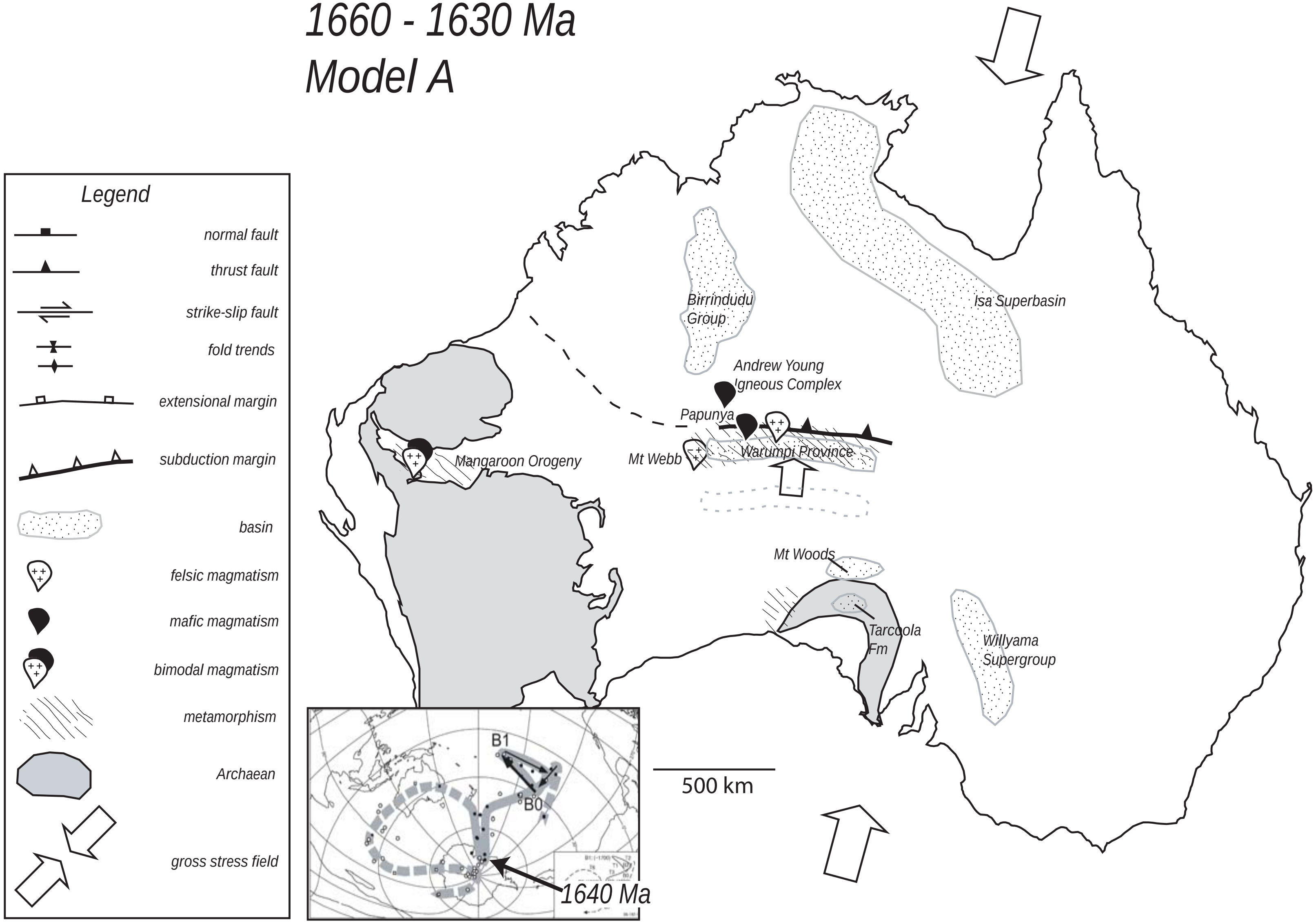
- Ni-Cu-PGE associated with mafic intrusions at Andrew Young Hills and Papunya, in the southern NAC,
- IOCG at Mt Webb, a possible westerly extension of the Warumpi Province,
- Unconformity-related U-mineralization through the Birrindudu Basin, linking with U-systems known to have been active in the Pine Creek Orogen, and extending southeast through the McArthur region into the Isa Superbasin. This system can also be predicted to extend southwards into the Willyama Supergroup in the Curnamona Province.

Model A: Subduction/accretion-dominated

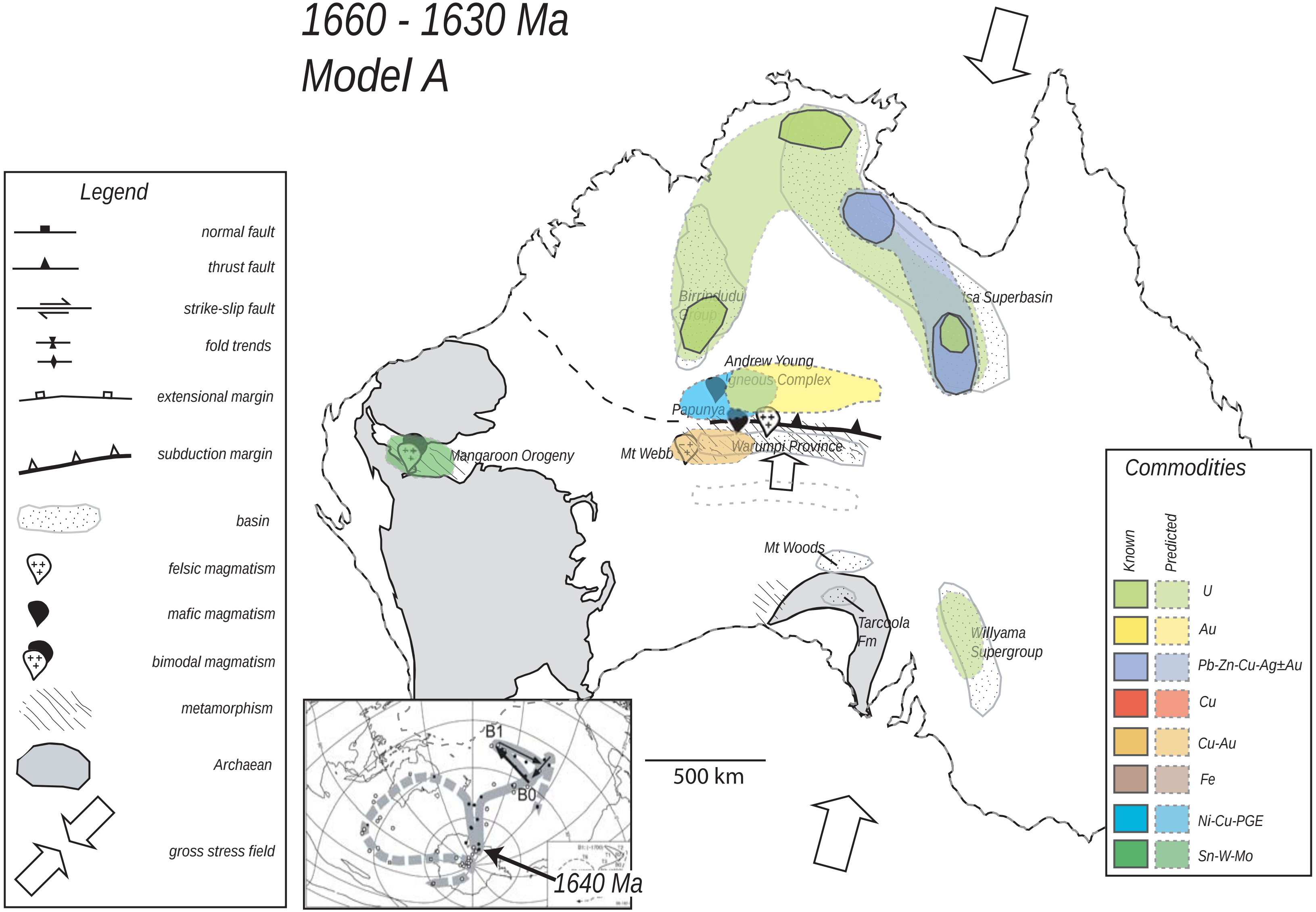
Predicted mineral systems specific to Model A include:

- lode-Au in the NAC north of the Warumpi/NAC suture, associated with the Leibig Orogeny.

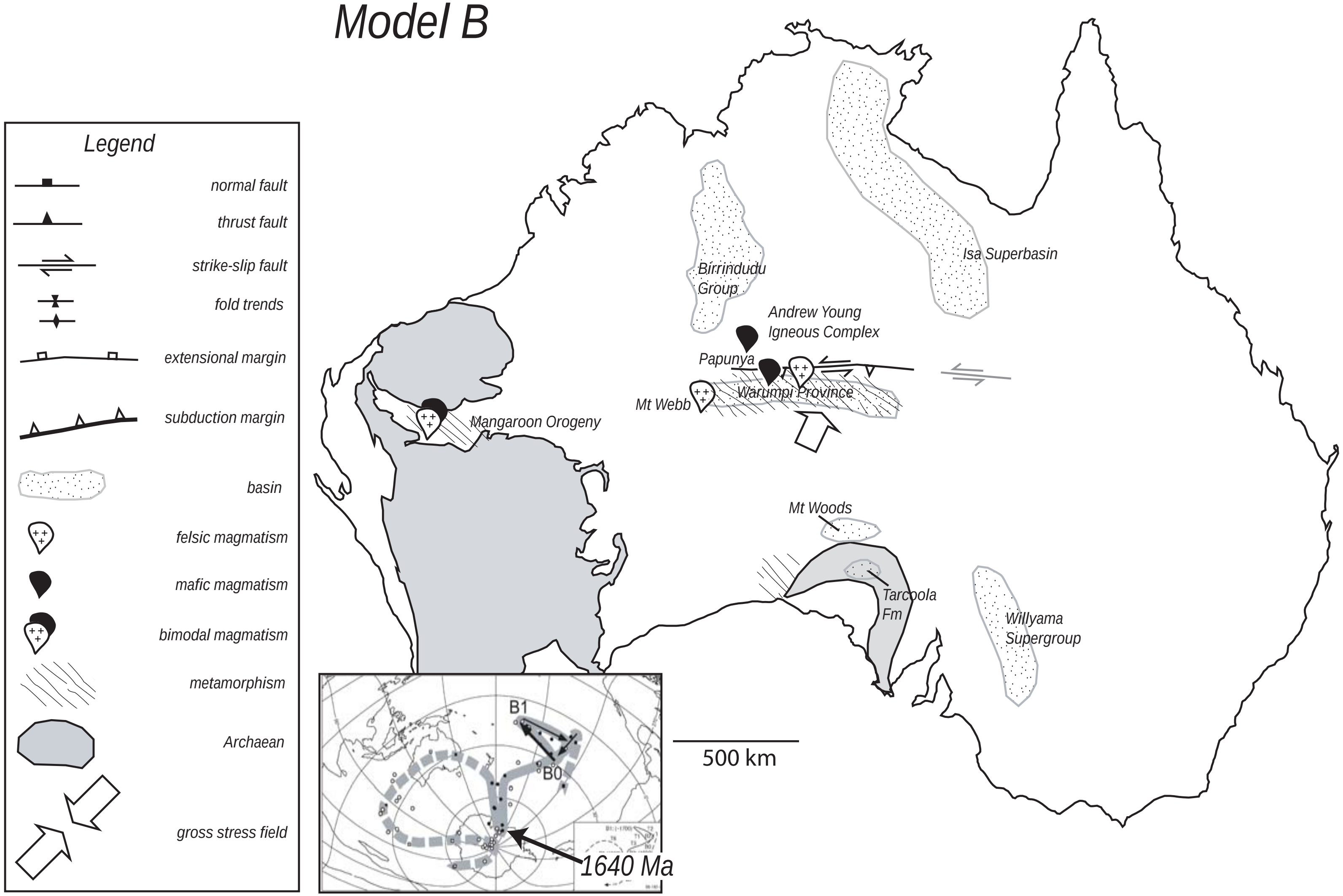
1660 - 1630 Ma
Model A



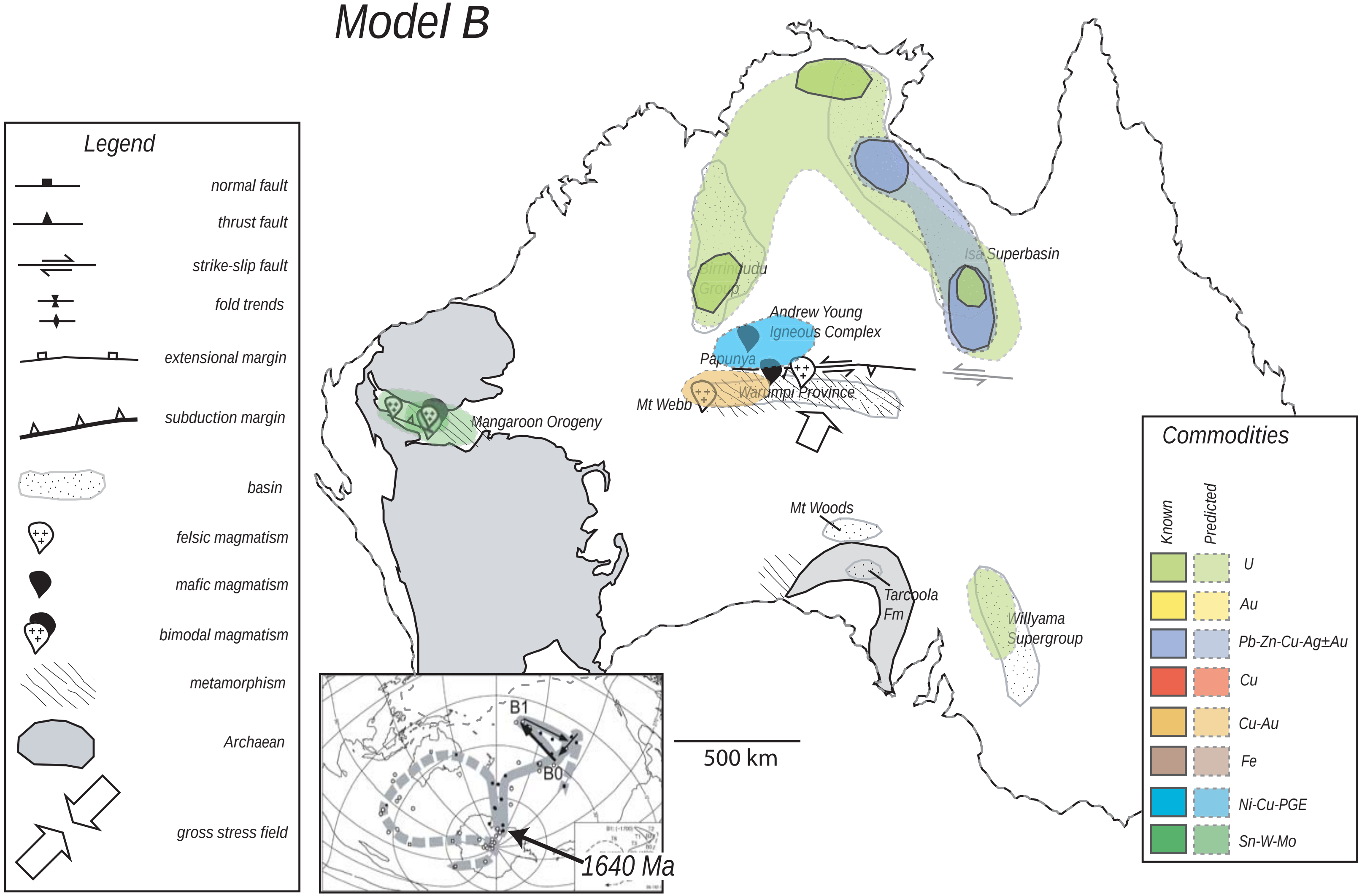
1660 - 1630 Ma
Model A



1660 - 1630 Ma
Model B



1660 - 1630 Ma
Model B



GEODYNAMIC AND METALLOGENIC MODELS FOR THE INTERVAL 1620 – 1550 Ma

Geological Elements

The following geological elements are depicted on the continental-scale tectonic diagrams, and require consideration in any tectonic models:

- Sedimentation of the upper parts of the Isa Superbasin in the southern McArthur and Lawn Hill Platform regions (Neumann, in press),
- High T – low P metamorphism, ranging from upper-greenschist to upper-amphibolite grade, occurred between ~1600 and ~1580 Ma in the Mt Isa Inlier, known as the Isan Orogeny, along with broadly north-directed thrusting (Neumann, in press), followed by intrusion of the Williams Batholith,
- Relatively localised high T – low P metamorphism, reaching granulite-facies in the southeast of the Reynolds Range, occurred between ~1590 and 1570 Ma, known as the Chewings Event (Williams et al., 1996). Lower temperature effects of the Chewings Event affected most, if not all, of the Aileron Province, as recorded by resetting of argon isotopic signatures (Fraser, 2004),
- Sedimentation of protoliths to the Iwupataka Metamorphic Complex in the Warumpi Province between ~1630 and 1610 Ma (Close et al., 2006). These sediments lie unconformably above rocks affected by the preceding Leibig Orogeny, and imply rapid exhumation and destruction of any topography following the Leibig Orogeny (Close et al., 2006),
- Amphibolite-facies metamorphism overprinted the Warumpi Province between ~1590 and 1570 Ma, associated with south-verging deformation (Close et al., 2006),
- Greenschist- to upper-amphibolite-facies metamorphism in the Georgetown, Coen and Yambo Inliers between ~1570 and 1550 Ma,
- High T – Low P metamorphism between ~1620 and 1590 Ma in the Curnamona Province (Forbes et al., 2005; Page et al., 2005),
- Magmatism in the Curnamona Province occurred at ~1580 Ma, resulting in the Benagerie Volcanics, Bimbowri Suite and Mundi Mundi Granite,
- Sedimentation of the Mount Adams and Freeling Heights Quartzites took place in the Mt Painter Province between ~1590 and 1575 Ma, closely followed by felsic intrusions between ~1575 and 1550 Ma (Cutten, in press),
- Felsic magmatism of the St Peter Suite occurred at ~1615 Ma in the southwestern Gawler Craton (Fraser and Reid, in press),
- Large-volume, widespread bimodal magmatism occurred in the Gawler Craton between ~1595 and 1575 Ma, including extrusion of the Gawler Range Volcanics and intrusion of numerous Hiltaba Suite plutons, from hereon termed the Hiltaba Event after Betts and Giles (2006),
- High-grade metamorphism of the Kararan Orogeny occurred along the northwestern margin of the Gawler Craton, in the Nawa Domain between ~1590 – 1560 Ma (Fanning et al., 2007; Payne et al., 2006),
- Grenvillian age high-grade gneisses in the Musgrave region typically yield inherited zircons with ages in the range ~1590 – 1550 Ma, interpreted as the age of igneous protoliths (Wade et al., 2006),
- Felsic and mafic intrusions of the Krackatinny Supersuite were emplaced into the Rudall Complex between ~1590 and 1550 Ma (Maidment and Kositcin, in press).

Continent-scale geodynamic Scenarios

Model A: Subduction/accretion-dominated

Continued convergence is envisaged between the NAC and SAC, with the development of protoliths to the Musgraves in an intervening arc setting, possibly with a change to south-dipping subduction-polarity (e.g. Wade et al. 2006). Collision between the NAC and SAC is interpreted to have occurred late in this time interval, accounting for palaeomagnetic evidence that suggests that the NAC and SAC were in close proximity by ~1500 Ma (Wingate and Evans, 2003).

In the NAC, north-south shortening during the Chewings and Isan Orogenies, and in the Georgetown region (Hand, 2006) is consistent with intracratonic effects of stresses transmitted from the convergent southern margin.

The Isan Orogeny along the eastern margin of NAC, and the Olarian Orogeny along the eastern margin of the SAC in the Curnamona Province, have been interpreted as a consequence of east-west contraction, possibly involving the collision of North America from the east (Betts et al., 2002). This model involves west-dipping subduction under the eastern margin of Proterozoic Australia. Although far from diagnostic, the broadly north-south orientation of the Olympic Cu-Au Province (Skirrow et al., 2002; 2006) along the eastern margin of the Gawler Craton is consistent with the orientation of the proposed west-dipping subduction zone. Such a model places the Olympic Cu-Au Province in a back-arc setting.

Alternatively, very extensive magmatism of the Hiltaba Event in the Gawler Craton has been interpreted as a consequence of back-arc extension related to south-dipping subduction between the NAC and SAC (Wade et al., 2006). In this model, collision between the NAC and SAC after ocean closure may account for transpressional deformation and metamorphism on the northwestern margin of the Gawler Craton at ~1570 – 1550 Ma. It is not clear how such a convergent scenario along the northern margin of the Gawler Craton can be reconciled with east-west contraction proposed for the same period to explain the Isan Orogeny and Olarian Orogeny to the east, as discussed above. Other models invoke a northeast-dipping subduction zone located south of the Gawler Craton to account for the extensive Hiltaba magmatism in the Gawler Craton (Ferris et al., 2002; Betts and Giles, 2006). Roll-back of this southern subduction zone is suggested to accommodate southwesterly translation of the SAC from a former position on the eastern margin of the NAC (Betts and Giles, 2006). These different models, therefore, variously propose subduction on the eastern, northern or south-eastern margin of the Gawler Craton, highlighting the uncertainties regarding geodynamic setting during the interval 1620 – 1550 Ma. A better understanding of the geodynamic setting of the SAC during this period is particularly important given the major IOCG mineralization (the Olympic Cu-Au Province) and significant Au mineralization (Central Gawler Gold Province) that occurred at this time.

In the WAC, subduction on the northeastern margin of the Pilbara Craton, in the Rudall Complex is suggested by the chemistry of the Krackatinny Suite (D. Maidment, pers. comm. 2007). The polarity of any possible subduction system is unknown, however, it is possible to speculatively link activity in the Rudall Complex with the proposed arc-setting of protoliths to the Musgrave Province (Wade et al,. 2006) via a continuous convergent margin. We note that subduction in the Rudall Complex at this time is not consistent with palaeomagnetic evidence suggesting the WAC and NAC were in close proximity by ~1800 Ma (Li, 2000; Williams et al. 2004).

Model B: Extension-dominated

This model envisages broadly north-south directed extension early in this time interval, resulting in a rift through central and western Australia, into which protoliths to the Musgrave Province are deposited and intruded. Similarly, the western part of this rift is intruded by the Krackatinny Suite in the Rudall Complex.

In the SAC very extensive bimodal magmatism of the Hiltaba/GRV association intrudes and extrudes across much of the Gawler Craton, and in this model is attributed to severe lithospheric attenuation and lower crustal melting. This contrasts with models discussed above that attribute the Hiltaba/GRV magmatism to subduction-related melting.

While this model envisages overall north-south extension, this period must also be punctuated by episodes of north-south shortening in the southern NAC, and east-west shortening on the eastern margin of the NAC.

The APWP passes through a bend at ~1590 Ma, less dramatic than the bend at ~1640 Ma, but perhaps providing an explanation for the switch from overall compression to extension. Note that Model B envisages continental extension from ~1870 to ~1640 Ma, compression from ~1640 to ~1590 Ma, then renewed extension, with the period of compression from ~1640 Ma to ~1590 Ma bracketed by two bends in the APWP.

Known mineral systems

Known mineralization of this age is concentrated predominantly in the SAC, as follows:

- IOCG±U mineralization on the eastern margin of the Gawler (Olympic Dam, Prominent Hill, Carrapateena, Moonta-Wallaroo), known as the Olympic Cu-Au Province (Skirrow et al., 2002),
- Au-mineralization in the central Gawler Craton (Central Gawler Gold Province),
- IOCG in Curnamona Province,
- U-mineralization in the Curnamona Province (Radium Hill, Crockers Well),
- VAMS in the Lawn Hill area of northeastern NAC (Century),
- Broken Hill-type VAMS in the Georgetown Inlier.

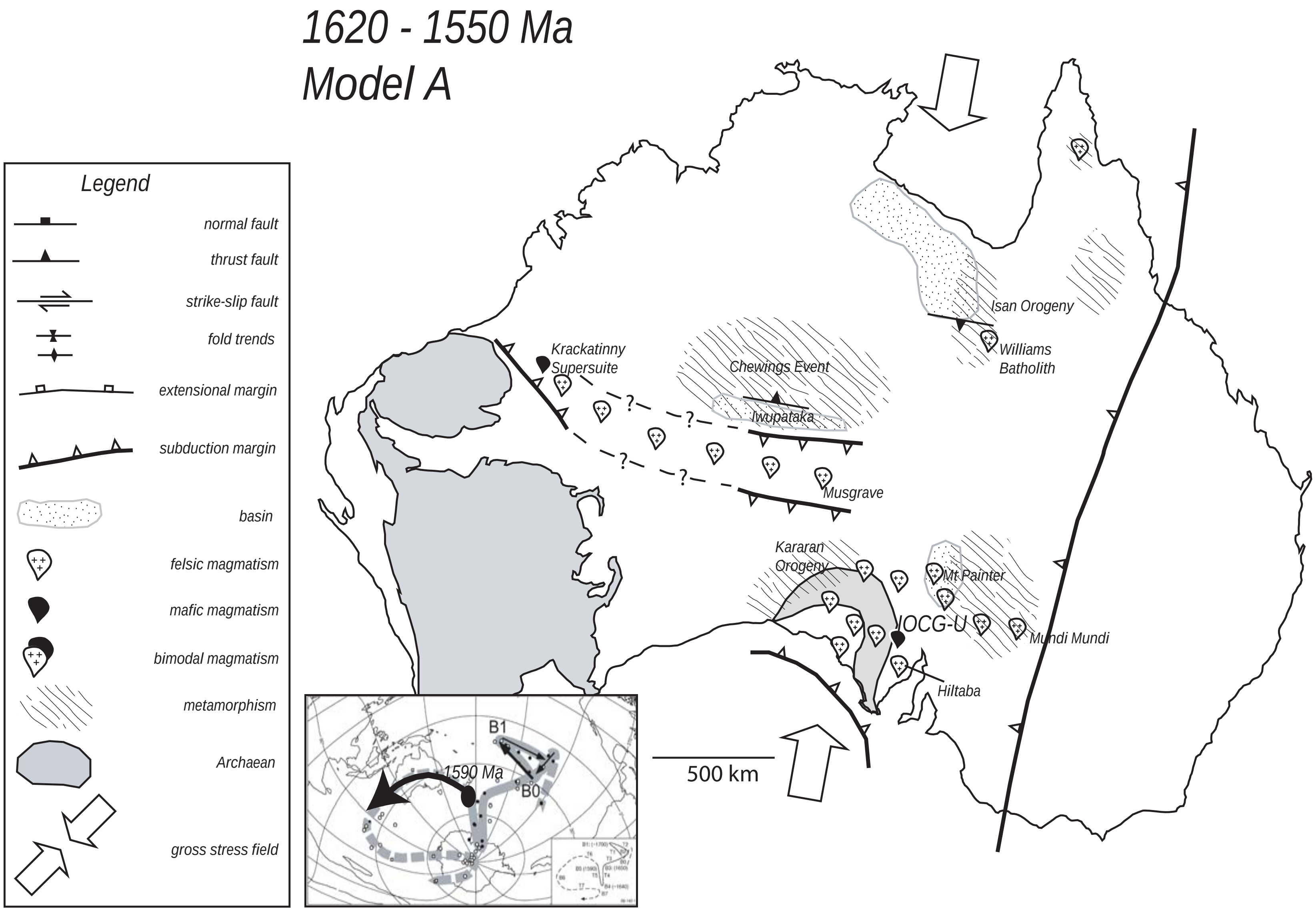
Predicted mineral systems

Model A: Subduction/accretion-dominated

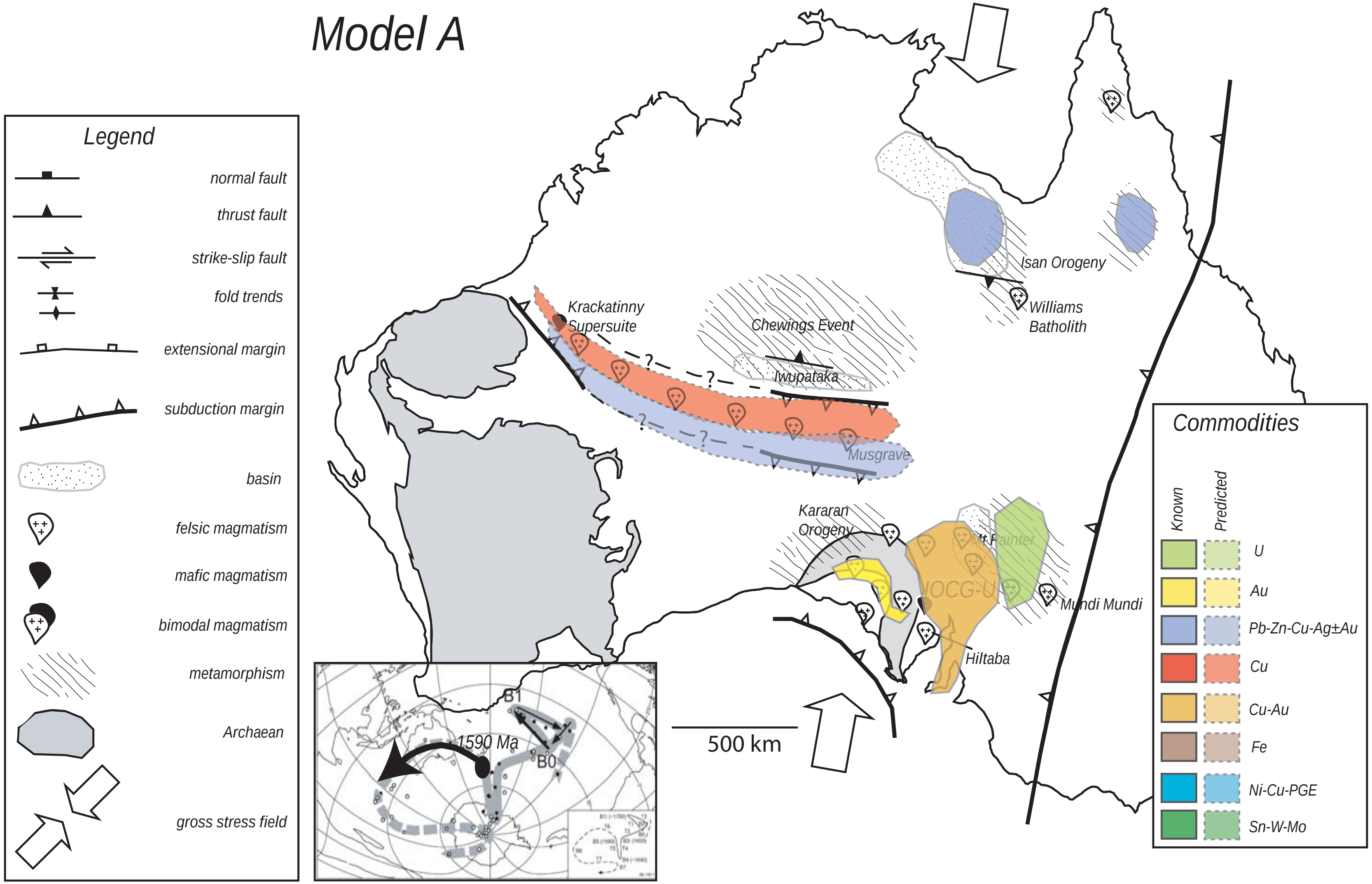
- Parallel belts of porphyry-Cu and back-arc VAMS from the Musgrave Province through to the Rudall Complex, on the basis of inferred former arc magmatism.

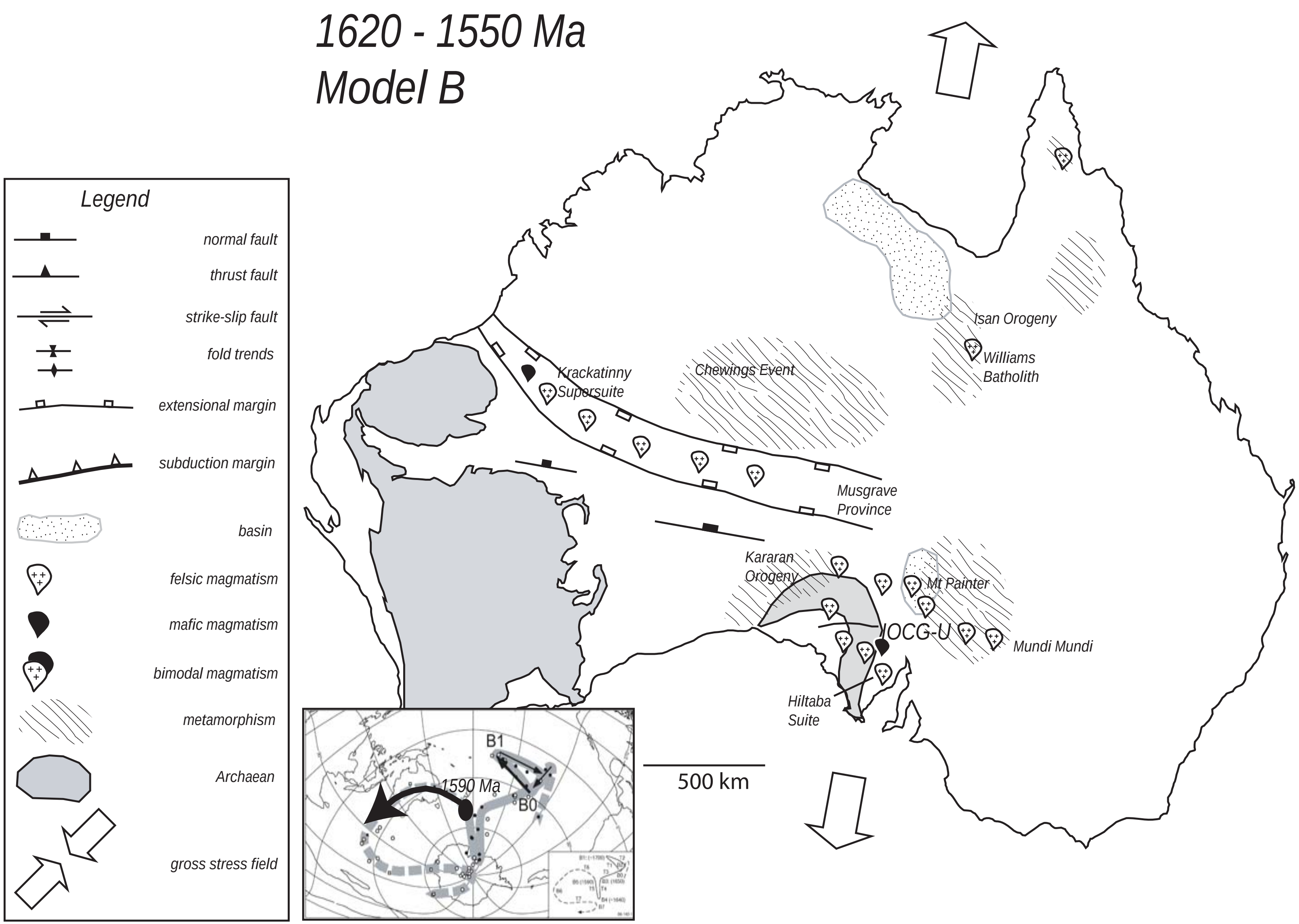
Model B: Extension-dominated

- VAMS in an extensional setting in a belt from the Musgrave Province through to the Rudall Complex, on the basis of an inferred rift.

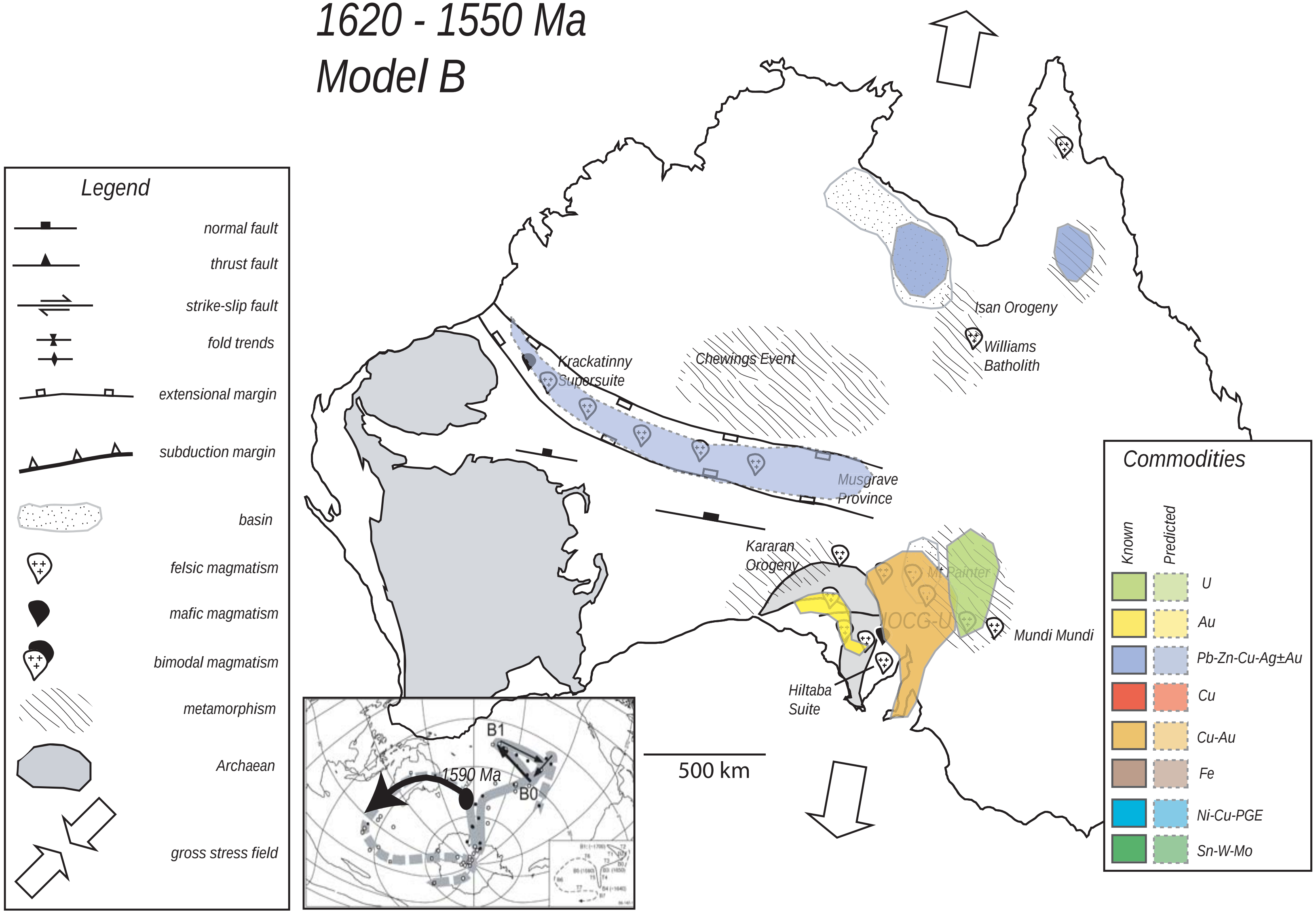

1620 - 1550 Ma
Model A
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Krackatinny Supersuite
Chewings Event
Iwupataka
Musgrave
Isan Orogeny
Williams Batholith
Kararan Orogeny
Mt Painter
IOCG-U
Mundi Mundi
Hiltaba
500 km
B1
B0
1590 Ma

1620 - 1550 Ma
Model A




1620 - 1550 Ma
Model B
Legend
normal fault
thrust fault
strike-slip fault
fold trends
extensional margin
subduction margin
basin
felsic magmatism
mafic magmatism
bimodal magmatism
metamorphism
Archaean
gross stress field
Krackatinny Supersuite
Chewings Event
Isan Orogeny
Williams Batholith
Musgrave Province
Kararan Orogeny
Mt Painter
IOCG-U
Mundi Mundi
Hiltaba Suite
500 km
B1
1590 Ma
B0

1620 - 1550 Ma
Model B



Conclusion

The models outlined above necessarily represent gross simplifications of the geological evidence and we regard them as at the level of ‘thought experiments’ to aid consideration of mineral system prediction. The contrasting geodynamic settings interpreted in the two alternate models point to questions that should be addressed in future studies to clarify which of these scenarios is more accurate. Several of these questions are listed at the end of Part I above.

The major point of difference between the two models considered here concerns the presence or absence of a long-lived convergent margin along the southern margin of the NAC. Most recent tectonic models derived from consideration of the geology of the southern margin of the NAC, and particularly those with an emphasis on intrusive igneous geochemistry, have envisaged such a convergent margin. In contrast, based on consideration of the relatively well-preserved geological record along the eastern margins of the NAC and SAC, particularly the sedimentary record, Gibson et al. (in press) regard the period ~1800 to ~1600 Ma to have been dominated by crustal extension and broadly east-west directed rifting. These two perspectives, from different geological viewpoints, appear to be clearly at odds, and either or both the models presented here will need substantial modification before any consensus regarding tectonic evolution is possible.

In the meantime, each model allows prediction of mineral systems at the conceptual level that may encourage new exploration strategies, or application of existing strategies in new areas.

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APPENDIX

Table 1: Geodynamic and tectonic classification of mineral systems

GEODYNAMIC ENVIROMMENT	TECTONIC SETTING	MINERAL SYSTEM GROUP	DEPOSIT TYPE	METAL ASSOCIATION	FLUIDS AND MAGMA
Convergent-extensional	Continental backarc	Basin-related fluid flow, with active magmatism	Carlin-type	Au-Ag-As-Sb-Hg	Meteoric, magmatic-hydrothermal
			BHT/Sullivan-type Zn-Pb-Ag	Zn-Pb-Ag-Cu-Au	Basinal brines
			Kuroko-type VAMS	Zn-Cu-Pb-Ag-Au	Evolved seawater; magmatic-hydrothermal
			Algoma-type BIF	Fe	Evolved seawater
		Magmatic-related hydro-thermal	Intrusion-related Au	Au-Ag-Sb-Cu-Pb-Zn-Sn-W-Mo-Bi-Te	Magmatic-hydrothermal; metamorphic
			Olympic Dam-type IOCG	Fe-Cu-Au-Ag-U-REE-Co-Mo-P-Nb	Magmatic-hydrothermal, meteoric
			Cloncurry-type IOCG	Fe-Cu-Au-Ag-As-Co-Mo-P	Magmatic-hydrothermal, metamorphic
Convergent-extensional	Island backarc	Basin-related fluid flow, with active magmatism	Kuroko-type VAMS	Zn-Cu-Pb-Ag-Au	Evolved seawater; magmatic-hydrothermal
			Cyprus style VAMS	Cu-Zn-Co-Ag-Au	Evolved seawater; magmatic-hydrothermal
			Algoma-type BIF	Fe	Evolved seawater
		Ortho-magmatic	Podiform chromite	Cr	Tholeiitic ultramafic magmas
Convergent-contractional	Continental arc	Magmatic-related hydro-thermal	Porphyry	Cu-Au-Ag-Mo	Magmatic-hydrothermal
			Epithermal (adularia-sericite)	Au-Ag	Meteoric; magmatic-hydrothermal
			Epithermal (advanced argillic)	Au-Cu-Ag	Magmatic-hydrothermal
			Skarn	Fe-Cu-Zn-Pb-Sn-W-Mo	Magmatic-hydrothermal

			Candelaria style IOCG	Fe-Cu-Au-Ag-U-As-Co-Mo-P-Nb-Ni-REE	Magmatic-hydrothermal
		Ortho-magmatic	Intrusion-hosted Ni-Cu-PGE	Ni-Cu-Pt-Pd-Au-Co	Tholeiitic mafic magmas
			Strata-bound Cr-PGE	Cr-Pt-Pd	Tholeiitic mafic-ultramafic magmas
			Merensky Reef-type Ni-PGE	Ni-Pt-Pd	Tholeiitic mafic-ultramafic magmas
			Podiform chromite	Cr	Tholeiitic ltramafic magmas
Convergent-contractional	Island arc	Magmatic-related hydro-thermal	Porphyry	Cu-Au-Ag-Mo	Magmatic-hydrothermal
			Epithermal (adularia-sericite)	Au-Ag	Meteoric; magmatic-hydrothermal
			Epithermal (advanced argillic)	Au-Cu-Ag	Magmatic-hydrothermal
			Skarn	Fe-Cu-Zn-Pb-Sn-W-Mo	Magmatic-hydrothermal
	Forearc accretion-ary wedge	Not known			
	Forearc basin	Magmatic-related hydro-thermal	Intrusion-related Au	Au-Ag-Sb-Cu-Pb-Zn-Sn-W-Mo-Bi-Te	Magmatic-hydrothermal; metamorphic
		Weathering and regolith, physical concentration, reduced atmosphere	Palaeo-placer Au-U	Au-U-Pt-Pd	Meteroric
	Pro-foreland	Not known			
	Retro-foreland	Basin-related fluid flow, without active magmatism	MVT style Pb-Ag-Zn	Zn-Pb-Ag	Basinal brines
	Collisional	Deformation and metamorphism	Lode Au	Au-Ag-As-Sb-Te-W-Bi	Metamorphic; magmatic-hydrothermal
			Mt-Isa type Cu	Cu	Metamorphic

			Cobar style Pb-Zn-Cu-Au	Pb-Zn-Ag-Cu-Au	Metamorphic
			Tennant Creek-type IOCG	Cu-Au-Bi-Se-Pb-Zn-U	Magmatic-hydrothermal, basinal brines and metamorphic
Divergent	Mid-oceanic ridge	Basin-related fluid flow, with active magmatism	Cyprus style VAMS	Cu-Zn-Co-Ag-Au	Evolved seawater; magmatic-hydrothermal
		Ortho-magmatic	Ophiolite hosted Cr, Ni	Cr-Ni	Mafic magmas
	Continental rift	Basin-related fluid flow, with active magmatism	BHT/Sulli-van-type	Zn-Pb-Ag-Cu-Au	Basinal brines
		Ortho-magmatic	Carbona-tite-hosted REE	REE-P-F-Mo-Cu-Pb-Zn	Alkaline carbonatitic magmas
			Diamonds	Dia-mond	Alkaline ultramafic magmas
			REE and P-rich nepheline syenite	REE-P-F	Alkaline felsic magmas
			Anortho-site-hosted Fe-Ti-V	Fe-Ti-V	Tholeiitic mafic magmas
			Intrusion-hosted Ni-Cu-PGE	Ni-Cu-Pt-Pd-Au-Co	Tholeiitic mafic magmas
			Komatiitic-hosted nickel sulphide	Ni-Cu-Pt-Pd-Au	Komatiitic mafic magmas
	Rifted arc	Basin-related fluid flow, with active magmatism	Kuroko-type VAMS	Zn-Cu-Pb-Ag-Au	Evolved seawater; magmatic-hydrothermal
			Algoma-type BIF	Fe	Evolved seawater
		Magmatic-related hydro-thermal	Epithermal (adularia-sericite)	Au-Ag	Meteoric; magmatic-hydrothermal

Hotspot	Oceanic	Basin-related fluid flow, with active magmatism	Cyprus style VAMS	Cu-Zn-Co-Ag-Au	Evolved seawater; magmatic-hydrothermal
	Continental	Ortho-magmatic	Flood-basalt associated Ni-Cu-PGE	Ni-Cu-Pt-Pd-Au-Co	Mafic magmas
Intraplate	Ocean basin	Sedimentary	Mn-Ni-Co nodules	Mn-Ni-Co	Oxidized seawater
	Passive margin	Sedimentary	Hammersley-type BIF	Fe	Reduced seawater
			Sedimentary manganese	Mn-Ni-Co	Reduced seawater
			Sedimentary sulphate	SO4-Ca-Ba	Oxidized seawater
			Sedimentary phosphate	P	Oxidized seawater
		Basin-related fluid flow, without active magmatism	Mt Isa-type Zn-Pb-Ag	Zn-Pb-Ag	Basinal brines
	Distal contraction	Basin-related fluid flow, without active magmatism	MVT style Pb-Ag-Zn	Zn-Pb-Ag	Basinal brines
			Irish-style Pb-Zn	Zn-Pb-Ag	Basinal brines
			Sediment-hosted Cu-Co	Cu-Co-Ag	Basinal brines
			Unconformity U	U-P-REE-Cu-Au	Basinal brines
			Kipushi-type Cu-Zn-Pb	Cu-Zn-Pb	?
			Laisval-type Pb	Pb	Basinal brines
	Inactive continental	Basin-related fluid flow, without active magmatism	Rollfront-palaeochannel U	U-P-REE	Basinal brines
		Weathering and regolith, chemical concentration	Lateritic Ni	Ni-Au	Meteoric
			Lateritic bauxite	Al	Meteoric
			Calcrete Au-U	Au, U	Meteoric

			Supergene enrichment	Au-Cu-Pb-Zn	Meteoric
			Placer Ti-Zr-Th-Hf	Ti-Zr-Th-Hf	Meteoric
			Placer Au	Au	Meteoric
			Placer Sn-Ta	Sn-Ta	Meteoric
		Weathering and regolith, physical concentration	Placer Ti-Zr-Th-Hf	Ti-Zr-Th-Hf	Meteoric
			Placer Au	Au	Meteoric
			Placer Sn-Ta	Sn-Ta	Meteoric
	Variable	Orthomagmatic	Pegmatite	Ta-Sn	Felsic magmas
Strike-slip	Pull-apart basin	Basinal fluid flow	Salton Sea-type Zn-Pb-Cu	Zn-Pb-Cu	Basinal brines
	Pop-up	Deformation and metamorphism	Lode Au	Au-Ag-As-Sb-Te-W-Bi	Metamorphic; magmatic-hydrothermal