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Narelle L. Neumann and Geoffrey L. Fraser, editors

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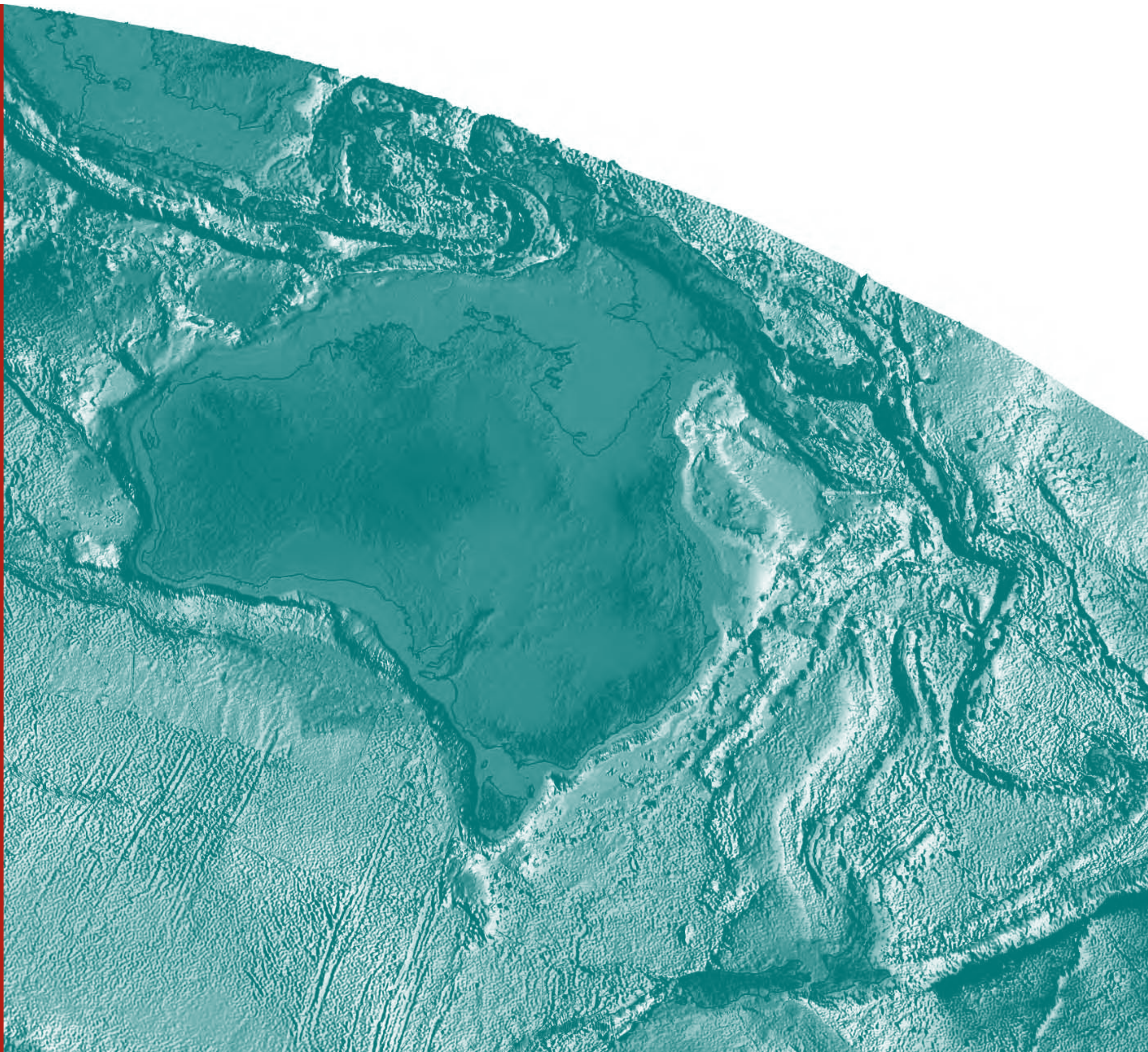

SPATIAL INFORMATION FOR THE NATION

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Narelle L. Neumann[1] and Geoffrey L. Fraser[1], editors

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Contents

Introduction and Methodology

Determining the timing, duration and extent of geological events is a key component in the development of geodynamic models for any geological region. A useful way to depict this information is via Time-Space plots. This report presents Time-Space plots for each of the Proterozoic Inliers of Australia, together with explanatory notes describing the geological interpretation of the available data and highlighting major knowledge gaps. This series of Time-Space plots was produced in the period September 2006 to April 2007, as a component of the Proterozoic Synthesis of Australia Project within the Onshore Energy and Minerals Division, Geoscience Australia.

We acknowledge the significant contribution of colleagues from Primary Industries and Resources SA, NSW Department of Primary Industries, Geological Survey of Queensland, Northern Territory Geological Survey and the Geological Survey of Western Australia towards this report.

CONSTRUCTING THE TIME-SPACE PLOTS

When constructing the Time-Space plots, there was a strong focus on evaluating the geochronological data used to determine the timing and duration of geological events (sedimentary, magmatic, metamorphic, deformational and mineralising). Given that different isotopic and mineral systems record different age information, the data compilation initially involved all available geochronological data from a range of data sources:

- A data-extraction from the Geoscience Australia geochronological database OZCHRON in August 2006
- All available State, Territory and Commonwealth geochronological reports
- All available geochronological data from published manuscripts

The geochronological data were evaluated according to a range of criteria including outcrop relationships, isotopic system/mineral/method, number of analyses and interpretation confidence. This age-information was then interpreted according to the geological event-type (e.g. felsic magmatic intrusive age, sedimentary maximum depositional age, fluid flow age, cooling age).

The geochronological data were compiled in Microsoft Excel and sorted into geological domains. The Time-Space plots were created by depicting the age-information via symbol and colour, according to the isotopic and mineral method and geological interpretation. In general, where samples have both U-Pb multi-grain TIMS and U-Pb SHRIMP age information, the SHRIMP age was used as the preferred age interpretation. Also, unless supported by $^{40}Ar/^{39}Ar$ mineral age information, most of the K-Ar age information has not been included in the plots.

Once the geochronological data were compiled and plotted in Excel, plots were exported into Adobe Illustrator and a process of interpretation and simplification was undertaken to produce a more geologically interpretable Time-Space plot. Geochronological data were divided into four thematic layers: (i) sedimentary, (ii) magmatic, (iii) metamorphic and deformational, and (iv) mineralisation. Within each of these thematic layers, clusters of data regarded as indicating important geological ‘events’ were highlighted. For example, clusters of magmatic ages from related samples were highlighted by coloured bands spanning the age range indicated by the geochronology data. Similarly, periods of deformation, metamorphism or mineralisation were depicted symbolically at the time-intervals indicated by the geochronology. Stratigraphy was depicted based on published geological interpretations with reference to the geochronological constraints from the Time-Space plot, such as maximum depositional age, or magmatic crystallisation age.

For this compilation, there has been a focus on the period 1900 Ma and 1400 Ma due to the abundance of mineral wealth associated with this time interval. However in some regions other time intervals have also been included where they include geological events important for the development of that area.

Each section within this report is focussed on a particular Australian Proterozoic terrane, and includes a written summary of the geology and geochronology of that terrane, a summary Time-Space plot, and discussion of significant geochronological gaps in that terrane. Plots of the four thematic Time-Space layers for each region are included as an appendix at the end of each chapter.

ACKNOWLEDGEMENTS

We thank the Geoscience Australia Proterozoic Synthesis team for their input throughout the project. Patrick Lyons, David Huston and Natalie Kositcin are thanked for internal reviews of this report, and Colin Conor, Wolfgang Preiss, Ian Withnall, Elizabeth Jagodzinski and Simon Bodorkos are also acknowledged for reviewing individual chapters.

Time-Space evolution of the Gawler Craton

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OVERVIEW

The Gawler Craton comprises variably deformed and metamorphosed sedimentary, volcanic and plutonic rocks that span the Late Archaean to Mesoproterozoic, ~2560 Ma to ~1490 Ma. The craton is subdivided into a series of domains as shown in Figure 1 (Ferris et al., 200). Given the paucity of outcrop in the Gawler Craton, many of these domain boundaries are defined by potential field data, particularly contrasting magnetic character and the presence of prominent curvilinear magnetic anomalies interpreted as bounding faults and shear zones. Mineralisation in the Gawler Craton is most predominantly associated with magmatism of the Mesoproterozoic ~1595-1575 Ma Hiltaba Suite and Gawler Range Volcanics (the Hiltaba-Gawler Range magmatic association of Budd et al., 2001 and Budd, 2006). This Mesoproterozoic mineralisation comprises extensive gold-only, and IOCG+U mineralisation, which respectively define two metallogenic provinces termed the Central Gawler Gold Province (Ferris and Schwarz, 2003) and the Olympic IOCG Province (Skirrow et al., 2002; Skirrow et al., 2006). Other mineralisation styles within the Gawler Craton are Late Archaean or very early Proterozoic gold at the Challenger mine in the northwest of the Craton (Poustie et al., 2002) and Palaeoproterozoic iron ore (Middleback Ranges; Yeates, 1990). The following presents an overview of the major tectonothermal events preserved within the Gawler Craton.

One of the key pre-existing data compilations used in this summary is the ‘Geochronology of the Gawler Craton: a compilation’ (Reid, in press), which includes data present within the recently-published Geological Survey of South Australia Bulletin 55, A Geochronological Framework for the Gawler Craton, South Australia (Fanning et al., 2007).

Geological summary

~2600-2400 Ma

The oldest known rocks in the Gawler Craton are found in the Coulta Domain, Christie Domain and Harris Greenstone Belt, which together comprise the Mulgathing and Sleaford complexes (Daly and Fanning, 1993).

The Coulta Domain on western Eyre Peninsula is largely composed of latest Archaean to earliest Proterozoic sedimentary rocks including felsic volcanic or volcaniclastic units known as the Hall Bay Volcanics (Teale et al., 2000). These rocks were intruded by the pre- to syn-tectonic Dutton Suite (Fanning et al., 2007) and have been metamorphosed to variable extent during the Sleafordian Orogeny between 2460 Ma and 2400 Ma (Daly and Fanning, 1993; Swain et al., 2005a).

The Christie Domain in the west of the craton is dominated by latest Archaean to earliest Proterozoic metasedimentary rocks (Christie Gneiss) metamorphosed in the earliest Proterozoic at ~2450 Ma during the Sleaford Orogeny. The Christie Gneiss forms part of the Mulgathing Complex and has been correlated with the Sleaford Complex of similar age in the Coulta Domain (Daly and Fanning, 1993; Daly et al., 1998; Swain et al., 2005a). If this correlation is correct the Mulgathing and

Sleaford Complexes together form an arcuate core to the Gawler Craton, with younger rocks both to the northeast and southwest.

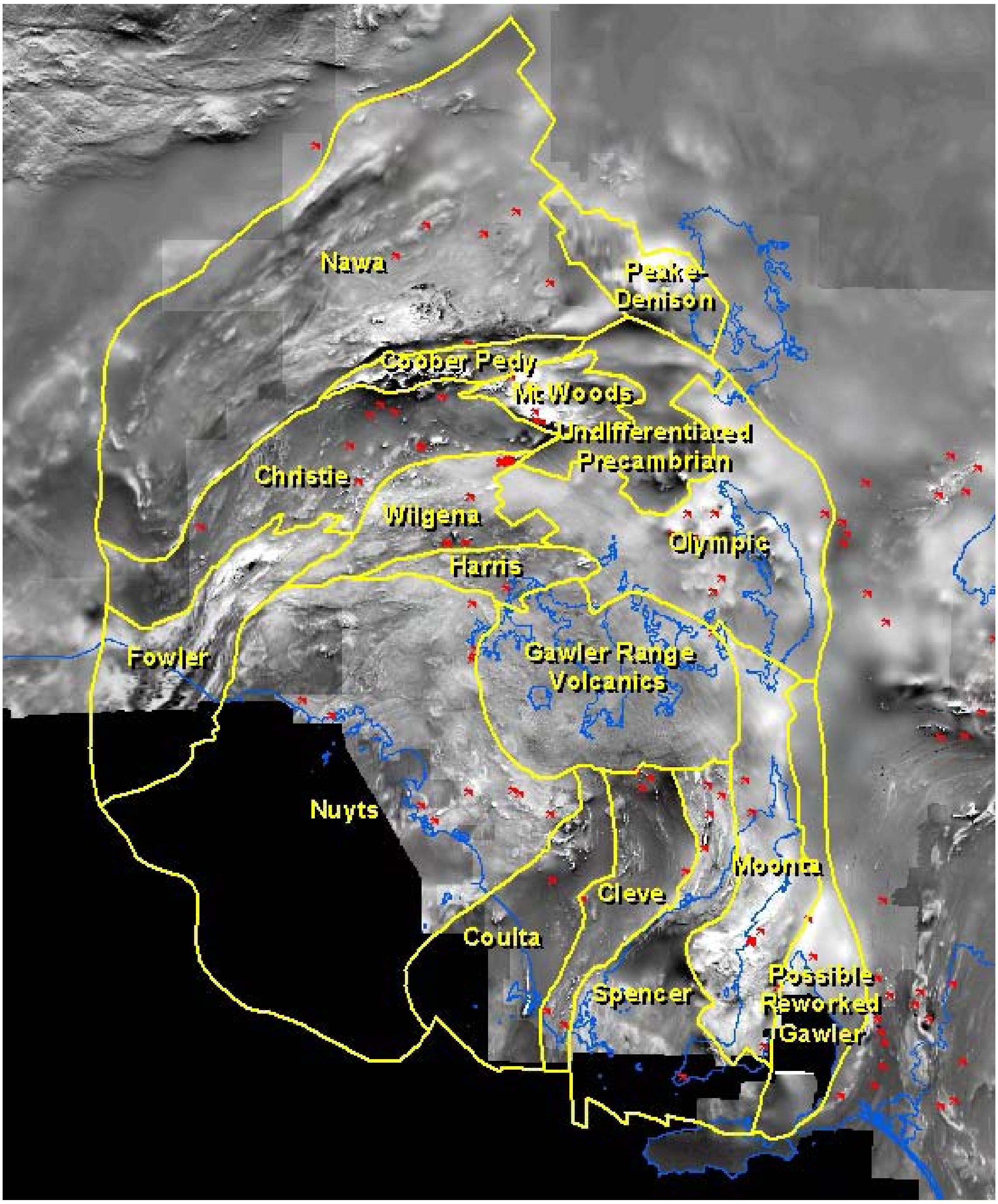


Figure 1: *Location and province divisions within the Gawler Craton (Ferris et al., 2002).*

The Harris Greenstone Belt is a relatively small, fault-bounded region in the central Gawler Craton composed of ultramafic-mafic extrusive rocks, including the Lake Harris Komatiite, interbedded with metasedimentary rocks and intruded by younger granites (Ferris et al., 2002; Hoatson et al., 2005; Swain et al., 2005a). Although massive sulphide mineralisation has not been discovered in the Lake Harris komatiites these ultramafic rocks remain prospective for Ni and PGE mineralisation, since they show broad geochemical similarities to other Archaean komatiites such as those in the

Yilgarn Craton (Hoatson et al., 2005). Sedimentation and ultramafic-mafic volcanism within the greenstone belt occurred at ~2520 Ma, followed by metamorphism and deformation at ~2450 Ma during the Sleafordian Orogeny.
No rocks with ages between ~2400 and ~2000 Ma have been identified in the Gawler Craton.

~2000 Ma
In the Cleve Domain on southern Eyre Peninsula the migmatitic, quartzo-feldspathic Miltalie Gneiss gives a U-Pb zircon age of ~2000 Ma, and forms the crystalline basement onto which the unconformably overlying Hutchison Group was deposited (Fanning et al., 1988; Fanning et al., 2007). No information on the geochemical affinities or petrogenetic processes that formed the Miltalie Gneiss has yet been published, thus little is known about this 2000 Ma event within the Gawler Craton.

~1900-1860 Ma
The only known rocks from the period ~1900-1860 Ma within the Gawler Craton are the Hutchison Group sediments found in the Cleve Domain. The Hutchison Group is an overall fining-upward sequence, probably several kilometres thick, consisting of a basal quartzite (Warrow Quartzite), and overlying semipelitic and chemical sediments of the Middleback Subgroup which host the massive iron-ore deposits of the Middleback Ranges (Parker and Lemon, 1982; Parker et al., 1993). The Hutchison Group has been interpreted as a passive margin sequence (Parker and Lemon, 1982). Timing of deposition of the Hutchison Group is constrained between ~2000 Ma (age of the underlying Miltalie Gneiss) and ~1850 Ma (age of the Donington Suite granites). A tighter constraint on the age of deposition comes from a U-Pb zircon age of 1866 ± 10 Ma from the Bosanquet Formation, interpreted as a volcanic unit within the upper Hutchison Group (Fanning et al., 2007). Note, however, that there is considerable uncertainty regarding the geological relationship between the Bosanquet Formation and the Hutchison Group as the original nature of the contact is obscured by deformation. Consequently, alternative interpretations have been proposed in which the Hutchison Group is suggested to be younger than the Donington Suite (Vassallo and Wilson, 2001). However, the presence of metasedimentary enclaves within the Donington Suite with detrital zircon populations ~2500 and ~2000 Ma confirms that sedimentation did occur in the region prior to emplacement of the Donington Suite (Howard et al., 2006; Fanning et al., 2007).

~1850 Ma
Extensive granite intrusions known as the Donington Suite (Schwarz, 2003) occur within the Spencer and Olympic Domains on the eastern margin of the Gawler Craton (Jagodzinski, 2005; Jagodzinski et al., 2006; Reid et al., in press). No granites of this age have been identified elsewhere in the Gawler Craton.

~1800-1750 Ma
Rocks formed within the interval ~1800-1750 Ma are found only in the Spencer, Olympic and Peak and Denison Domains in the east and north of the craton, with the exception of the local occurrence of the ~1760 Ma Investigator Granite Gneiss as a large enclave within Mesoproterozoic granites within the Nuyts Domain (Cooper and Belousova, 2004).
In the Spencer Domain, the Tournefort mafic dykes that intrude the Donington Suite have been dated at ~1800 Ma (Schaefer, 1998), although the reliability of this Pb-Pb Kober age is uncertain. Also in the Spencer Domain the Myola Volcanics were extruded at ~1790 Ma (Fanning et al., 1988).
In the Moonta Domain the Wardang Volcanics yield a U-Pb zircon age of ~1770 Ma (Fanning et al., 2007), and the Bills Lookout gabbro gives an age of ~1765 Ma (Johnson, 1993). In the Peake and Denison Domain, in the northern Gawler Craton, felsic volcanics (Tidnamurkana Volcanics;

Ambrose et al., 1981) and felsic intrusions range in age between ~1800 and 1780 Ma (reported in Ferris et al., 2002).

~1750-1710 Ma

The end of this period appears to mark a change in the locus of geological activity within the Gawler Craton. Prior to this time, activity appears to have been localised within regions to the east and north of the Archaean to earliest Proterozoic arcuate core of the craton. After ~1710 Ma geological activity is predominantly localised in the western parts of the craton. The period ~1750-1710 Ma includes a cycle of sedimentation leading up to, and perhaps terminated by, the Kimban Orogeny at ~1720-1700 Ma.

In the east of the craton, in the Olympic Domain, sediments of the Wallaroo Group were deposited at ~1740 Ma. These sediments host the IOCG deposits of the Moonta-Wallaroo area on Yorke Peninsula, and include the Moonta Porphyry dated at ~1740 Ma (Fanning et al., 2007). Contemporaneous felsic volcanics and intrusives of age ~1740 to 1730 Ma are found in the Spencer Domain (McGregor Volcanics, Fanning et al., 1988) and Cleve Domain (Middlecamp Granite, Moody Suite; Fanning et al., 2007).

The Labyrinth Formation in the Wilgena Domain is a sequence of shallow water sediments, at least 1000 m thick, including stromatolitic units and abundant volcaniclastic and volcanics (Cowley and Martin, 1991). A rhyolite within this sequence gives a U-Pb zircon age of ~1715 Ma (Fanning et al., 2007) indicating sedimentary deposition within the Wilgena Domain contemporaneous with local Paxton Suite granite intrusions (Budd and Fraser, 2004), and, more regionally, with the Kimban Orogeny.

Upper amphibolite to granulite-facies metamorphism at ~1720-1710 Ma is recorded by metamorphic zircon and monazite ages in the Fowler, Christie and Nawa domains in the west of the craton (Teasdale, 1997; Swain et al., 2005b; Fanning et al., 2007).

~1710-1670 Ma

Felsic magmatism during this period extended across most of the craton, showing a broad trend of decreasing age from east to west. Moody Suite granites of age ~1700 Ma occur within the Spencer, Cleve and Coulta Domains, synchronous with syn-Kimban Orogeny reworking of the Donington Suite and partial melting of the Hutchison Group and Sleaford Complex (Jagodzinski et al., 2006; Fanning et al., 2007). Farther west in the Nuyts, Wilgena, Fowler and Christie Domains the timing of magmatism shifted to the period ~1690 Ma to ~1670 Ma, present as the predominantly I-type Tunkillia Suite (Ferris and Schwarz, 2004).

At this time, farther east, in the Spencer Domain, metamorphic monazite ages of ~1690 Ma are attributed to the late stages of the Kimban Orogeny, with probable movement along the Kalinjala Shear Zone that separates the Spencer Domain from the Cleve Domain (Swain et al., 2005b).

~1670-1630 Ma

The age of the Tarcoola Formation, deposited in the Wilgena Domain (Daly et al., 1990), is constrained by a U-Pb zircon age of ~1655 Ma from a tuffaceous unit. In the far west of the craton, in the Nawa Domain, metamorphic zircons within the Moondrah Gneiss suggest granulite-facies metamorphism at this time (Fanning et al., 2007).

~1630-1600 Ma

Rocks of this age are known only from the Nuyts Domain. The Nuyts Volcanics were erupted at ~1630 Ma (Rankin et al., 1990) and the St Peter Suite granites emplaced from ~1620-1610 Ma (Flint et al., 1990).

~1600-1570 Ma

With the exception of the Nawa and Christie Domains in the west, felsic magmatism of this age has been identified throughout the Gawler Craton. This is the time of the extensive lavas of the Gawler Range Volcanics, and the broadly contemporaneous intrusive equivalents of the Hiltaba Suite granitoids. In the east of the craton this is the time of IOCG mineralisation in the Moonta-Wallaroo region, at Olympic Dam and the surrounding Olympic province, and Prominent Hill in the Mount Woods Inlier (Skirrow et al., 2002). This is also the time of gold deposition in the Central Gawler Gold Province, including the deposits and prospects of Tarcoola, Tunkillia, Barns and Weednanna (Ferris and Schwarz, 2003; Budd and Fraser, 2004; Fraser, 2004).

~1570-1500 Ma

There is very limited evidence for a high-grade metamorphic event within the Nawa Domain at ~1550 Ma. This evidence comes from samples from two drill holes within the Mabel Creek Ridge in which poorly defined metamorphic zircon ages of ~1550 Ma and ~1560 Ma have been reported (Payne et al., 2006; Fanning et al., 2007). The accuracy and meaning of these ages requires further testing, although, at face-value, they suggest a distinct metamorphic event at ~1550 Ma that is present only to the west of the Karari Shear Zone.

Metamorphic monazites from the Fowler and Nuyts Domains have yielded EPMA chemical ages at ~1510 Ma (Swain et al., 2005b). Several mica $^{40}Ar/^{39}Ar$ cooling ages of ~1520-1500 Ma have been measured in the Moonta-Wallaroo region (Fraser, unpublished data).

~1500-1400 Ma

Little magmatism is recorded for the Gawler Craton during this time, with the exception of the ~1500 Ma Spilsby Suite (Fanning et al., 2007) and an isolated pegmatite in the Fowler Domain at ~1490 Ma (Fanning et al., 2007). Deformation associated with intracontinental reworking of major shear zones throughout the western Gawler Craton probably occurred at ~1450 Ma (Fraser and Lyons, 2006).

The Pandurra Formation (Cariewerloo Basin) and Blue Range Beds (Itiledoo Basin) may have been deposited in this time interval. However, apart from a Rb-Sr wholerock age of 1424 ±51 Ma for the Pandurra Formation (Fanning et al., 1983), there are no other geochronological constraints available for depositional ages of these units.

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

In this section, geological domains of the Gawler Craton are discussed with an emphasis on geochronological constraints, as shown in the accompanying Time-Space plots (Figure 2). Geological domains are discussed in the order in which they are plotted on the Time-Space plots, from left to right across the plots. This order broadly corresponds to a progression from west to east across the craton.

Yoolperlunna Inlier

The Yoolperlunna Inlier is an isolated exposure of crystalline basement to Adelaidean sediments of the Officer Basin between the Gawler Craton and Musgrave Province. The Yoolperlunna Inlier is bounded to the south by major faults and is situated to the east of the predominantly east-west striking Musgrave Province, suggesting the possibility that this inlier represents an easterly exposure of the Musgrave Province rather than part of the Gawler Craton. Rocks in the Yoolperlunna Inlier consist of mylonitic and retrogressed granitic gneiss intruded by granitic dykes (Krieg, 1993).

The only radiometric constraint from the Yoolperlunna Inlier is from a granitic gneiss yielding a magmatic crystallisation U-Pb zircon age of 1738 ± 17 Ma (Fanning et al., 2007). In contrast to the expectation that the Yoolperlunna Inlier may be part of the Musgrave Province, this single age suggests more affinity with the Gawler Craton. The age of 1738 ± 17 Ma is older than any radiometric age published from the Musgrave Province (e.g. Edgoose et al., 2004; Wade et al., 2006), and is contemporaneous with felsic intrusive ages from the Mount Woods, Fowler, Wilgena and Cleve domains of the Gawler Craton. This result supports the inferred margin of the Gawler Craton being to the northwest of the Yoolperlunna Inlier.

No geochronometers sensitive to post-crystallisation thermal overprinting have been applied to rocks from the Yoolperlunna Inlier to test for the possible influence of Musgravian (~1250–1150 Ma) or Peterman (~550 Ma) orogeny overprints.

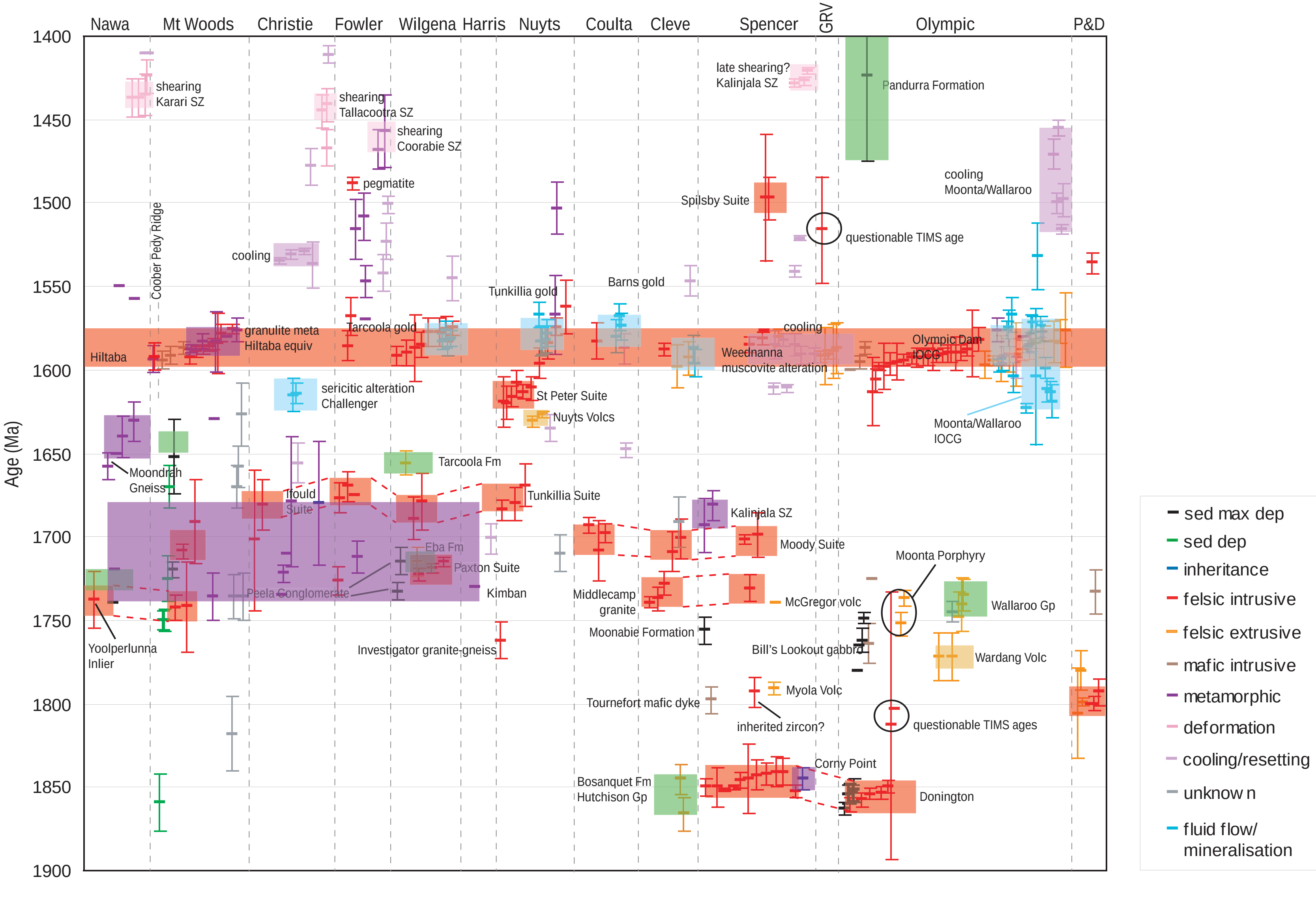
Ammaroodinna Inlier

The Ammaroodinna Inlier is situated ~50 km SSW of the Yoolperlunna Inlier, in the Officer Basin. Outcrop is restricted to an area of only ~100 m^2 and consists of "strongly weathered … fine-grained quartz-biotite-muscovite schist and gneiss, quartz veins and granitoids" (Krieg, 1993). A muscovite-rich rock yielded a K-Ar age of 1104 Ma and Rb-Sr ages of 1050 and 973 Ma (Webb, 1985), suggestive of influence by the Musgravian Orogeny. No U-Pb zircon ages have been determined from this inlier, hence the question of whether these rocks have more in common with the Musgrave Province or the Gawler Craton remains open.

Coompana Domain

This domain is situated to the west of the Karari Shear Zone at the southern extent of that structure, and lies to the west of the Christie Domain and southwest of the Nawa Domain. The Coompana Domain spans the region between the Gawler Craton and the Albany-Fraser Province to the west. This region is entirely covered by Phanerozoic sedimentary rocks and the basement geology is, consequently, extremely poorly known. Granitic gneiss from the base of petroleum drillhole Mallabie 1 yielded a U-Pb zircon age of 1455 ± 16 Ma, interpreted to record the time of granite crystallisation (Fanning et al., 2007). K-Ar ages of 1185 Ma from hornblende and 1159 Ma on biotite (Webb et al., 1982), are consistent with a thermal influence from the Grenvillian-age Musgravian and Albany-Fraser orogens.

Figure 2 (overleaf): *Geochronological data and summary Time-Space plot for the Gawler Craton.*


Nawa
Mt Woods
Christie
Fowler
Wilgena
Harris
Nuyts
Coulta
Cleve
Spencer
GRV
Olympic
P&D
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
shearing Karari SZ
shearing Tallacootra SZ
shearing Coorabie SZ
pegmatite
cooling
Coober Pedy Ridge
late shearing? Kalinjala SZ
Pandurra Formation
Spilsby Suite
questionable TIMS age
cooling Moonta/Wallaroo
Tunkillia gold
Barns gold
granulite meta Hiltaba equiv
Tarcoola gold
cooling
Olympic Dam IOCG
Hiltaba
Weednanna muscovite alteration
sericitic alteration Challenger
St Peter Suite
Nuyts Volcs
Moonta/Wallaroo IOCG
Tarcoola Fm
Moondrah Gneiss
Tunkillia Suite
Tould Suite
Kalinjala SZ
Moody Suite
Eba Fm
Paxton Suite
Moonta Porphyry
Peela Conglomerate
Kimban
Middlecamp granite
McGregor volc
Wallaroo Gp
Moonabie Formation
Yoolperlunna Inlier
Investigator granite-gneiss
Bill's Lookout gabbro
Wardang Volc
Myola Volc
Tournefort mafic dyke
inherited zircon?
questionable TIMS ages
Corny Point
Bosanquet Fm Hutchison Gp
Donington
sed max dep
sed dep
inheritance
felsic intrusive
felsic extrusive
mafic intrusive
metamorphic
deformation
cooling/resetting
unknow n
fluid flow/ mineralisation

The granitic gneiss in the base of the Mallabie 1 drill hole is overlain by a thick (~425 m) package of coarse sandstones and mafic volcanics, the age of which is unknown. These volcanics have variously been correlated with Gawler Range Volcanics (~1590 Ma) through to Cambrian volcanics of the northern Officer Basin.

Given the total lack of outcrop, and the lack of drill holes intersecting basement, it appears unlikely that the basement geology of the Coompana Domain will become any better known in the foreseeable future. Thickness of cover appears to decrease somewhat to the west, yet is still sufficiently deep to discourage drilling into crystalline basement. If a seismic line across the Albany-Fraser province crosses into the westerly extension of the Coompana Domain and indicates relatively shallow cover, then stratigraphic drilling should be considered to evaluate the nature of the basement interface between the Albany-Fraser Province and Gawler Craton.

Nawa Domain

The Nawa Domain is situated to the northwest of the Karari Shear Zone, and north of the Coompana Block. The region of relatively high magnetic intensity known as the Moondrah Gneiss is included as part of the Nawa Domain. The Nawa Domain is entirely covered by Phanerozoic sedimentary rocks and geological knowledge of the crystalline basement is limited to sparse drill-hole intersections and interpretation of potential field data. The southern Nawa Domain is characterised by a northwest trending, highly magnetised belt of rocks known as the Moondrah Gneiss (Daly et al., 1998). Geological observations and geochronological constraints are limited to samples from four basement-intersecting drill-holes; Ooldea 1, 2 and 3 which intersect the Moondrah Gneiss in the south of the Nawa Domain, and AMPB2 within the Mabel Creek Ridge of the northern Nawa Domain. Separating the Ooldea region from the Mabel Creek Ridge is a ~200 km long tract characterised by relatively low magnetisation, from which no basement-rock samples are available.

The Moondrah Gneiss consists of variably mylonitised, iron-rich, magnetite-bearing migmatitic gneisses that preserve UHT metamorphic conditions (~950°C, 9.5 kbar), as evidenced by sapphirine-quartz and corundum-bearing assemblages in aluminous bulk compositions. These rocks represent the highest-grade metamorphic conditions yet documented in Australian Proterozoic rocks. The P-T-t path at near peak metamorphic conditions appears to have been relatively isobaric and anticlockwise (Teasdale, 1997), although the preservation of fine-grained UHT assemblages has also been used to argue for relatively rapid exhumation and cooling of these rocks (Teasdale, 1997), presumably implying a phase of relatively isothermal decompression then cooling subsequent to peak metamorphism.

A sample of the Moondrah Gneiss from diamond drill hole (DDH) Ooldea 2 yielded a U-Pb zircon age of 1659 ± 6 Ma, interpreted as a metamorphic zircon age with inherited zircons at ~1700 Ma (Fanning et al., 2007). Monazite from Ooldea 1 yields an EPMA age of 1640 ± 12 Ma (Swain et al., 2005b), within uncertainty of the zircon age from Ooldea 2. It is not clear whether the inherited zircons at ~1700 Ma represent detrital zircons, and therefore a maximum deposition age for the sedimentary protoliths of the Moondrah Gneiss or, alternatively, represent an earlier phase of metamorphism. This is a very important distinction as the only other constraint on the age of the sedimentary protoliths to the Moondrah Gneiss comes from Kober Pb-Pb analyses with an age of 2424 ± 6 Ma (Teasdale, 1997); note however, that no zircons of this age were identified by Fanning et al. (2007). The possible presence of ~2420 Ma zircons within the Moondrah Gneiss suggests a possible correlation with gneisses from the Christie Domain on the eastern side of the Karari Shear Zone. Such a correlation contrasts with tectonic models in which the rocks of the Nawa Domain, including the Moondrah Gneiss, have a history distinct from that of the Mulgathing Complex, and were juxtaposed with the Mulgathing Complex at ~1550 Ma (Daly et al., 1998; Direen et al., 2005; Payne et al., 2006).

Rocks from the Mabel Creek Ridge have been sampled by the AMPB2 and AMPB3 drill holes. A sample from AMPB2 (Paragon Bore) yielded a U-Pb SHRIMP zircon age of ~1550 Ma, reported without supporting data in Daly et al. (1998), and interpreted as a metamorphic age. Presentation of these data in Fanning et al. (2007) reveals that a total of only 10 zircon analyses were conducted, yielding scattered results with three of these analyses yielding ages close to ~1560 Ma. The reliability and meaning of this apparent age remains uncertain. LA-ICP-MS analyses of zircon from drill hole AMPB3 (~10 km SSE of AMPB2) yielded a range of ages, with the majority between ~1900 Ma and ~1700 Ma, and a few analyses with ages ~2500-2400 Ma (Payne et al., 2006). Payne et al. (2006) suggest a maximum depositional age of ~1740 Ma for this sample. This is an important conclusion as it implies that these rocks are part of a distinctly younger sedimentary package compared with rocks of the Mulgathing Complex to the southeast across the Karari Shear Zone.

Based on limited data, Payne et al. (2006) suggested a minimum age for deposition is provided by metamorphic zircon with age ~1720 Ma. If correct, these constraints imply sedimentary deposition between ~1740 and 1720 Ma, immediately followed by relatively high-grade metamorphism accompanied by metamorphic zircon growth. Payne et al. (2006) also report the presence of metamorphic zircon growth at ~1650 Ma and ~1550 Ma in the Nawa Domain. However, the evidence for this is not clear and further work on samples from these drill holes is warranted, particularly with the spatial precision of SHRIMP, to identify any younger metamorphic ages with greater resolution.

The overall zircon age pattern documented by Payne et al. (2006) for the rocks in AMPB3, with a minor zircon component at ~2400 Ma, and a large population at ~1850-1750 Ma is somewhat similar to the age pattern documented from the Moondrah Gneiss (Teasdale, 1997); i.e. an age component at ~2420 Ma, another component at ~1700 Ma, and a younger metamorphic growth event at ~1640 Ma.

Karari Shear Zone

The Karari Shear Zone (KSZ) separates the Nawa Domain to the northwest from the Christie Domain to the southeast. No exposure of the KSZ has been found, and its trace is identified from magnetic images, and from a single drill hole (Ooldea 3) that intersected the KSZ near its southern end, where it bounds the eastern margin of the Moondrah Gneiss. It is not clear from magnetic images where the main trace of the KSZ goes at its southernmost extent, specifically whether the KSZ extends southwest to the Australian coastline, or whether it swings to the west and forms a southern boundary to the magnetically distinctive Moondrah Gneiss. This raises questions regarding the nature of the boundary between the Coompana and Christie domains, and Coompana and Nawa domains, but these questions will be impossible to confidently resolve without access to rock samples from the relevant domains.

The KSZ, where intersected by DDH Ooldea 3, forms a 280 m thick zone of mylonitic gneisses (Rankin et al., 1989; Teasdale, 1997). The dominant rock type is a fine to medium grained quartz-magnetite-feldspar-biotite±garnet±sillimanite gneiss, with a variably developed mylonitic fabric. Sillimanite, where present, is aligned parallel with the mylonitic fabric suggesting mid- to upper-amphibolite facies conditions during at least some of the deformation. However, high-strain domains also contain a distinctly lower metamorphic grade assemblage in which sillimanite is boudinaged within a chlorite-biotite-sericite fabric.

Age constraints from the KSZ come from two studies which produced contrasting results and interpretations. Swain et al. (2005b) reported an EPMA monazite age of 1631 ± 12 Ma from the KSZ and interpreted this as the time of shearing. Fraser and Lyons (2006) reported muscovite and biotite $^{40}Ar/^{39}Ar$ ages from the mylonitic fabric of ~1440 Ma and interpreted this age as a period of deformation and mylonitic fabric development at low- to medium-metamorphic grade. Fraser and Lyons (2006) noted that the ~1630 Ma monazite age of Swain et al. (2005b) is within uncertainty of metamorphic zircon ages from the Moondrah Gneiss to the west of the KSZ. They, therefore, suggested that this monazite age reflects high-grade metamorphism prior to movement on the KSZ. The alternative interpretation of Swain et al. (2005b), that the monazite reflects KSZ deformation closely following peak metamorphism of the Moondrah Gneiss, is possible and implies multiple periods of movement along the KSZ. Note that at its northern end, the KSZ appears to bifurcate around the Coober Pedy Ridge, with one strand of the KSZ separating the poorly documented ~1590 Ma magmatic and metamorphic rocks of the Coober Pedy Ridge from the ~2450 Ma gneisses of the Christie Domain, implying movement along the KSZ at ~1590 Ma or later.

Coober Pedy Ridge

The Coober Pedy Ridge is situated north of the Christie Domain, apparently bounded to both north and south by splays of the KSZ. In common with most of the northwest Gawler Craton outcrop of basement rock is extremely rare (perhaps non-existent?) and geological knowledge is limited to observation from sparse drill holes. A granodiorite gneiss from drill hole CR9119 yields a magmatic crystallisation age of ~1590 Ma (Fanning et al., 2007). Samples from drill hole CR9125 are interlayered ironstones and aluminous granulites with peak P-T conditions of ~9 kbar and 950°C (Daly et al., 1998). Metamorphic zircon rims in cordierite-garnet-sillimanite gneiss yield a U-Pb SHRIMP age that was originally reported as 1565 ± 8 Ma (Daly et al., 1998), but the same analyses have been reinterpreted to indicate metamorphism at ~1590 Ma (Fanning et al., 2007). These are the only published radiometric age constraints from the Coober Pedy Ridge, indicating the scope for further work if additional samples of basement rock can be obtained.

Mount Woods Domain

The Mount Woods Domain is situated to the east of the Coober Pedy Ridge, and northwest of the Olympic Domain, in the far north of the Gawler Craton. The geology is relatively poorly known due to sparse outcrop but has received increased mineral exploration attention over the past five years, particularly since the discovery of the Prominent Hill IOCG deposit.

Constituent rocks of the Mount Woods Domain include supracrustal successions of interlayered banded iron formation, leucocratic gneiss, psammitic and pelitic schists and calc-silicates (Betts et al., 2003). The depositional age of these sedimentary rocks is poorly known. Conventional U-Pb ID-TIMS data have been reported from a quartzo-feldspathic gneiss, yielding an upper intercept concordia age of 1742 ± 27 Ma, interpreted to be the timing of magmatic crystallisation (Fanning et al., 1988). The sedimentary rocks have been correlated with the Hutchison Group of the southern Gawler Craton, and interpreted to have been deposited in the Palaeoproterozoic on the margin of an Archaean Craton. Betts et al. (2003) report the presence of conglomerate and sandstone unconformably overlying gneisses and schists, and containing clasts of the underlying rocks. The conglomerates are reported to have been contact-metamorphosed during emplacement of the Balta Granite Suite (Ambrose and Flint, 1980), thus providing relative timing constraints on deposition, metamorphism and exhumation of the underlying units. The Balta Granite has yielded a U-Pb zircon age of 1584 ± 18 Ma (Finlay, 1993).

The recent increase in mineral exploration interest in the Mount Woods Inlier led to an extensive program of geochronology at Geoscience Australia, with 34 radiometric age constraints now available for this region. All these ages are U-Pb zircon ages and, in several cases, multiple zircon ages have been reported from a single sample. Of these 34 radiometric ages, only one has been formally published (Fanning et al., 1988), 29 are unpublished ages (from 15 samples) in the OZCHRON database (Holm), another 3 are documented in a Geoscience Australia Record (Jagodzinski, 2005), and three are from an unpublished honours thesis (Finlay, 1993). The absence of publications that fully document the geological context of the analysed zircons makes thorough assessment of the geological meaning of much of these data difficult.

The majority of radiometric ages from the Mount Woods Domain are ~1740 Ma, ~1690 Ma or ~1585 Ma. Two felsic intrusive zircon ages are reported at ~1740 Ma, one of which has large uncertainty (± 27 Ma). At face-value, these ages are slightly older than ages attributed to the Kimban Orogeny in the south of the Gawler Craton (~1730-1710 Ma), although given only two ages and the large uncertainty on one of them, it remains for future work to assess whether this apparent difference is significant. The relationship between these felsic intrusions and the sedimentary units within the domain is uncertain, but the sediments are interpreted to largely predate the intrusion of the ~1740 Ma granite (Fanning et al., 1988). The Engenina Adamellite is a foliated granite that intruded the supracrustal metamorphic package and has an age of 1691 ± 25 Ma (Finlay, 1993).

A relatively tight cluster of ages occurs in the Mount Woods Domain between 1594 ± 5 Ma and 1575 ± 3 Ma, including mafic and felsic intrusives, and metamorphic zircon ages (Jagodzinski, 2005; Skirrow et al., 2006). Bimodal igneous rocks of this age range are widespread over the Gawler Craton (Hiltaba Suite and Gawler Range Volcanics). The presence of Hiltaba-aged zircon interpreted as metamorphic (Holm, OZCHRON) in quartzites and felsic gneisses suggests that metamorphic grade in the Mount Woods Inlier at ~1590 Ma to ~1580 Ma was significantly higher-grade than is typical for this time-period elsewhere in the Gawler Craton. This, in turn, suggests that the Mount Woods region was at deeper crustal levels at ~1590-1580 Ma than the adjacent Olympic, Christie and Wilgena Domains.

In the Mount Woods Inlier, the age of the stratigraphy is poorly constrained. Betts et al. (2003) refer to conglomerates and sandstones that unconformably overlie the older gneisses, also indicating the presence of at least two stratigraphic packages. However, data of Holm (OZCHRON) shows consistently younger maximum depositional ages, with three samples taken from the drillholes Engenina 20 and 38 having age clusters that range from ~1860 Ma to ~1750 Ma and down to as young as ~1670 Ma. Two further samples from the drillholes Warrina Creek 1 and Enginina 61 have detrital zircons with ages of ~1720 Ma and ~1650 Ma respectively. If the interpretation of the zircons as detrital is correct, these ages place important constraints on the age of the stratigraphy in the Mount Woods region, requiring sedimentary deposition of the protoliths to gneisses in the Engenina and Warrina Creek regions to post-date ~1670 Ma. This is not consistent with the speculative correlation of these sediments with the Hutchison Group sediments of the Cleve Domain, although it should be noted that the age of the Hutchison Group is currently being reassessed (see discussion below for Cleve Domain). The Mount Woods sedimentary rocks contain a zircon component with an age of ~1750 Ma, consistent with their derivation from local (?) ~1750 Ma granites, implying exhumation and exposure of these granites and a renewed cycle of sedimentation prior to extensive bimodal magmatism at Hiltaba/Gawler Range Volcanics time.

It is also noted that a felsic gneiss from Enginina 61 has five zircon age components (Holm, OZCHRON); ~1820 Ma, ~1740 Ma, ~1670 Ma, ~1660 Ma, and ~1630 Ma. The petrogenesis of these zircons is unknown and is critical to the geological significance of their ages. If the youngest zircon component, at 1627 ± 19 Ma is detrital, this places a relatively tight age constraint on deposition of the sedimentary package that was then intruded and metamorphosed at mid-crustal levels at ~1590-1580 Ma. However, Betts et al. (2003) report that the Engenina Adamellite is syn-orgenic and intruded the supracrustal metamorphic package. This would imply a stratigraphic package that predates ~1690 Ma, and is therefore older than the package that contains detrital zircons as young as ~1630 Ma as reported by Holm (OZCHRON). Recall that Betts et al. (2003) refer to conglomerates and sandstones unconformably overlying the older gneisses, also indicating the presence of at least two stratigraphic packages. A question then arises: do the metasediments dated by Holm correlate with the conglomerate and sandstone mentioned by Betts et al. (2003) ?, or, alternatively, is there a problem with the interpretation of one or more of the age relationships?

Betts et al. (2003) also refer to an age of ~1736 Ma for zircon from "…first generation partial melts at Spire Hills..." without providing reference to the source of the age. This age places metamorphism and partial melting broadly synchronous with felsic intrusives at ~1742 Ma, and also implies the presence of a pre- ~1740 Ma sedimentary package.

Betts et al. (2003) tentatively correlated the overlying conglomerate and sandstone with the Tarcoola Formation. This appears broadly consistent with the detrital zircon results of Holm (OZCHRON), although some of these may indicate even later sedimentation e.g. 1630 Ma or younger.

Christie Domain

The Christie Domain is a large, northeast trending arcuate region bounded to the north by the Karari Shear Zone, and to the east by the Tallacootra and Coorabie Shear Zones. This region is characterised by latest Archaean metasedimentary rocks that were metamorphosed to granulite-facies in the earliest Proterozoic at 2480-2420 Ma during the Sleaford Orogeny (McFarlane, 2006). Collectively, these metasedimentary rocks are termed the Christie Gneiss (Daly and Fanning, 1993).

Numerous age determinations exist for the Christie Gneiss, but these mostly come from the Challenger gold mine, raising some question as to how representative of the entire domain these ages are. Eight U-Pb ages of zircon and monazite from the Challenger mine range from 2454 Ma to 2428 Ma, with one slightly younger monazite age at 2414 Ma. These ages are interpreted as the time of high-grade metamorphism and partial-melting, with McFarlane (2006) arguing for relatively prolonged high-grade conditions to explain the spread in ages. Peak pressure and temperature conditions of the Christie Gneiss are estimated at ~7.5 ± 1.5 kbar and 800-850°C (Tomkins et al., 2004), indicative of at least mid-crustal depth. The depositional age of gold-hosting sedimentary protoliths that were metamorphosed at this time remains largely unconstrained. This Archaean history is not the focus of the current Geoscience Australia study into the Australian Proterozoic and is not considered further here.

No Palaeo- or Mesoproterozoic sedimentary rocks are known from the Christie Domain, in contrast to several domains farther east e.g. Mount Woods, Olympic, Wilgena. The history of the Christie Domain post ~2400 Ma is one of variable metamorphic reworking, intrusion by sparsely distributed granites, and cooling, presumably related to exhumation.

Palaeoproterozoic felsic intrusives have been dated at 1702 ± 42 Ma (the Wynbring West Granite) and 1681 ± 15 Ma (Fanning et al., 2007). Given the relatively large uncertainties on each of these ages, they may well have intruded contemporaneously.

Fanning (2002) has reported U-Pb monazite ages from the Challenger mine at ~1735 Ma, ~1722 Ma and ~1710 Ma. These results suggest a second episode of relatively high-grade reworking of the Christie Gneiss. Note that the detailed study of McFarlane (2006) on the Christie Gneiss from the Challenger mine did not report any evidence of this ~1720 Ma event. The significance of these ~1720 Ma ages, both locally to the Challenger mine and more regionally, remains unknown. Tomkins et al. (2004) report two $^{40}Ar/^{39}Ar$ sericite ages from Challenger at ~1615 Ma, interpreted by those authors as an episode of fluid influx and hydrous retrogression. This age coincides broadly with the time of the St Peter Suite intrusions farther south in the Gawler Craton, although whether there is any causal link is speculative.

The cooling history of the Christie Gneiss is somewhat constrained by a $^{40}Ar/^{39}Ar$ biotite age of ~1650 Ma from Christie Corner (Fraser and Lyons, 2006) and consistent minimum ages from K-feldspar $^{40}Ar/^{39}Ar$ age spectra of ~1530 Ma (Tomkins et al., 2004). These results indicate that the Christie Domain was relatively cool (<~350°) and by implication at relatively shallow crustal levels by ~1650 Ma, while high-grade metamorphism was occurring at much deeper crustal levels in the Moondrah Gneiss to the west, and high-grade metamorphism may have occurred at ~1550 Ma in the Mabel Creek Ridge. The coincidence of the $^{40}Ar/^{39}Ar$ ages at ~1650 Ma and ~1530 Ma in the Christie Domain with periods of high-grade metamorphism in adjacent regions to the west and north suggests that these $^{40}Ar/^{39}Ar$ ages probably represent episodes of relatively minor thermal disturbance in the Christie Domain causally related to the deeper crustal events occurring at these times in adjacent regions. The $^{40}Ar/^{39}Ar$ ages are therefore regarded as indicative of successive thermal pulses rather than very slow continuous cooling.

Tallacootra and Coorabie Shear Zones

These are two of the longest and most prominent of a series of anastomosing northeast trending structures visible in magnetic images of the western Gawler Craton. In combination, the Tallacootra Shear Zone (TSZ) and Coorabie Shear Zone (CSZ) form the eastern boundary of the Christie Domain. Cross-cutting relationships apparent in magnetic images suggest the TSZ and CSZ predate final movement on the Karari Shear Zone to the west (Teasdale, 1997).

Age constraints from within the Tallacootra and Coorabie Shear Zones come from both EPMA analyses of monazite (Swain et al., 2005b) and $^{40}Ar/^{39}Ar$ analyses of mica and K-feldspar (Fraser and Lyons, 2006), with the two methods yielding contrasting results. Swain et al. (2005b) report essentially identical results from a sample from within the main trace of the TSZ at Lake Tallacootra, and from a migmatite sample to the west at Lake Ifould. These samples both have a monazite component with age ~2350 Ma, broadly similar to, but slightly younger than, the numerous U-Pb isotopic ages from zircon and monazite from the Christie Gneiss, through which the TSZ cuts. In addition, both samples contain a monazite age component at ~1680 ± 40 Ma. This age has been interpreted by Swain et al. (2005b) to reflect the time of deformation along the TSZ at relatively high-grade metamorphic conditions. Fraser and Lyons (2006) report $^{40}Ar/^{39}Ar$ mica ages from the mylonitic fabric at Lake Tallacootra of ~1440 Ma and suggest that these ages represent a period of deformation and hydrous fabric development. The contrasting age results from monazite and mica from the TSZ raise the question of whether this structure experienced multiple episodes of movement, and if so, which of these episodes were more geologically important in juxtaposing crustal blocks into their current relative crustal levels and along-strike positions. Fraser and Lyons (2006) note that the 1680 ± 40 Ma monazite ages are within uncertainty of ~1680 Ma granites intruding the Christie Domain (Ifould Suite) and the ~1720 Ma metamorphic monazites reported by Fanning (2002) from the Christie Gneiss at the Challenger Mine. On this basis, Fraser and Lyons (2006) raise the possibility that the ~1680 Ma monazite ages reported by Swain et al. (2005b) represent metamorphic monazite that pre-dates the development of the TSZ. Development of the TSZ post-dating 1680 Ma is consistent with the evidence of high-grade metamorphism at ~1550 Ma within the Fowler Domain that is dissected by the TSZ. It would appear that the TSZ must have been active post- ~1550 Ma, probably as late as ~1450 Ma, but periods of movement as old as ~1680 ± 40 Ma are also possible.

Rocks from the CSZ yield a range of radiometric ages from ~1530 Ma to ~1460 Ma. Samples from near the southern end of the CSZ, from DDH Nundroo 5, and from outcrop at Cape Adieu, each yield two distinct monazite EPMA ages. Monazite inclusions in garnet yielded ages of ~1510 Ma while monazite from within the mylonitic fabric yielded ages of ~1460 Ma. In contrast, mica from an outcrop of protomylonitic granite within the northern part of the CSZ yielded $^{40}Ar/^{39}Ar$ ages of ~1540 and ~1520 Ma. The ~1460 Ma monazite ages were interpreted by Swain et al. (2005b) to be the time of deformation, consistent with the ~1490 Ma U-Pb zircon age from a pegmatite from drill hole Nundroo 2 which itself is cut by narrow brittle-ductile shear zones (Teasdale, 1997; Fanning et al., 2007). Given the evidence for ~1460 Ma deformation in the southern part of the CSZ the significance of the older (~1530 Ma) $^{40}Ar/^{39}Ar$ mica ages from the northern part of the CSZ is unclear. The deformed granite sampled by Fraser and Lyons (2006) may not be representative of the main trace of the CSZ, and the $^{40}Ar/^{39}Ar$ ages may simply reflect cooling ages. This would be consistent with similar cooling ages of ~1530 Ma from K-feldspar from the northern Christie Domain at the Challenger mine, that have been tentatively linked to high-grade metamorphic events at this time in the Coober Pedy, Mabel Creek and southern Fowler Domains. Alternatively, the $^{40}Ar/^{39}Ar$ ages from the northern CSZ may be minimum ages for deformation at this locality, implying multiple periods of movement along the CSZ.

Fowler Domain

The Fowler Domain is a NNE trending zone of high magnetic intensity bounded and dissected by anastomosing northeast trending shear-zones including the Tallacootra and Coorabie Shear Zones. The Fowler Domain appears to consist of a series of fault-bounded crustal slices, with both peak metamorphic conditions and timing varying between the difference slices. Teasdale (1997) and Swain et al. (2005b) have subdivided the Fowler Domain into four main subdomains on the basis of metamorphic grade and timing.

Magmatism within the Fowler Domain comprises felsic intrusives with ages of 1726 ± 11 Ma (Kimban age) to ~1675 Ma (Tunkillia age) to ~1575 (Hiltaba age) and a single age from a late stage pegmatite at ~1490 Ma (Fanning et al., 2007). Mafic magmatism is also known from the Fowler Domain and comprises metagabbro intersected by the Colona drillholes (Daly et al., 1994), a sample of which was emplaced at 1726 ± 9 Ma (Fanning et al., 2007).

The Fowler Domain apparently lacks the late Archaean basement rocks observed in the Christie Domain to the northeast. The age and provenance of the Fowler Domain stratigraphy is poorly constrained, with only a handful of zircon U-Pb analyses available from a single metasedimentary rock from the domain. This sample yielded zircon cores with ages ~1750 Ma and ~1685 Ma, with metamorphic rims with ages ~1566 Ma (Fanning et al., 2007).

Metamorphic grade across the Fowler Domain varies from medium-high pressure granulite-facies (~800°C, 8-9 kbar) to medium-pressure upper amphibolite-facies (~650°C, ~6 kbar; Teasdale, 1997). This variation in crustal depth and metamorphic age in different slices within the Fowler Domain suggests that a fruitful future study may involve $^{40}Ar/^{39}Ar$ analyses from rocks from the various crustal slices to compare cooling and exhumation ages to help determine the timing of vertical movement along the intervening shear zones.

Geochronology on the metamorphic episodes within the Fowler Domain indicate that there have been multiple events. The oldest is a monazite SHRIMP age ~1712 Ma (Teasdale, 1997) which suggests that Kimban-aged deformation and metamorphism is likely to have affected rocks in the Fowler Domain. A mafic granulite has a zircon age of ~1550 Ma, and zircon rims within a metapelite gave ages ~1566 Ma, which is interpreted as the time of high-grade metamorphism (Fanning et al., 2007). Swain et al. (2005b) reported two EPMA ages of ~1510 Ma from monazite inclusions within garnet in rocks deformed by the Coorabie Shear Zone.

Wilgena Domain

The Wilgena Domain lies to the east of the Fowler and Christie Domains, across the Coorabie Shear Zone. The Wilgena Domain differs substantially from the domains to the west in that it is relatively undeformed and unmetamorphosed, and appears to have been relatively stable in the upper crust since at least the early Mesoproterozoic (~1590 Ma).

The Wilgena Domain comprises late Archaean to earliest Proterozoic metasediments and meta-igneous rocks of the Mulgathing Complex, which are overlain by Wilgena Hill Jaspilite, in turn, overlain by Tarcoola Formation.

Banded iron formation (BIF), chert, carbonate, calc-silicate and aluminous metasediments in the Wilgena Domain have been interpreted as low-grade equivalents of the Christie Gneiss (Daly et al., 1998), implying that the Wilgena Domain has not been deeply buried and metamorphosed since sedimentary deposition in the late Archaean. Note, however, that there is little geochronological evidence available to test this suggested correlation. Jagodzinski (2005) reports detrital zircons with age ~2540 Ma from a sample in the northeastern Wilgena Domain, which could be interpreted to indicate a sediment derived from Sleaford Orogeny age gneisses, and therefore a post-Sleaford depositional age.

The Wilgena Hill Jaspilite is a folded, fine-grained, finely laminated BIF, with folding attributed to the Kimban Orogeny (Parker et al., 1993). Age constraints are poor, permitting this unit to have been deposited any time between deformation and metamorphism of the underlying Mulgathing Complex (~2450 Ma) and deposition of the overlying Tarcoola Formation (~1650 Ma). If the folding in the Wilgena Hill Jaspilite is, indeed, of Kimban age, then deposition must have predated the Kimban Orogeny (i.e. >1730 Ma).

In the vicinity of the Tarcoola goldfield, granites of the Paxton Suite intruded at ~1715 Ma (Budd and Fraser, 2004; Budd, 2006). Intrusion of these granites was followed by deposition of the Tarcoola Formation. The Tarcoola Formation is a ~800 m thick, fining upwards sequence, ranging from the basal Peela Conglomerate through quartzites and sandstone upwards into upper Sullivan Shale Member interpreted to have been deposited in fluvial to marginal-marine conditions (Daly, 1993). Water-lain tuffs within the Sullivan Shale Member have yielded a U-Pb zircon age of 1656 ± 7 Ma (Fanning, 1990).

Archaean and Palaeoproterozoic sedimentary rocks in the Wilgena Domain were intruded by the voluminous Hiltaba Suite granitoids at ~1590-1580 Ma. This is also the time of gold mineralisation in the Tarcoola goldfield (Budd and Fraser, 2004).

Harris Greenstone Domain

The Harris Greenstone Belt is a relatively small, fault bounded region in the central Gawler Craton composed of ultramafic-mafic extrusive rocks including the Lake Harris Komatiite (Hoatson et al., 2005), which is interbedded with metasedimentary rocks and intruded by younger granites (Glenloth Granite and equivalents; Fanning et al., 2007). Sedimentation and ultramafic-mafic volcanism occurred at ~2520 Ma, and was followed by metamorphism at ~2450 Ma during the Sleaford Orogeny (Swain et al., 2005a).

Nuyts Domain

The Nuyts Domain, situated in the southwest of the Gawler Craton, is the largest domain in the Gawler Craton but is also one of the least well understood due to the lack of outcrop. Basement geology in the Nuyts Domain is interpreted to be dominated by late-Palaeoproterozoic to Mesoproterozoic magmatic intrusive rocks (Fairclough et al., 2003).

The oldest radiometric age from the Nuyts Domain comes from the Investigator Granite Gneiss from Flinders Island, with a LA-ICPMS U-Pb zircon age of 1762 ± 11 Ma (Cooper and Belousova, 2004). A SHRIMP zircon U-Pb age of 1710 ± 11 Ma has been reported for the magmatic crystallisation of a quartzo-feldspathic gneiss from near Poverty Corner (Fanning et al., 2007), consistent with magmatic intrusions to the east in the Coulta, Cleve and Spencer Domains (Moody Suite).

A cluster of three U-Pb zircon ages at ~1680 Ma is assigned to the Tunkillia Suite. These three samples all come from the eastern side of the Nuyts Domain, in the region containing the central Gawler gold deposits and prospects (e.g. Tunkillia, Myall, Sheoak, Little Pinbong rockhole; Fanning et al., 2007).

A mid-1980’s U-Pb TIMS age of 1631 ± 3 Ma (Cooper et al., 1985) comes from felsic volcanics on St Francis Island, also termed the Nuyts Volcanics. Another example of these volcanics from St Peter Island has been dated at 1627 ± 2 Ma (Rankin et al., 1990).

A wide range of U-Pb zircon ages from granites is reported, spanning the interval 1616 ± 16 Ma to 1562 ± 16 Ma. The two oldest ages in this range (1619 ± 15 and 1615 ± 8 Ma) are assigned to the St Peter Suite granites, and regarded as distinct from the slightly younger Hiltaba Suite granites that, in the Nuyts Domain, range from 1596 ± 9 Ma to 1562 ± 16 Ma. It is worth noting that the St Peter Suite age is defined only by one TIMS zircon age (1619 ± 15 Ma; Fanning, 1997) and another slightly more precise SHRIMP zircon age (1616 ± 6 Ma; Fanning et al., 2007). St Peter Suite granites are inferred to underlie the majority of the Nuyts Domain (Fairclough et al., 2003), implying addition of a very large volume of magma to the upper crust at this time.
Evidence for tectonic activity in the Nuyts Domain post-dating the Hiltaba granites is limited to an EPMA monazite age of 1503 ± 16 Ma reported by Swain et al. (2005b) from the Yerda Shear Zone which forms the northern margin of the Nuyts Domain.

Coulta Domain

The Coulta Domain occupies the western half of Eyre Peninsula, in the south of the Gawler Craton. The Coulta Domain is dominated by late Archaean-early Proterozoic gneisses and granites. These include the ~2485 Ma Wangary Gneiss, ~2525 Ma Hall Bay Volcanics and the intrusive Dutton Suite, which includes the ~2460 Ma Kiana Granite and the 2520 Ma Coulta Granodiorite (Fanning et al., 2007).

The Hutchison Group overlies these basement gneisses and granites, and includes the Warrow Quartzite that contains detrital zircons as young as ~2000 Ma, providing a maximum depositional age (Fanning et al., 2007).

Mafic dykes at the Barns prospect contain zircons of age ~1700 Ma, interpreted as xenocrystic zircons (Holm, unpublished data), and implying the presence of Kimban age metamorphic and/or intrusive rocks within the Coulta Domain, although these have not been directly dated. Hiltaba Suite intrusions are also known from the northwestern region within the Coulta Domain, in particular the 1583 ± 11 Ma Calca Granite (Fanning et al., 2007).

$^{40}Ar/^{39}Ar$ ages from muscovite and hornblende from the western side of Eyre Peninsula indicate muscovite closure to argon diffusion at ~1650 Ma, and local resetting of hornblende at ~1590 Ma coincident with intrusion of the Hiltaba Suite (Foster and Ehlers, 1998). A K-feldspar $^{40}Ar/^{39}Ar$ age spectrum shows a range in ages from a maximum at ~1540 Ma to a minimum at ~800 Ma. This is very similar to K-feldspar age spectra from further northwest in the Gawler Craton (Fraser and Lyons, 2006), with the ~800 Ma minimum ages possibly representing thermal resetting associated with continental rifting and intrusion of the associated Gairdner dyke swarm.

Cleve Domain

The Cleve Domain on the eastern side of Eyre Peninsula, contains rocks representing much of the geological history of the Gawler Craton. The oldest rocks in the Cleve Domain are Sleafordian Gneisses exposed on the southern coast of Eyre Peninsula.

The migmatitic, quartzo-feldspathic Miltalie Gneiss gives a U-Pb zircon age of ~2000 Ma (Fanning et al., 2007), and forms the crystalline basement onto which the unconformably overlying Hutchison Group sediments were deposited.

The Hutchison Group is an overall fining-upward sequence, probably several kilometres thick, consisting of a basal quartzite (Warrow Quartzite), and overlying semipelitic and chemical sedimentary rocks of the Middleback Subgroup, which host massive iron-ore deposits of the Middleback Ranges (Yeates, 1990). Timing of deposition of the Hutchison Group is generally considered to have occurred between ~2000 Ma (age of the underlying Miltalie Gneiss) and ~1850 Ma (age of the Donington Suite granites). A tighter age constraint on deposition comes from a U-Pb zircon age of 1866 ± 10 Ma from the Bosanquet Formation (Fanning et al., 2007), interpreted as a volcanic unit within the upper Hutchison Group. Note, however, that there is considerable uncertainty regarding the geological relationship of the Bosanquet Formation to the Hutchison Group, as the contact is not exposed. Radically different interpretations have been proposed in which the Hutchison Group is suggested to be younger than the Donington Suite (e.g. Vassallo and Wilson, 2001).

No examples of Donington Suite granites (~1850 Ma; see Spencer Domain discussion below) have been dated in the Cleve Domain. The Middlecamp and Refuge Rocks granites are both foliated, interpreted as a result of the Kimban Orogeny. The ages of these granites, ~1740-1730 Ma (Fanning et al., 2007), therefore provide a maximum age constraint for the timing of at least some Kimban deformation. Also present in the Cleve Domain are granites of the Moody Suite, with ages of ~1710-1700 Ma, and Hiltaba Suite granites and Gawler Range Volcanics with age ~1600-1590 Ma, particularly around the northern margin of the domain (e.g. Menninnie Dam; Fanning et al., 2007).

Spencer Domain

This region on the easternmost side of Eyre Peninsula is dominated by Donington Suite granites. Several U-Pb zircon ages, via TIMS, SHRIMP and Kober evaporation methods, yield ages in the range 1840 Ma to 1850 Ma. The Donington Suite includes the quartz gabbronorite sample used as a zircon standard at ANU, known as QGNG. Extensive TIMS and SHRIMP U-Pb analyses of this sample yield an age of ~1850 Ma (Black et al., 2003). Compositions of Donington Suite granites range from mafic gabbro-norite to evolved leucogranites. Donington Suite rocks were derived from the fractionation of a mafic magma that incorporated a significant component of pre-existing crustal material (Schaefer, 1998; Reid et al., submitted).

According to Ferris et al. (2002) Hutchison Group metasedimentary rocks are folded into Donington Suite granitoids in the northern part of the Spencer Domain, although the available age dataset from with the Spencer Domain does not include any rocks older than Donington Suite granitoids.

Note that there is no geochronological evidence for Archaean rocks in the Spencer Domain.

Donington Suite granitoids are intruded by Tournefort mafic dykes, dated by the zircon Pb-Pb Kober method at ~1812 Ma (Schaefer, 1998). This is similar in age to the Myola Volcanics (1791 ± 4 Ma; Fanning et al., 1988). Also present in the Spencer Domain are granites of the ~1700 Ma Moody Suite, and ~1590-1580 Ma Hiltaba Suite (Creaser and Fanning, 1993).

Metamorphic monazite ages of ~1690 Ma (Swain et al., 2005b) are attributed to the late stages of the Kimban Orogeny, and with probable movement along the Kalinjala Shear Zone that separates the Spencer Domain from the Cleve Domain.

Several $^{40}Ar/^{39}Ar$ ages from hornblende yield ages close to Hiltaba age (Foster and Ehlers, 1998), suggesting the Spencer Domain cooled through ~500°C immediately after Hiltaba/GRV magmatism. Lower temperature thermochronometers (biotite and K-feldspar) reveal a more protracted lower temperature cooling history that extends to ~800 Ma (Foster and Ehlers, 1998), corresponding to intrusion of the Gairdner Dyke Swarm. It is notable that there are clusters of argon ages at ~1540 Ma and ~1430 Ma, corresponding to ages recorded much further west in the Gawler Craton (see discussion of Fowler and Nawa Domains above), and perhaps representing reactivation of the Kalinjala Shear Zone during tectonic events that were focussed further west.

Gawler Range Volcanics Domain

This domain is entirely covered by the extensive mafic and felsic lavas of the Gawler Range Volcanics. The most precise age constraints for this large volcanic event come from two TIMS U-Pb zircon ages of 1592 ± 3 Ma and 1591 ± 3 Ma (Fanning et al., 1988).

Olympic Domain

The Olympic Domain forms the eastern margin of the Gawler Craton, bounded to the east by Adelaidean rift sediments. As for the Spencer Domain, no rocks in the Olympic Domain have been dated at older than ~1850 Ma, raising the question of what rocks the 1850 Ma Donington Suite granites intruded into.

Donington Suite granites in the Olympic Domain span the age range 1860-1850 Ma, apparently about 10 Ma older than Donington Suite in the Spencer Domain (Jagodzinski, 2005).

Wallaroo Group metasediments in the Olympic Domain contain detrital zircons of ~1850 Ma age, presumably sourced from Donington Suite granitoids or volcanic equivalents, and a younger zircon population at ~1760-1750 Ma (Jagodzinski, 2005). This younger population corresponds broadly to the Wardang Volcanics at ~1770 Ma and volcanics within the Wandearah sediments at ~1740 Ma. The dated stratigraphy is, therefore, constrained to have been deposited at ~1740 Ma and younger.

This stratigraphy is extensively intruded by Hiltaba Suite granites and covered by Gawler Range Volcanics, associated with highly significant regional mineralisation in this domain (Creaser and Cooper, 1993; Johnson and Cross, 1995; Jagodzinski, 2005).

Overlying the Gawler Range Volcanics is the Pandurra Formation, which has a poorly constrained Rb-Sr age of 1421 ± 54 Ma (Fanning et al., 1983).

Peake and Denison Domain

The Peake and Denison domain is situated on the northeastern margin of the Gawler Craton. Few geochronological constraints are available for rocks from this domain. The Tidnamurkana Volcanics yield a relatively imprecise TIMS U-Pb zircon age of 1806 ± 27 Ma (Fanning et al., 1988). Hopper (2001) reports TIMS U-Pb zircon ages of ~1800 Ma from both a pegmatite and mafic sill, as well as an age of ~1733 ± 13 Ma from a metatonalite. Ferris et al. (2002) report a SHRIMP U-Pb zircon age from a granite of 1536 ± 6 Ma.

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

Stratigraphic Constraints

Stratigraphic age constraints and the understanding of stratigraphic relationships within the Gawler Craton are severely lacking when compared with stratigraphic understanding in other Australian Proterozoic terrains. This can be seen by the paucity of data in the Gawler Craton Time-Space plot layer that considers only stratigraphy (see Appendix), particularly as compared with the equivalent plot for the Mount Isa or Curnamona regions. The lack of stratigraphic constraints in the Gawler Craton is largely a consequence of the lack of outcrop and the difficulty of developing stratigraphic understanding from limited drill holes. Any future work that can address stratigraphic development will significantly improve geological understanding of the Gawler Craton.
Particular examples of stratigraphic uncertainty include:

- The timing of deposition of the Hutchison Group, and the extent to which these represent a single stratigraphic package, or multiple packages that are either unconformity bounded or thrust repetitions.
- The timing of deposition of the Pandurra Formation, which overlies the Gawler Range Volcanics.

The position, nature and timing of the boundary between the Gawler Craton and Musgrave Province

The question could be addressed by:

- $^{40}Ar/^{39}Ar$ geochronology of rocks from the Yoolperlunna and Ammaroodinna Inliers, or from stratigraphic holes drilled through the Officer Basin between the Gawler Craton and Musgrave Province in support of the proposed Gawler-Musgrave reflection seismic line.
- SHRIMP U-Pb zircon and monazite geochronology of samples from the Yoolperlunna and Ammaroodinna Inliers. For example, (i) in the Yoolperlunna Inlier target the granitic dykes

that intrude the granitic gneiss (ii) look for metamorphic monazite in gneissic rocks from both inliers.

- Targeting detrital or inherited zircons in either of both of the Yoolperlunna and Ammaroodinna Inliers for comparison with zircon age spectra from the Musgrave and Gawler Cratons.
- If a stratigraphic hole is drilled in this region, looking for development of mica fabrics in fault zones that might indicate timing of movement on major structures between the Gawler Craton and Musgrave Province.
- U-Pb zircon geochronology on rocks from the Ammaroodinna Inlier, to test whether these represent Musgrave Province or Gawler Craton crust.

The nature and timing of the Karari Shear Zone boundary

This problem is severely limited by lack of rock samples, particularly from northwest of the Karari Shear Zone in the Nawa Domain. The recent studies of Payne et al. (2006), Direen et al. (2005) and Fraser and Lyons (2006) have suggested that the Karari Shear Zone may represent a crustal-scale boundary (suture?) between Archaean to earliest Proterozoic rocks of the Mulgathing Complex to the southeast with a distinct terrain to the north-west, with juxtaposition of these distinct crustal blocks occurring in the Mesoproterozoic. The timing of this suggested juxtaposition is uncertain, and could be ~1650 Ma, ~1550-1530 Ma, or perhaps as late as ~1450 Ma.

If any new samples become available in future, for example in association with a seismic line from the Gawler Craton to the Musgrave Province, thorough geochronology will be extremely important to assess current ideas.

Scope may exist for re-examining existing samples with SHRIMP zircon analyses. For example, thin zircon rims in the sample from the Moondrah Gneiss (Ooldea 2) have not been dated (Fanning in Teasdale, 1997, p. 57). Metamorphic zircon in the sample used by Payne et al. (2006) from the northern Nawa Domain may be worth revisiting with SHRIMP as compared with the LA-ICP-MS analyses. The metamorphic growth history was not the main focus of the Payne et al. (2006) study, and the poorer spatial resolution of LA-ICP-MS would, in any case, have limited that study.

A search for monazite in the rocks analysed by Fanning from Ooldea 2, PB2, and Coober Pedy may be worthwhile.

$^{40}Ar/^{39}Ar$ analyses of samples from the Moondrah Gneiss would provide a useful comparison with such ages from the Christie Domain, and would provide further evidence for the timing of movement across the KSZ. Further $^{40}Ar/^{39}Ar$ analyses coupled with in–situ U-Pb SHRIMP monazite analyses along a systematic traverse through the Karari Shear Zone in the Ooldea 2 drill hole from high-strain to low-strain may provide much clearer evidence for the timing of movement along this major structure.

The southernmost trace of the Karari Shear Zone, and the nature of the Coompana-Nawa boundary and the Coompana-Christie boundary.

A reinterpretation of magnetics and gravity at the southern end of the Karari Shear Zone may be worthwhile, although the thick sedimentary cover over the Coompana Domain may hinder potential field modelling.

Geochronology of the Coober Pedy Ridge

Only a single radiometric age exists from the Coober Pedy Ridge. Any significant new geochronology will probably require new drilling to provide samples. A $^{40}Ar/^{39}Ar$ study of the CR9125 drill hole (as dated by Daly et al., 1998) together with samples from the Mabel Creek Ridge, may provide a useful cooling history comparison with the Christie Domain and hence information about the timing of juxtaposition across the Karari Shear Zone.

History of the Mount Woods Inlier

Revisiting the samples that were dated by Holm may provide increased confidence in the geological meaning of these age data. Specifically, geological relationships in drill core, sample descriptions, and thin-section descriptions of the dated samples, and careful documentation of the zircon morphologies and internal structure are required before these data can confidently be assigned geological significance and published. In particular, the stratigraphic constraints suggested by the reported data are extremely important and require further testing.

Betts et al. (2003) report numerous scattered outcrops within the Mount Woods Domain, most of which lack geochronological control. These outcrops may provide useful samples for additional geochronology, or at least field relationships with which to interpret existing geochronology.

No $^{40}Ar/^{39}Ar$ data exists from the Mount Woods Inlier. It may be useful to compare the cooling history of this crustal block, which appears to have been at relatively deep crustal level at Hiltaba time against the adjacent upper crustal Olympic and Wilgena Domains, and with the Coober Pedy Domain that experienced younger high-grade metamorphism at ~1550 Ma. A $^{40}Ar/^{39}Ar$ study across the northern domains of Nawa, Coober Pedy and Mount Woods would help document the thermal history of this region relative to the upper crustal domains to the south (Olympic, Wilgena, Christie) and also help to define the thermal extent of the younger Musgravian Orogeny focussed to the north. Any such future study should also consider including samples from the Ammaroodinna and Yoolperlunna Inliers, and from the Peake and Denison Domain.

Geological history of the Christie Domain

What is the significance of the ~1720 Ma monazite ages from the Challenger mine reported by Fanning (2002), and why do these ages not appear in the samples studied by McFarlane (2006)?. Is there some cryptic control on monazite growth that varies on the outcrop or mine scale? For example, a control related to subtle bulk compositional effects, or to channelised fluid-influx.

Is the stratigraphy and geological history the same throughout the Christie Domain? Our current understanding is heavily biased by extensive sampling at the Challenger mine and at nearby Mount Christie, with very few geological observations elsewhere. Yet this is one of the largest domains in the Gawler Craton. There is a distinct package of high-magnetic response with northerly structural grain in the central Christie Domain that is truncated by the Karari Shear Zone. These more magnetic rocks sit within the more typically bland magnetic region of the northern Christie. Is this variation in magnetic response simply a function of depth of cover, or does it reflect distinctly different basement rock packages with possibly different stratigraphic ages and/or geological histories?

The Tallacootra Shear Zone appears to die away to the north in magnetic images. Is this simply due to depth of cover, or does it imply a fault tip? Given that the Tallacootra Shear Zone dissects at least part of the Christie Domain, we might expect some pressure differences in preserved metamorphic assemblages in the basement gneisses on either side of this structure. Can this be recognised?

Tackling any of these questions will be severely limited by available rock samples.

Timing of variable exhumation of mid-crustal slices across the Fowler Domain

The variation in crustal depth and metamorphic age in different slices within the Fowler Domain suggests that an interesting future study would involve $^{40}Ar/^{39}Ar$ analyses from rocks from the various crustal slices to compare cooling and exhumation ages to help determine the timing of vertical movement along the intervening shear zones. This would make an excellent Ph.D. study, combining structural geology, metamorphic petrology, U-Pb monazite and $^{40}Ar/^{39}Ar$ geochronology.

The age of the metamorphosed stratigraphy within the Fowler Domain is totally unconstrained by geochronology. There is currently no evidence for the 2450 Ma signature of the Christie Domain gneisses, suggesting the gneisses of the Fowler Domain may have a completely different and younger origin. This remains to be investigated via a U-Pb study of zircon cores within Fowler Domain paragneisses.

How well established is the presence of 'Archaean' basement in the Wilgena Domain ?

In the Time-Space geochronology compilation, there is no definitive geochronological evidence for Archaean, or earliest Proterozoic (~2450 Ma) metasediments within the Wilgena Domain. The interpreted presence of basement rocks of this age must be based on field correlations. The basement sedimentary succession is interpreted as the low-grade equivalent of the Christie gneisses, but perhaps this deserves more explicit testing. For example, a comparison of detrital and inherited zircon populations within the Wilgena and Christie Domains.

Nuyts Domain

How well established is the timing and spatial extent of the St Peter Suite intrusives, and the Nuyts Volcanics? Relatively limited geochronology exists, and much of it is ~20 year old multigrain TIMS zircon analyses.

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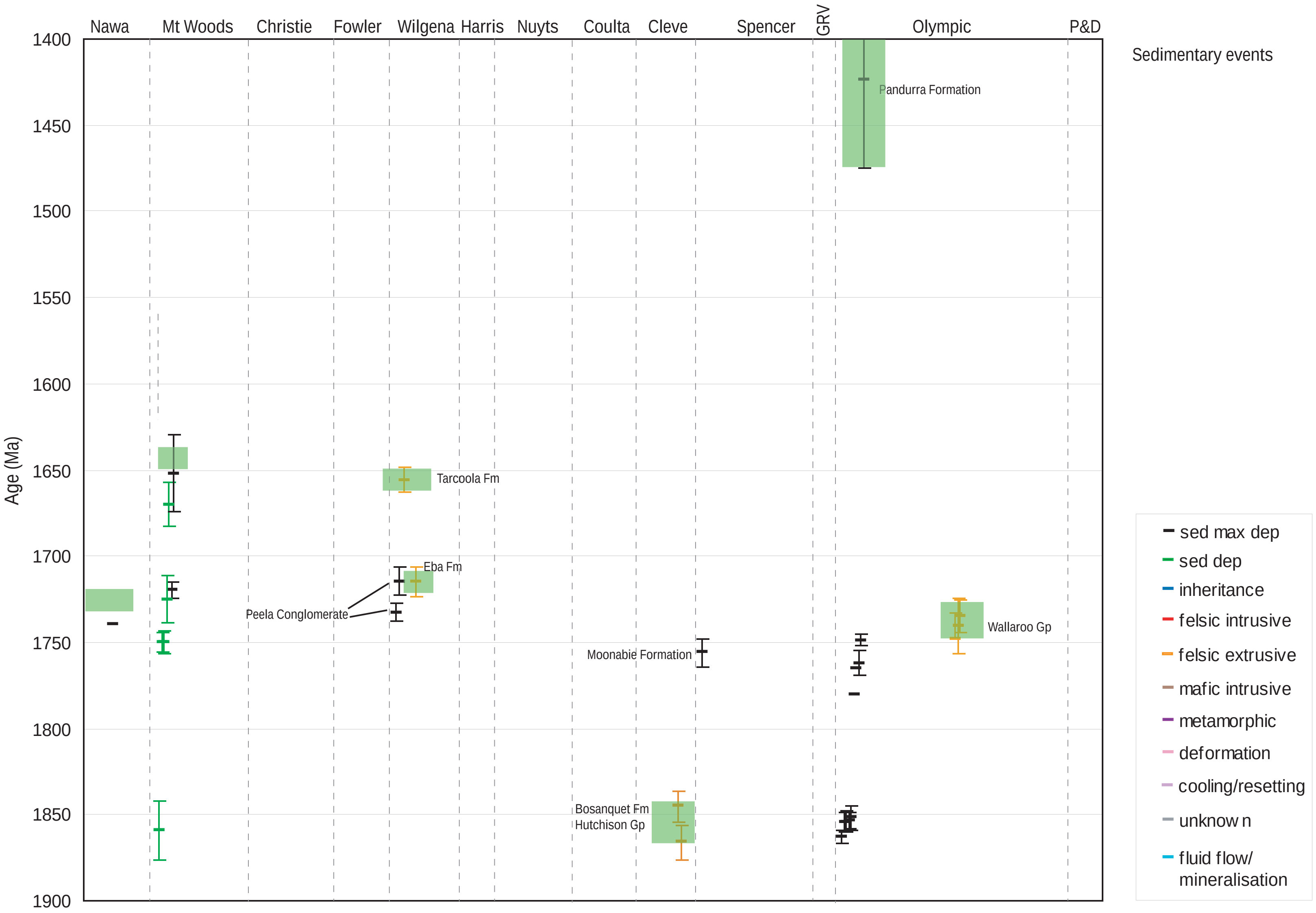
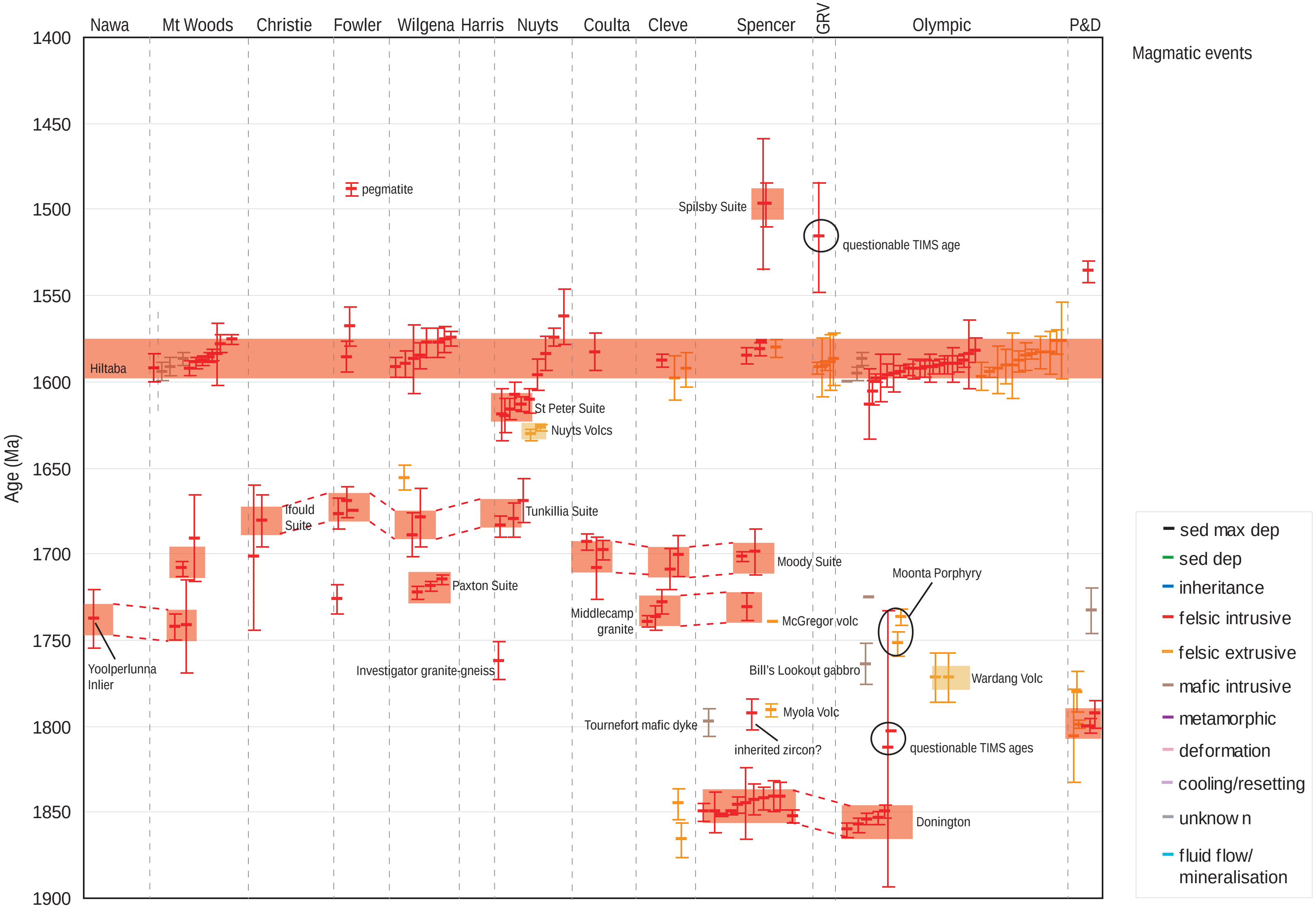
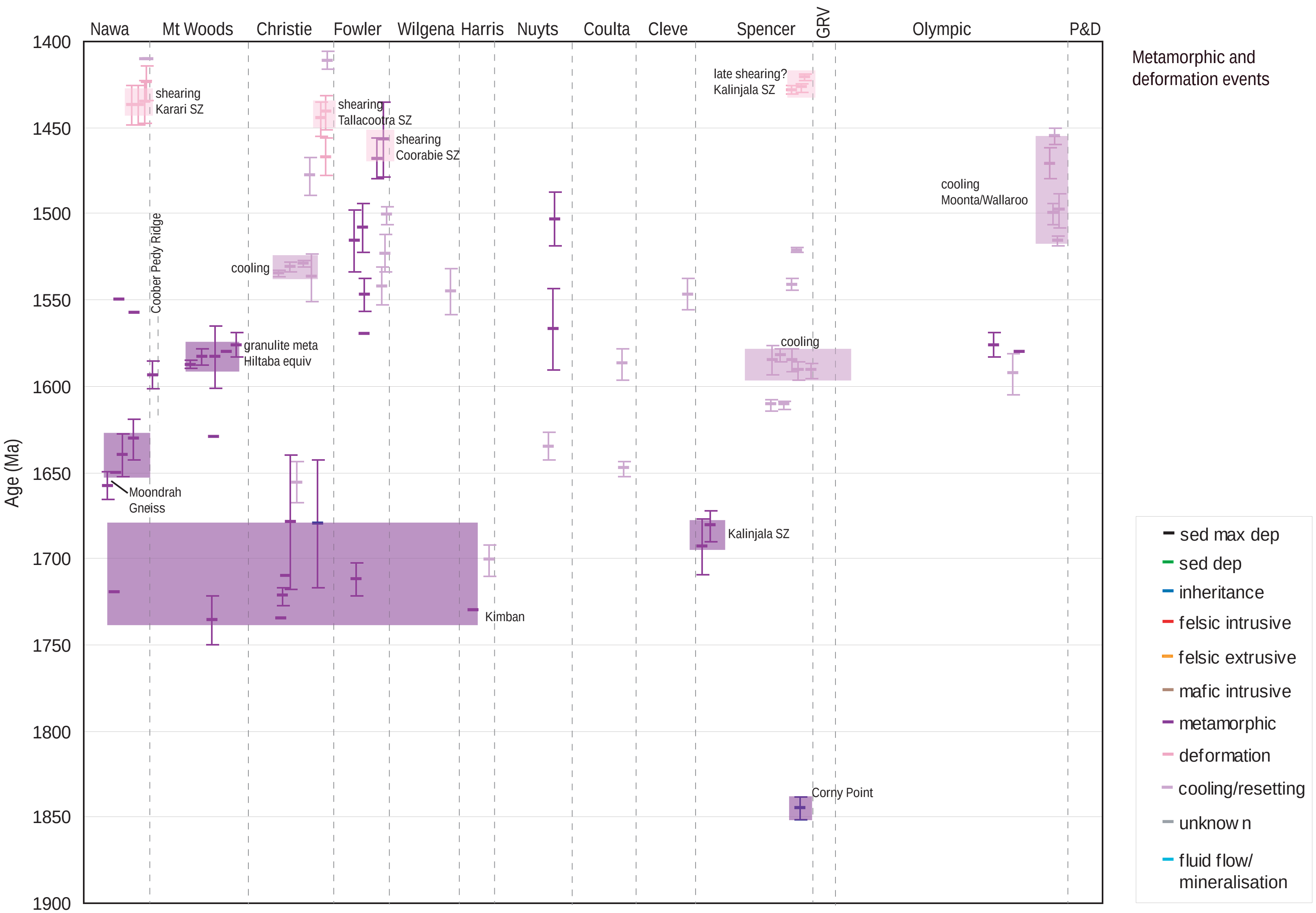
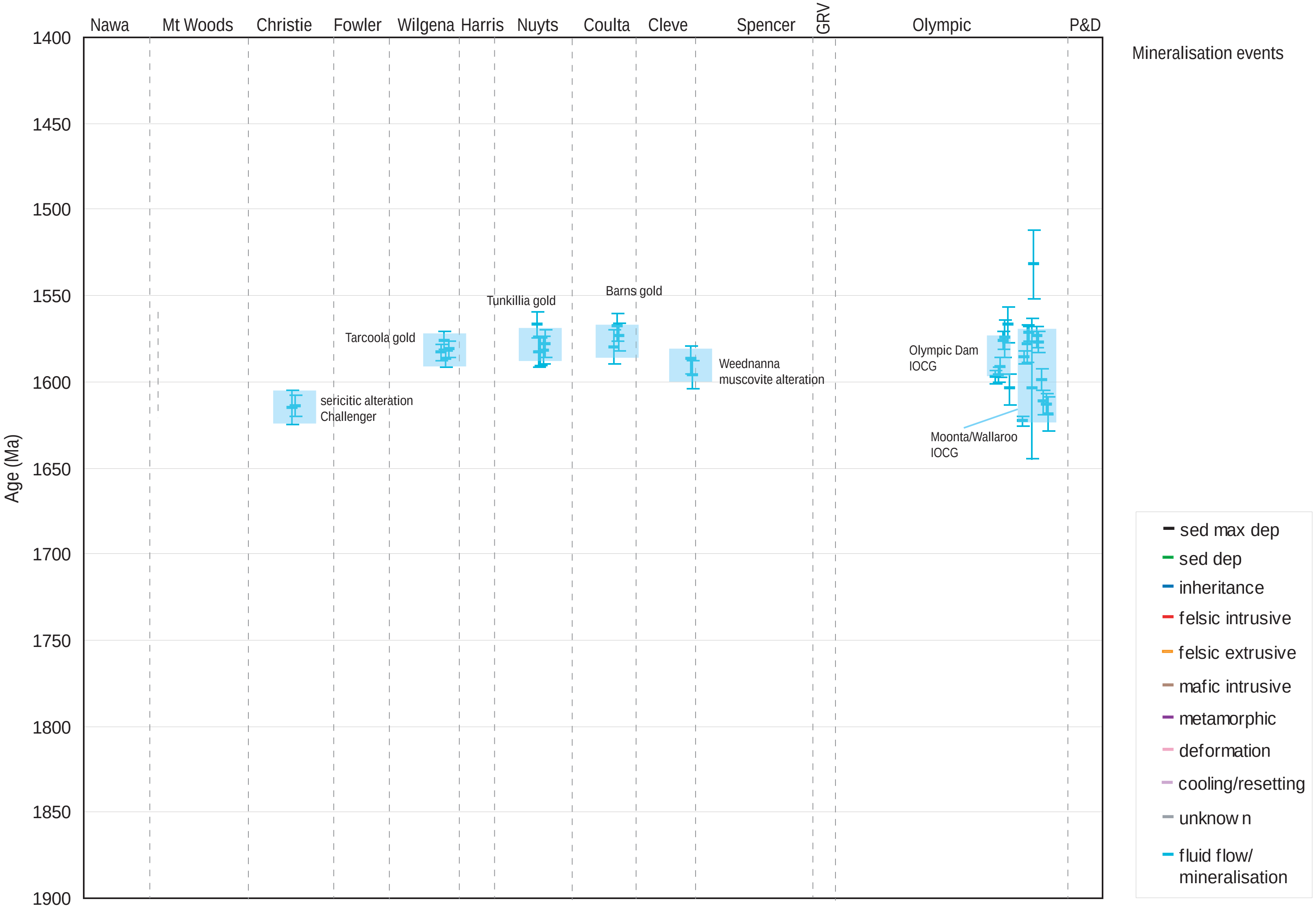

Nawa
Mt Woods
Christie
Fowler
Wilgena
Harris
Nuyts
Coulta
Cleve
Spencer
GRV
Olympic
P&D
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Pandurra Formation
Tarcoola Fm
Eba Fm
Peela Conglomerate
Wallaroo Gp
Moonabie Formation
Bosanquet Fm
Hutchison Gp
Sedimentary events
sed max dep
sed dep
inheritance
felsic intrusive
felsic extrusive
mafic intrusive
metamorphic
deformation
cooling/resetting
unknow n
fluid flow/
mineralisation



Nawa
Mt Woods
Christie
Fowler
Wilgena
Harris
Nuyts
Coulta
Cleve
Spencer
GRV
Olympic
P&D
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
pegmatite
Spilsby Suite
questionable TIMS age
Hiltaba
St Peter Suite
Nuyts Volcs
Ifould Suite
Tunkillia Suite
Moody Suite
Paxton Suite
Moonta Porphyry
Middlecamp granite
McGregor volc
Yoolperlunna Inlier
Investigator granite-gneiss
Bill's Lookout gabbro
Wardang Volc
Tournefort mafic dyke
Myola Volc
inherited zircon?
questionable TIMS ages
Donington
sed max dep
sed dep
inheritance
felsic intrusive
felsic extrusive
mafic intrusive
metamorphic
deformation
cooling/resetting
unknow n
fluid flow/ mineralisation


Metamorphic and deformation events
Nawa
Mt Woods
Christie
Fowler
Wilgena
Harris
Nuyts
Coulta
Cleve
Spencer
GRV
Olympic
P&D
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
shearing
Karari SZ
Coober Pedy Ridge
shearing
Tallacootra SZ
shearing
Coorabie SZ
cooling
granulite meta
Hiltaba equiv
Moondrah
Gneiss
Kimban
late shearing?
Kalinjala SZ
cooling
Kalinjala SZ
Corny Point
cooling
Moonta/Wallaroo
sed max dep
sed dep
inheritance
felsic intrusive
felsic extrusive
mafic intrusive
metamorphic
deformation
cooling/resetting
unknow n
fluid flow/
mineralisation



Nawa
Mt Woods
Christie
Fowler
Wilgena
Harris
Nuyts
Coulta
Cleve
Spencer
GRV
Olympic
P&D
Mineralisation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
sericitic alteration
Challenger
Tarcoola gold
Tunkillia gold
Barns gold
Weednanna
muscovite alteration
Olympic Dam
IOCG
Moonta/Wallaroo
IOCG
sed max dep
sed dep
inheritance
felsic intrusive
felsic extrusive
mafic intrusive
metamorphic
deformation
cooling/resetting
unknow n
fluid flow/
mineralisation

Time-Space evolution of the Curnamona Province

H. Cutten
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GPO Box 378, Canberra ACT 2601, Australia

OVERVIEW

The Curnamona Province (Figure 3), which straddles the New South Wales-South Australia border, covers an area of approximately 80,000 km^2 and for the purposes of this discussion is divided into two principle domains, the Broken Hill Domain and the Olary Domain. The Broken Hill Domain is located largely in New South Wales, but extends to the southwest into South Australia. The Olary Domain is located to the west of the Broken Hill Domain in the south-western part of the Curnamona Province. The Curnamona Province also includes the Mount Painter Province in the northwest, and the central Benagerie Ridge, covered by Cainozoic and Mesozoic sediments. A more detailed subdivision of stratotectonic domains and inliers is described in Conor and Preiss (in press). The Broken Hill and Olary Domains are dominated by Palaeoproterozoic metasedimentary rocks of the Willyama Supergroup (1719-1640 Ma) which is subdivided into different groups and formations in each domain, with approximate correlations between the domains being based on geochronology. Much of the succession in the Broken Hill Domain, such as the Broken Hill Group, is greatly thinned or absent in the Olary Domain. It is interpreted that sedimentation in the Broken Hill Domain occurred in the central region of a rift, whereas sedimentation in the Olary Domain occurred on the rift flank (Laing, 1996; Conor and Page, 2003).

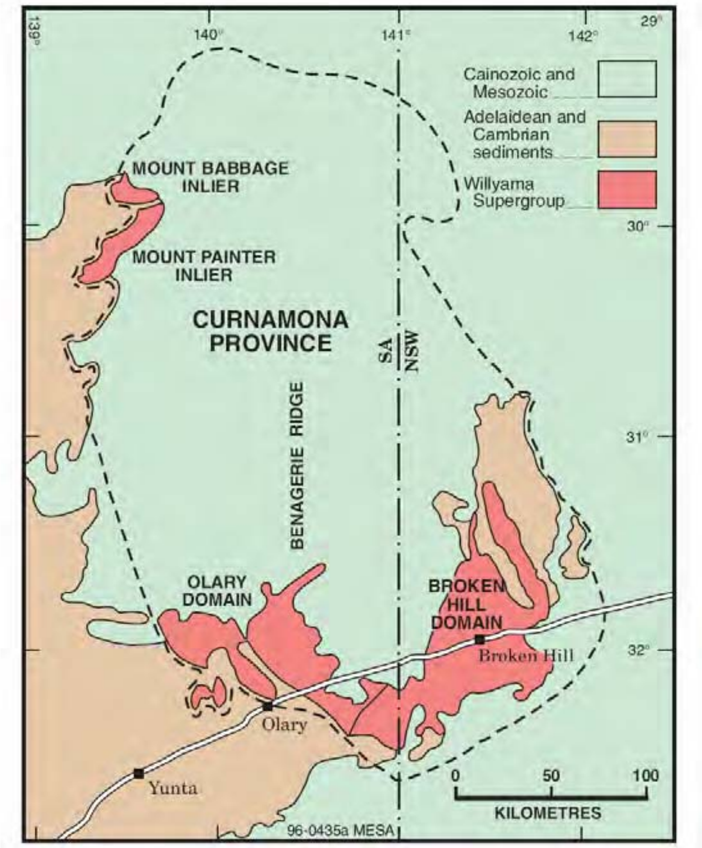


Figure 3: *Location of domains within the Curnamona Province (from Robertston et al.,1998)*

The Willyama Supergroup is largely composed of shallow marine sedimentary rocks, including psammites, pelites, calc-silicates and carbonates in the lower succession, and meta-pelite in the upper succession. These packages have been metamorphosed to granulite-facies in the south and greenschist-facies to the north. Intrusions into the lower succession are represented by granitic gneisses and amphibolite sills. The Willyama Supergroup includes the Broken Hill Group, which hosts the Broken Hill ore deposit, the world's largest Pb-Zn-Ag deposit. In the Olary Domain, the Willyama Supergroup is commonly in fault-contact with Adelaidean sedimentary rocks to the west and southwest, or is onlapped by Adelaidean sedimentary rocks in the north and northeast. The Olarian Orogeny at ~1600 Ma is recognized throughout the Curnamona Province (Page et al., 2005a; Page et al., 2005b), but there is debate about the existence of an earlier low-P high-T metamorphic event (~1690-1640 Ma) associated with bimodal intrusions, major mylonitic zones (Forbes et al., 2005), and an interpreted major extensional detachment separating the lower and upper Willyama Supergroup (Gibson et al., 2004a). The suggested detachment surface approximates a redox boundary, with the lower succession albitised and oxidized.

There are numerous SHRIMP U-Pb zircon ages for rocks of the Willyama Supergroup, with the youngest detrital zircons constraining a maximum age of deposition, magmatic zircons from intrusions indicating minimum age of deposition, and magmatic zircons from tuff beds providing well-constrained depositional ages for stratigraphic units. The stratigraphic subdivision of Willis et al. (1983) is generally accepted and widely used, but recent modifications, particularly in the Olary Domain, are presented by Conor and Preiss (in press). Early mapping of the Willyama succession was based on lithostratigraphy but was complicated by the high metamorphic grade and complex folding and thrusting leading to inversion and structural repetition. More recent work (Stevens, 2006; Conor et al., in press) including detailed geochronology (e.g. Page et al., 2005a; Page et al., 2005b) now provides improved constraints on the stratigraphy.

This geochronological data compilation for the Curnamona Province includes data held in the Geoscience Australia database OZCHRON, as well as recently-published ages and some unpublished data. Some ages in OZCHRON are as reported in an abstract by Page et al. (2000) but have been slightly modified in Page et al. (2005a). The Time-Space plot (Figure 5) uses the updated ages reported in Page et al. (2005a).

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Broken Hill Domain

Stratigraphy and Geochronology

Basement to the Willyama Supergroup is unknown as it is not exposed. The Lower Willyama Supergroup includes migmatites, and metasedimentary rocks, psammitic to psammopelitic gneisses, often abitised and rich in magnetite, passing up into quartzo-feldspathic gneisses interpreted as metamorphosed rhyodacitic lava flows or tuffs. Intrusions in the lower Willyama succession are represented by granitic gneisses and amphibolite sills. The basal units, the Clevedale Migmatite and Thorndale Composite Gneiss (Figure 4), have maximum depositional ages of ~1710 Ma. The Redan Gneiss forms a similar aged basal unit in the Redan Subdomain in the southeastern region of the Broken Hill Domain, where abundant magnetite produces a pronounced magnetic anomaly. The Redan Gneiss is overlain by the Ednas Formation, the Mulculca Formation and the Farmcote Gneiss. Leucocratic intrusions in the latter constrain the minimum age of the Redan succession at 1705 ± 5 Ma (Stevens, 2006). These intrusions correlate with the S-type Alma Gneiss which is dated at 1704 ± 3 Ma (Page et al., 2005a) and intruded the Lady Brassey Formation and Cues Formation of the Thackaringa Group. These intrusions are absent in the upper unit of the Thackaringa Group, the Himalaya Formation, which is thus considered to be younger than ~1704 Ma.

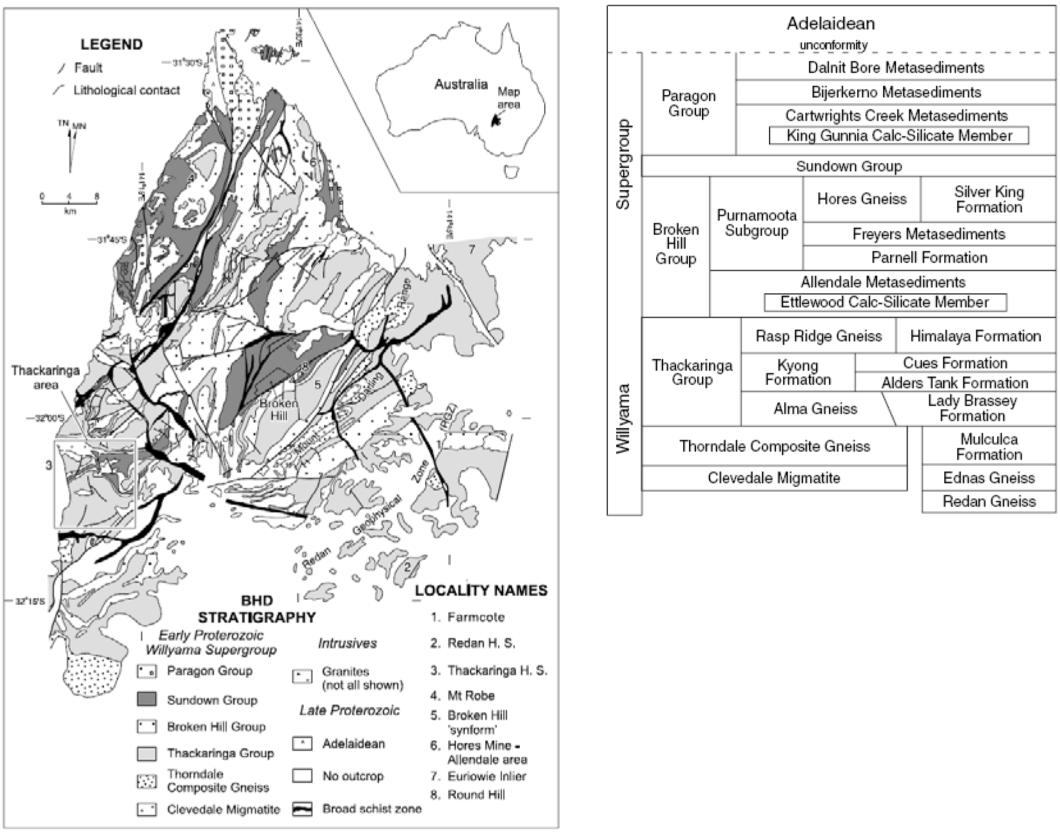
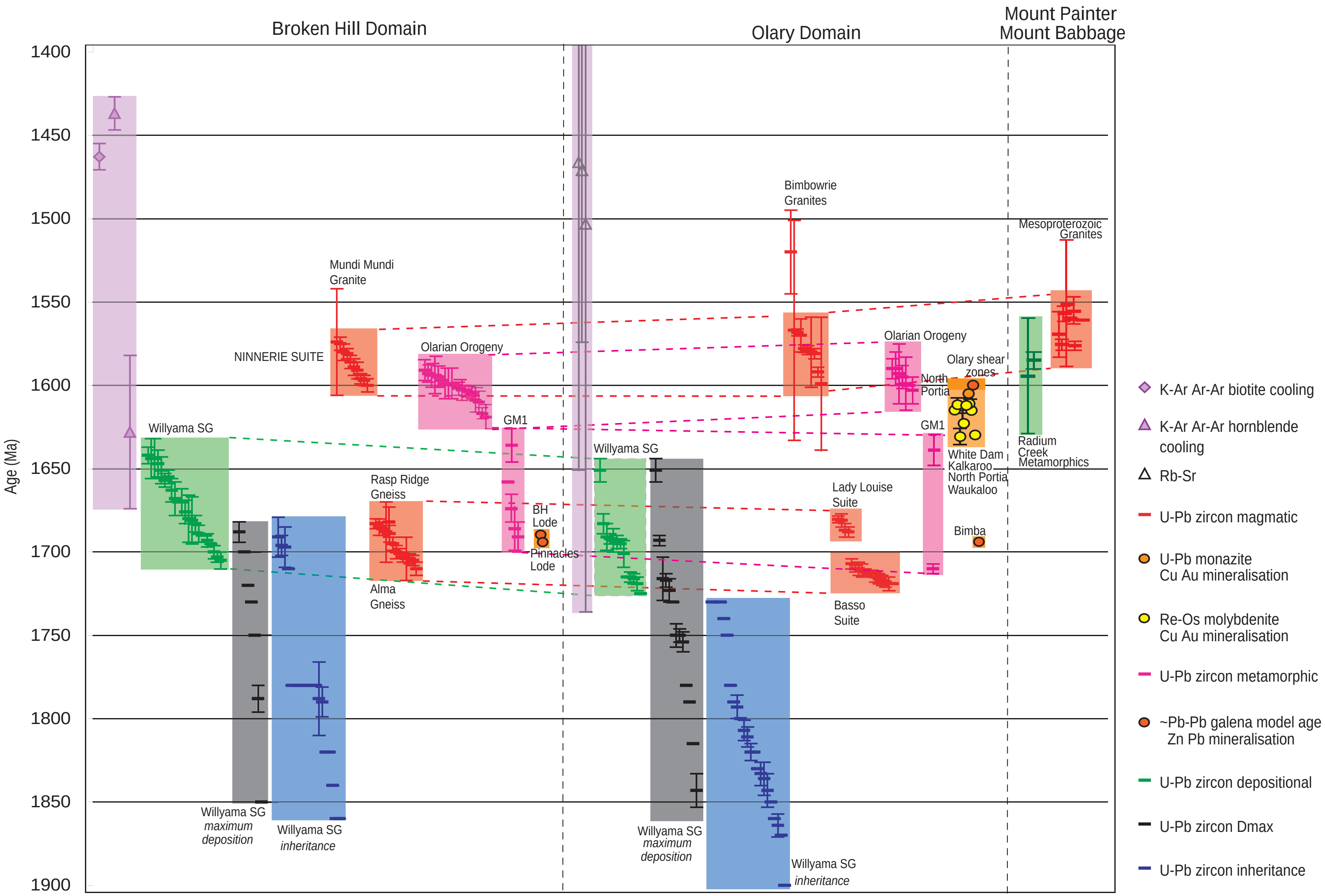


Figure 4: *(a) Geology and localities in the Broken Hill Domain (Raetz et al., 2002, modified from Willis et al., 1983). (b) Stratigraphic column of the Willyama Supergroup, Broken Hill Domain (from Forbes et al., 2005, adapted from Willis et al., 1983 and Stevens et al., 1988)*

Figure 5 ***(overleaf):*** *Geochronological data and summary Time-Space plot for the Curnamona Province.*



Broken Hill Domain
Olary Domain
Mount Painter
Mount Babbage
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Mundi Mundi
Granite
NINNERIE SUITE
Olarian Orogeny
Willyama SG
GM1
Rasp Ridge
Gneiss
BH
Lode
Pinnacles
Lode
Alma
Gneiss
Willyama SG
maximum
deposition
Willyama SG
inheritance
Willyama SG
Willyama SG
maximum
deposition
Willyama SG
inheritance
Bimbowrie
Granites
Olarian Orogeny
Olary shear
zones
North
Portia
GM1
White Dam
Kalkaroo
North Portia
Waukaloo
Lady Louise
Suite
Basso
Suite
Bimba
Mesoproterozoic
Granites
Radium
Creek
Metamorphics
K-Ar Ar-Ar biotite cooling
K-Ar Ar-Ar hornblende
cooling
Rb-Sr
U-Pb zircon magmatic
U-Pb monazite
Cu Au mineralisation
Re-Os molybdenite
Cu Au mineralisation
U-Pb zircon metamorphic
~Pb-Pb galena model age
Zn Pb mineralisation
U-Pb zircon depositional
U-Pb zircon Dmax
U-Pb zircon inheritance

The upper Willyama Supergroup, like the lower Willyama Supergroup, contains largely shallow-water successions and includes the Broken Hill Group, Sundown Group and Paragon Group. The basal Broken Hill Group, the Allendale Metasediments, contains thin bedded pelite to psammopelite with minor mafic gneiss and calc-silicate nodules. This unit represents a transition in sedimentation from feldspar-rich psammitic metasediments, found in the Thackaringa Group, to the more quartz-rich psammitic metasediments and pelitic metasediments typical of the Broken Hill Group. The Allendale Metasediments contain the Ettlewood calc-silicate member, a metamorphosed carbonate and an adjacent tuffaceous metasiltstone dated at 1693 ± 4 Ma (Page et al., 2005a). These are overlain by the Parnell Formation, characterised by the association of amphibolite/mafic granulite and garnetiferous quartzo-feldspathic gneiss, interpreted as the product of bimodal rhyodacitic to tholeiitic basalt volcanism, with associated Zn- and/or Mn-rich rocks interpreted as exhalites. The overlying Freyers Metasediments are well-bedded pelite to psammopelite/psammite with rare mafic gneisses.

The upper unit of the Broken Hill Group is the Hores Gneiss, comprised of quartz-feldspar-garnet-biotite gneiss and quartzo-feldspathic gneiss, with intercalated metasedimentary rocks. The Hores Gneiss hosts the Broken Hill Pb-Zn-Ag lode. The protoliths are interpreted to have been mass-flow felsic volcanics, and have an age of 1685 ± 3 Ma (Page et al., 2005a). The overlying Sundown Group consists of thin-bedded, commonly graded pelite, psammopelite and psammite, with calc-silicate nodules. Dating of detrital zircons indicates maximum depositional ages of 1688 ± 6 Ma in the Euriowie Block, and 1672 ± 7 Ma in the Monuments area (Page et al., 2005a). Uppermost of the Willyama Supergroup is the Paragon Group which has been divided into three formations. The Cartwrights Creek Metasediments comprise thin bedded to laminated graphitic pelite and psammopelite and include the King Gunnia calc-silicate member. These are overlain by the Bijerkerno Metasediments, comprising thin-bedded to laminated, cross-bedded, fine feldspathic graphitic psammite, with a maximum depositional age of 1657 ± 4 Ma (Page et al., 2005a) and by the Dalnit Bore Metasediments, consisting of laminated graphitic phyllite and rare graphitic psammite. A sample from a highly feldspathic psammopelitic bed, interpreted to represent an airfall tephra, produced a unimodal zircon population with an age of 1642 ± 5 Ma (Page et al., 2005a). The Dalnit Bore Metasediments, unlike the shallow-water sediments of the rest of the Willyama Supergroup, are interpreted as deep water turbidites.

Igneous intrusions

Two pre-orogenic magmatic events have been recorded in the Broken Hill Domain, represented by the Alma Gneiss (1704 ± 3 Ma; Page et al., 2005a), which intruded as high as the Cues Formation, and the Rasp Ridge Gneiss (1683 ± 3 Ma; Page et al., 2005a), which intruded the Broken Hill Group. Both magmatic events include S-type granites and the second event is bimodal with mafic sills (now amphibolites). Recently, Stevens (2006) named the Silver City Suite to include these two events plus three newly identified magmatic units: Oakdale Granite Gneiss (Georges Bore Granite) dated at 1695 ± 4 Ma, the Stephens Creek Granite Gneiss dated at 1689 ± 5 Ma in the lower part, and 1686 ±4 Ma in the upper part, and the Wondervale Well Granite Gneiss, dated at 1685 ± 5 Ma. These units all intrude the Thackaringa Group and/or the Broken Hill Group. Three syn- to post- orogenic granites are the Purnamoota Leucogneiss (1597 ± 5 Ma), Cusin Creek Granite (1596 ± 3 Ma) and Mundi Mundi Granite (1591 ± 5 Ma) (Page et al., 2005a).

Deformation and metamorphism

Metamorphic grades in the Willyama Supergroup in the Broken Hill Domain vary from amphibolite-facies in the north to granulite-facies in the south (Hobbs et al., 1984; Clark et al., 1987). Unravelling the stratigraphy of the Willyama Supergroup in the Broken Hill and Olary Domains has been complicated by multiple folding, the earliest of which inverted the succession in overturned fold limbs. Three phases of folding are generally recognized (D_1, D_2, D_3), which have been linked with an extended granulite-facies metamorphic event associated with the Olarian Orogeny at ~1600 Ma. However, some authors (e.g. Gibson et al., 2004) have invoked an earlier deformation (~1690-1670 Ma); a major extensional detachment zone associated with pre-orogenic magmatism and granulite-grade metamorphism which continued to ~1640 Ma. This produced a S_1 layer-parallel fabric but no associated folding. A review of the metamorphic age data shows the ubiquitous presence of ~1600 Ma ages, while older metamorphic ages have been interpreted by some authors (e.g. Page et al., 2005) as mixed ages or ages compromised by lead loss. Gibson and Nutman (2004) dated zircons from three amphibolites and dykes in the Clevedale Migmatite and Thorndale Composite Gneiss (1674 ± 9 Ma, 1686 ± 13 Ma, and 1691 ± 9 Ma), which were interpreted to date high-grade metamorphism and associated magmatism. White et al. (2006) reported EMPA chemical ages of monazites (3000 spot ages from 80 samples) and noted a broad peak of ages ranging from ~1720 to 1600 Ma. Monazite with cores showing ages at the older end of this range also showed rim ages in the younger part of the age-range and this was interpreted as indicating a protracted thermal-tectonic event. Other authors (e.g. Forbes et al., 2005) have reported ~1620 Ma monazites from shear zones within the Broken Hill Domain. Late Olarian Orogeny (D_3) retrograde metamorphism to greenschist facies has occurred particularly in shear zones. Further retrograde metamorphism took place during the ~490 Ma Delamerian Orogeny (Rutherford et al., 2006).

Metallogeny of the Broken Hill Domain

In both the Broken Hill and Olary Domains there is a regional magnetic gradient with magnetite-bearing rocks in the lower part of the Willyama Supergroup succession and less magnetic rocks in the upper succession. In detail, the magnetic boundary does not adhere to a particular stratigraphic horizon (Conor et al., 2006). Pb-Zn-Ag mineralisation occurs in the non-magnetic, upper part of the succession and Cu-Au mineralisation dominates the magnetic lower part of the succession in stratabound and discordant zones.

The Broken Hill Pb-Zn-Ag orebody is a stratabound deposit hosted by the Hores Gneiss. There are a number of Pb-isotope model ages and interpretations for the age of mineralisation. Page et al. (2005a) adopted Pb-isotope values measured by Bierlein et al. (1996) from the least radiogenic, conformable lens of galena in ~1693 Ma Bimba Formation rocks of the Olary Domain as a local anchor point for the Pb-isotope growth curve in the Curnamona Province. Given the similarity of the Pb-isotope signature of the Olary Domain sample with the Broken Hill lode, Page et al. (2005a) suggested a ~1690 Ma age for Pb mineralisation associated with the Broken Hill lode. This is older than the determination of ~1675 Ma by Sun et al. (1996). Numerous smaller Pb-Zn ore bodies also occur, mostly within the Broken Hill Group, but the Pinnacles deposit is hosted in the Cues Formation. Parr et al. (2004) suggested a Pb-isotope model age of 1695 Ma for the Pinnacles lode. The stratabound nature of the Pb-Zn lodes of the Broken Hill Domain and the concordance of Pb model ages with the age of the host sediment supports a syn-depositional or syn-diagenetic origin for these lodes. A similar observation has been made for Pb-Zn lodes in the Olary Domain. A favoured mechanism is chemical precipitation on the ocean floor by hydrothermal exhalative or inhalative processes.

Cu-Au-Mo hydrothermal deposits in the Broken Hill Domain include the Copper Blow and Mundi Mundi deposits. The genesis of these is likely the same as those in the Olary Domain where none of the Cu-Au-Mo deposits have been shown to be directly associated with the magmatic suites, although stable isotope evidence suggests hybrid magmatic and metamorphic fluid input (Williams and Skirrow, 2000). The age of Cu-Au-Mo mineralisation is bracketed between two distinct periods of alteration: an early phase of syn- to late-diagenetic regional albitisation ± magnetite alteration pre-dates the mineralisation, and a later phase of regional Na ± Cu-Fe alteration which post-dates mineralisation. Titanite U-Pb SHRIMP ages ranging between ~1588 Ma and ~1583 Ma represent a minimum for this later regional alteration (Williams and Skirrow, 2000), and therefore also a minimum age for Cu-Au-Mo mineralisation. The characteristic suite of hydrothermal mineral assemblages is chalcopyrite-pyrite ± molybdenite, associated with Fe-Ca rich veins and replacements of magnetite-actinolite ± K-feldspar ± quartz ± albite ± titanite ± allanite. Gold and molybdenite were deposited in association with biotite-quartz-pyrite ± K-feldspar potassic alteration or biotite-albite alteration. The timing of Cu-Au-Mo mineralisation in the few Broken Hill Domain deposits is unknown, but may be similar to Re-Os ages determined from molybdenum in OD deposits, and considered to be coeval with the earliest stages of the Olarian Orogeny (Skirrow et al., 2000).

Olary Domain

Stratigraphy and Geochronology

The Willyama Supergroup in the Olary Domain is thinner than that in the Broken Hill Domain, and subdivided into different units, but correlation between the two domains has been achieved by systematic geochronology (Figure 6). As in the Broken Hill Domain, basement is not exposed.

The basal part of the Willyama Supergroup, the Curnamona Group, is dated at ~1719 Ma, determined from detrital zircons and the age of the intruding Basso Suite (1710 ± 9 Ma, Conor et al., 2006; Page and Conor, in prep.). These basal rocks are a little older than the basal ~1710 Ma Redan Gneiss in the Broken Hill Domain. The Curnamona Group includes the Wiperaminga Subgroup and overlying Ethiudna Subgroup. The Wiperaminga Subgroup includes a number of correlated formations of different inliers and is comprised of pelite, psammopelite, psammite, albite granofels interlayered with migmatitic schist, magnetite-rich units and volcaniclastic units. These formations are dated at approximately 1719-1715 Ma (Conor et al., 2006; Page and Conor, in prep.). The overlying Ethiudna Subgroup has a basal quartzite and includes psammitic schist, mafic lavas, volcanic conglomerates, albite granofels, calc-silicates and bedded pelite, and yields depositional ages of approximately 1715-1713 Ma (Conor et al., 2006; Page and Conor, in prep.).

The Ethiudna Subgroup is unconformably overlain by the Saltbush Group, a greatly-thinned equivalent of the Broken Hill and Sundown Groups of the Broken Hill Domain. The base of the Saltbush Group is constrained by a 1693 ± 4 Ma age from a graphitic layer of the lower Plumbago Formation overlying the basal Bimba Formation. The age of this layer correlates with the Ettlewood Calc-Silicate Member within the lower Broken Hill Group in the Broken Hill Domain. This correlation indicates that there was a depositional hiatus in the Olary Domain while the Thackaringa Group was being deposited in the Broken Hill Domain, from ~1705 to 1693 Ma. The Bimba Formation is a <50m thick unit, comprised of sulphidic micaceous psammite with calc-silicates and marble, and contains disseminated, laminated and vein sulphides that are, at least in part, stratiform or stratabound (Bierlein et al., 1996). Overlying the Bimba Formation is the Plumbago Formation, a tuffaceous biotite psammite. This in turn is overlain, above another possible unconformity, by the Raven Hill Subgroup, comprised of pelite and psammopelite with minor psammite layers. It is locally graphitic, contains calc-silicate ellipsoids and well-laminated sanguiferous banded iron formations.

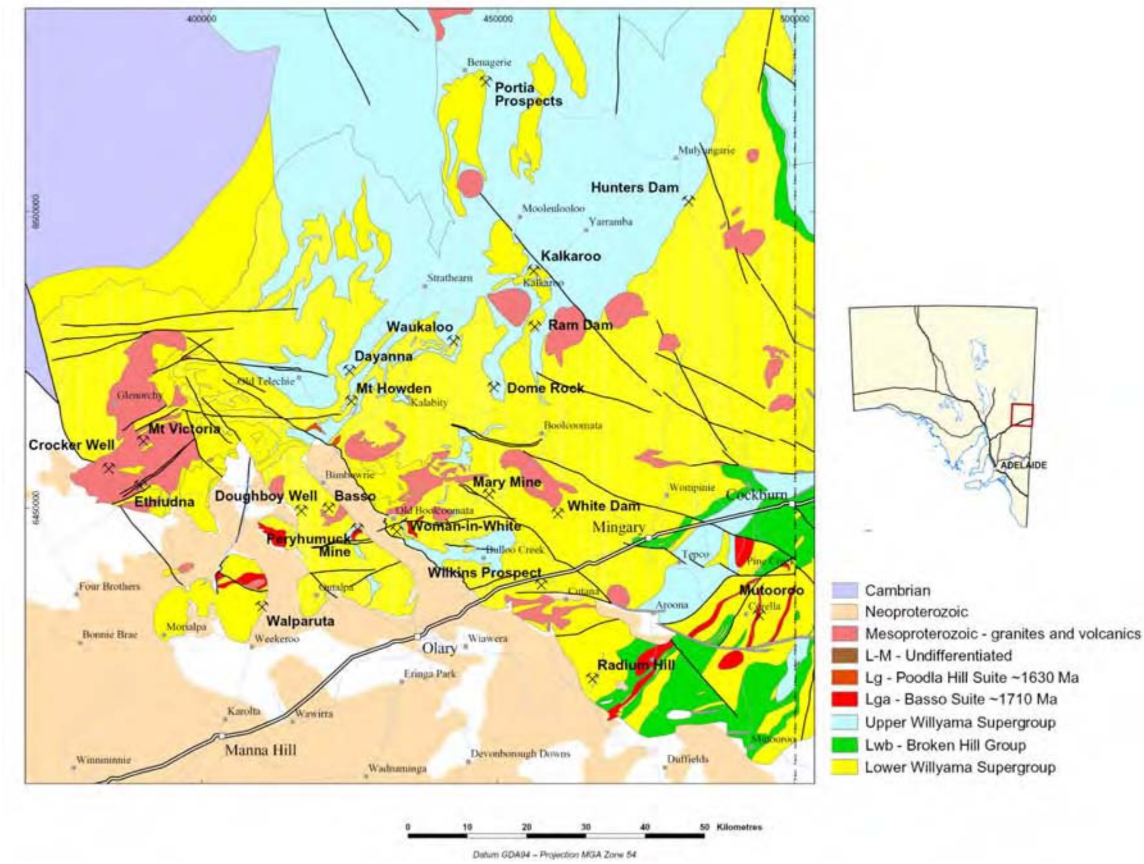


Figure 6: *Geology and selected mineral deposits of the Olary Domain (Conor, 2004).*

Another possible hiatus preceded deposition of the Walparuta Formation, considered the time-equivalent of the Sundown Group in the Broken Hill Domain (Conor and Preiss, in press). It is composed of pelite and psammopelite with minor psammite layers and rare calc-silicate nodules. A possible hiatus also separates the Walparuta Formation from the overlying ~1667-1640 Ma Strathearn Group (Conor et al., 2006; Page and Conor, in prep.), which forms the uppermost unit in the Willyama Supergroup in the Olary Domain. Metasedimentary rocks of the Strathearn Group are locally tuffaceous, and include aluminous pelite, graphitic psammopelite, albitic psammite, brown mica schist and schists containing sillimanite, andalusite, and staurolite. U-Pb SHRIMP dating of zircons from a tuffaceous unit in the Mooleulooloo Formation of the Strathearn Group yielded a unimodal population at 1651 ± 7 Ma (Page et al., 2005b). This age is the only constraint on the depositional age of the Willyama Supergroup in the Olary Domain.

Igneous intrusions

There are two magmatic events recorded in the Olary Domain: the Basso Suite (~1717-1705 Ma) and the Lady Louise Suite (1685 ± 4 Ma; Page et al., 2005b). The Basso Suite is largely A-type, and includes the Amaroo Subsuite granite and Abminga Subsuite volcanics. The Poodla Hill Granodiorite has an I-type chemical signature and has a similar age (1719 ± 3 Ma, Page et al., in prep). The Monstephen Metabasalt is also of similar age and, if included in the Basso Suite, makes this bimodal. The Basso Suite intruded the Curnamona Group. The Lady Louise Suite is primarily mafic but includes some local felsic differentiates. It includes the Woman-in-White amphibolite dated 1685 ± 4 Ma (Conor and Fanning, 2001). This age is similar to that of the S-type Rasp Ridge granite gneiss, part of the Silver City Suite of Stevens (2006), and volcaniclastic Hores Gneiss in the

Broken Hill Domain. Syn- to post-orogenic granites of the Ninnerie Supersuite (Fricke, 2006) include the Bimbowrie Suite, dated at 1581 ± 3 Ma (Page et al., 2005b), the Crockers Well Suite, and other S-type granites.

Deformation and metamorphism

Metamorphic grades in the Willyama Supergroup of the Olary Domain varies from upper greenschist-facies in the north, to upper amphibolite-facies in the south. Late-Olarian Orogeny (D_3) retrograde metamorphism to greenschist-facies has occurred, particularly in shear zones. Further lower-grade retrogressive metamorphism took place during the Delamerian Orogeny (~490 Ma; Rutherford et al., 2006).

Metallogeny of the Olary Domain

In the Olary Domain, minor Pb-Zn sulphide mineralisation occurs in the Bimba Formation. The Bimba Formation contains disseminated, laminated and vein sulphides (pyrite, pyrrhotite with minor chalcopyrite, sphalerite, arsenopyrite, cobaltite, galena) that are in part stratiform or stratabound. As noted above, Page et al. (2005a) suggested a Pb model age of ~1693 Ma for the Bimba Formation, the same as the stratigraphic age. Epigenetic mineralisation is also associated with retrograde shear zones of the late Olarian Orogeny and the Delamerian Orogeny.

Cu-Au (-Mo) mineralisation occurs as stratabound replacement and vein networks in the northern Olary Domain in amphibolite- or upper-greenschist-facies albitic and calc-albitic metasedimentary rocks. This mineralisation is largely restricted to the upper Curnamona Group although, in places, alteration extends across the redox boundary near the Bimba Formation into the overlying lower Strathearn Group (Williams and Skirrow, 2000). Significant Cu-Au-Mo deposits in the Olary Domain are located at White Dam, Kalkaroo, Portia and Waukaloo. Re-Os dating of molybdenite from these deposits yielded ages of ~1616-1612 Ma with a few as old as ~1632 Ma (Skirrow et al., 2000; Williams and Skirrow, 2000). Uncertainties of approximately 1% are recognized due to uncertainty in the decay constants. Thus, Cu-Au-Mo mineralisation is considered coeval with the earliest stages of the Olarian Orogeny.

Mount Painter Province

Stratigraphy, Geochronology and Igneous Intrusions

The Mount Painter Province (comprising the Mount Painter and Mount Babbage Inliers) is located in the northern Flinders Ranges, South Australia, and are suggested to represent the northwest part of the Curnamona Province. Following early investigations of the Mount Painter region, there have been two major publications that discuss the Proterozoic and Phanerozoic stratigraphy and lithological characteristics of this region. Coats and Blissett (1971) provided a detailed overview of the structure, stratigraphy and economic geology of the Mount Painter and Mount Babbage Inliers and the overlying Adelaidean sequence, to accompany the 1:125,000 Mount Painter Province map sheet (Coats et al., 1969). The second main summary of the inliers (Teale, 1993) included new geochronological, metamorphic and structural data and revised the interpretation of the stratigraphy.

Initially, Proterozoic metasediments in the Mount Painter Province were correlated with stratigraphic units of the Willyama Supergroup on lithological grounds (Teale and Flint, 1993). However, Fanning et al. (2003) analysed detrital zircon from the Hot Springs Creek, Mawson Plateau, Gordon Springs Creek and Corundum Creek areas, concluding that deposition was later than 1630 Ma. The Mount Adams and Freeling Heights Quartzites produced detrital zircon peaks at ~1590-1580 Ma and were intruded by Mesoproterozoic granites, with ages ranging from ~1575 Ma to ~1550 Ma

(McLaren et al., 2006 and references therein). This magmatism may be associated with two separate magmatic pulses: one at ~1575 Ma (e.g. Mount Neill Granite, Pepegoona Porphyry, Hot Springs Gneiss), and a second at ~1555 Ma (e.g. Terrapinna, Wattleowie and Yerila granites; Neumann, 2001), although it should be noted that some of the later ages are from U-Pb multi-grain zircon TIMS analysis. These packages are overlain by a sequence of Neoproterozoic sediments, which were intruded by S- and I-type granites and granodiorites during and after the ~490 Ma Delamerian Orogeny (McLaren et al., 2006).

Metallogeny of the Mount Painter Province

The Mount Painter Province includes significant volumes of Proterozoic granites and granite gneisses, with an average surface heat production of 16 μWm^{-3}, with individual units recording heat production values of up to 60 μWm^{-3} (Neumann et al., 2000; McLaren et al., 2006). This heat production corresponds with high surface heat flow of the South Australia Heat Flow Anomaly (Neumann et al., 2000).

Quartz-hematite breccias of the Mount Gee and Mount Painter U-REE ± Cu-Mo system occur within Proterozoic basement rocks. These bodies form part of the Paralana ore system and host uranium mineralisation (Marathon Resources Ltd). Geochronological constraints on the timing of this mineralisation come from a range of different mineral/isotopic methods, and include a monazite age of 440 ± 50 Ma from hematite breccia (Pidgeon, 1979). Palaeomagnetic data suggests a Permo-Carboniferous age for a major hydrothermal event in the area (Idnurm and Heinrich, 1993).

Economic concentrations of uranium in the Tertiary sediments surrounding the Mount Painter Inlier, (e.g. the Beverley Uranium deposit) resulted from the leaching of uranium from the inlier during or after fluvial Tertiary sedimentation (Walker, 1999). Significant occurrences of anomalous Sn, Cu, Co, F, W, U, Y and REE have been recognised and a variety of mineralisation styles are present, but their ages are poorly known (Teale, 1993). Secondary copper mineralisation along fracture zones occurs at Hamilton, Pinnacles, British Empire, Mount Fitton South, Mount Shanahan and Gow’s copper mines (Moss, 2007). Mineralisation consists predominantly of chalcopyrite, pyrite, uraninite, monazite, allanite, cobalt sulphides and minor molybdenite, galena, scheelite, bismuthinite, illmanite and pyrrhotite. Tin mineralisation at Prospect Hill is contained within a siliceous, gahnite- and garnet-bearing zone in metavolcanics and granite. Mineralisation associated with the Parabarana Copper Prospect at the northwestern edge of the province occurs in veins and fractures cutting Palaeoproterozoic quartz–albite rocks with skarn-type alteration.

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

Age of metamorphism in the Curnamona Province

As described above, metamorphism associated with the ~1600-1580 Ma Olarian Orogeny is well-established in both the Olary and Broken Hill Domains. However, the presence of earlier metamorphic events in the Broken Hill Domain is still debated. Older U-Pb zircon ages (~1690-1640 Ma) are interpreted by some workers to represent an older metamorphic event associated with extension (e.g. Gibson and Nutman, 2004) while other studies interpret these ages to represent either lead loss or isotopic mixing between older crystallisation and younger metamorphic ages (e.g. Page et al., 2005).

Geological framework of the Mount Painter Province

Over the past twenty years there have been many geological studies in the Broken Hill and Olary Domains integrating mapping programs and mineral system studies with significant volumes of new geochronological data. In comparison, there have been few geochronological studies of the Mount Painter Province during this time. A regional study integrating basin analysis with structural and magmatic interpretations with new U-Pb zircon ion microprobe analysis for this area would improve our understanding of this area.

Age of rocks underlying the Willyama Supergroup

Currently, the oldest known units within the Curnamona Province are the Clevedale Migmatite, Thorndale Gneiss and Redan Gneiss, which have maximum depositional ages of ~1710 Ma. The underlying crust, as seen in seismic data, has not been identified in outcrop or in drillcore, and so its age and nature remain enigmatic. Any information regarding this underlying substrate would have important implications for correlation of the Curnamona Province with other Proterozoic terranes, including the Mount Isa Inlier, Gawler Craton and North Australia Craton.

Relationship between domains and provinces within the Curnamona Province

As discussed above, the geological evolution of the Broken Hill and Olary Domains can be correlated throughout their histories, even though the nature of these events differs between the two areas. In contrast, although the Mount Painter Province is included within the Curnamona Province, our current geological understanding of these areas suggests that they record a different history. For example, sedimentary packages equivalent to the Willyama Supergroup have not been identified in the Mount Painter Province. Further, current geochronological constraints on magmatism in the Mount Painter and Mount Babbage areas appear to be slightly younger than in the Olary and Broken Hill Domains, although, as noted above, some of the evidence for younger ages is based on multi-grain zircon TIMS analysis and should be re-evaluated using ion microprobe techniques.

Age and characteristics of undercover areas of the Curnamona Province

A large proportion of the Curnamona Province is covered by Cainozoic and Mesozoic sediments, so the age and characteristics of the underlying rock units is unknown apart from a small number of drillholes in the Benagerie Ridge area. A program of seismic data collection integrated with surface drilling would provide new information regarding the geological characteristics and evolution of the province.

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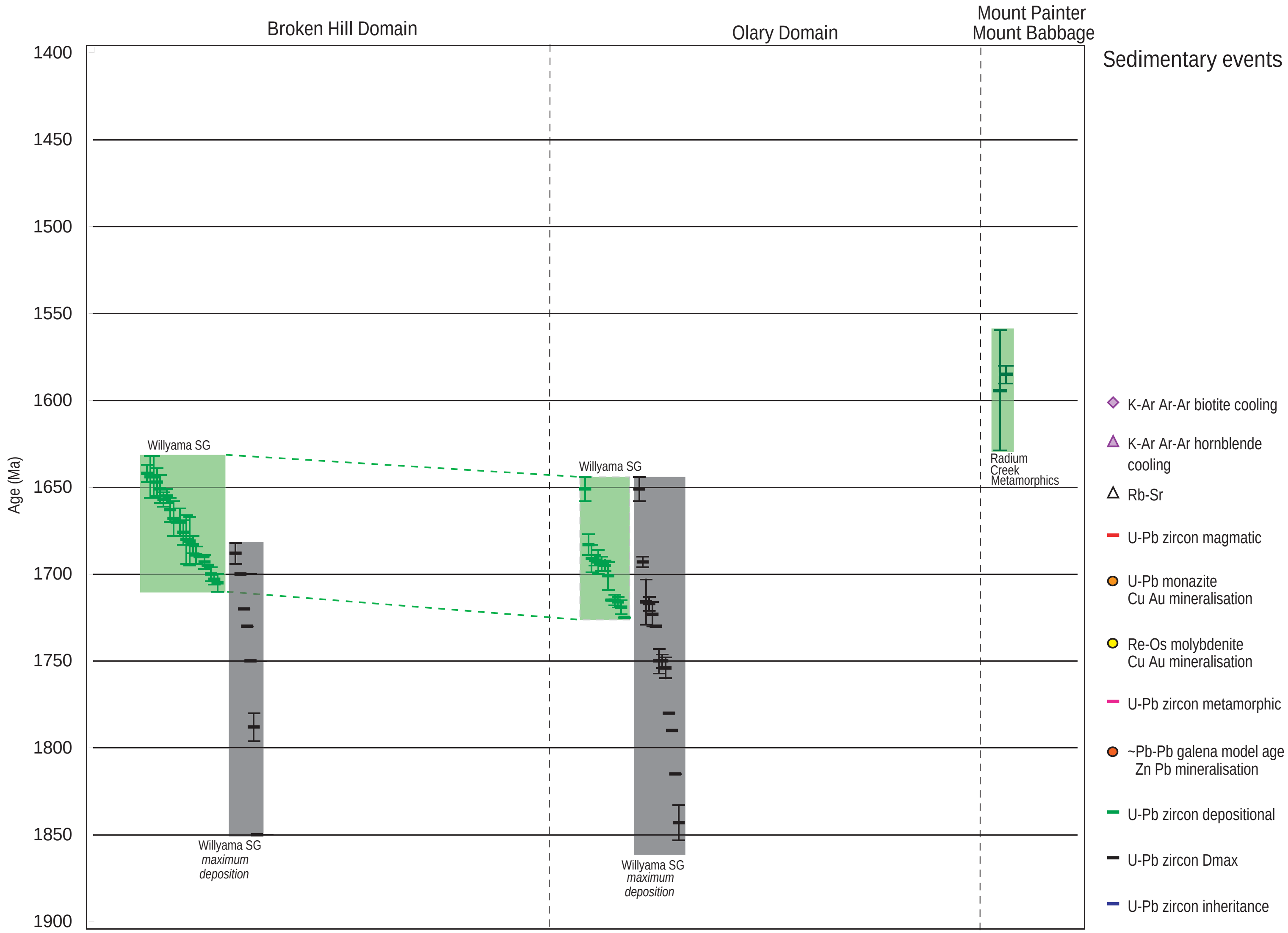
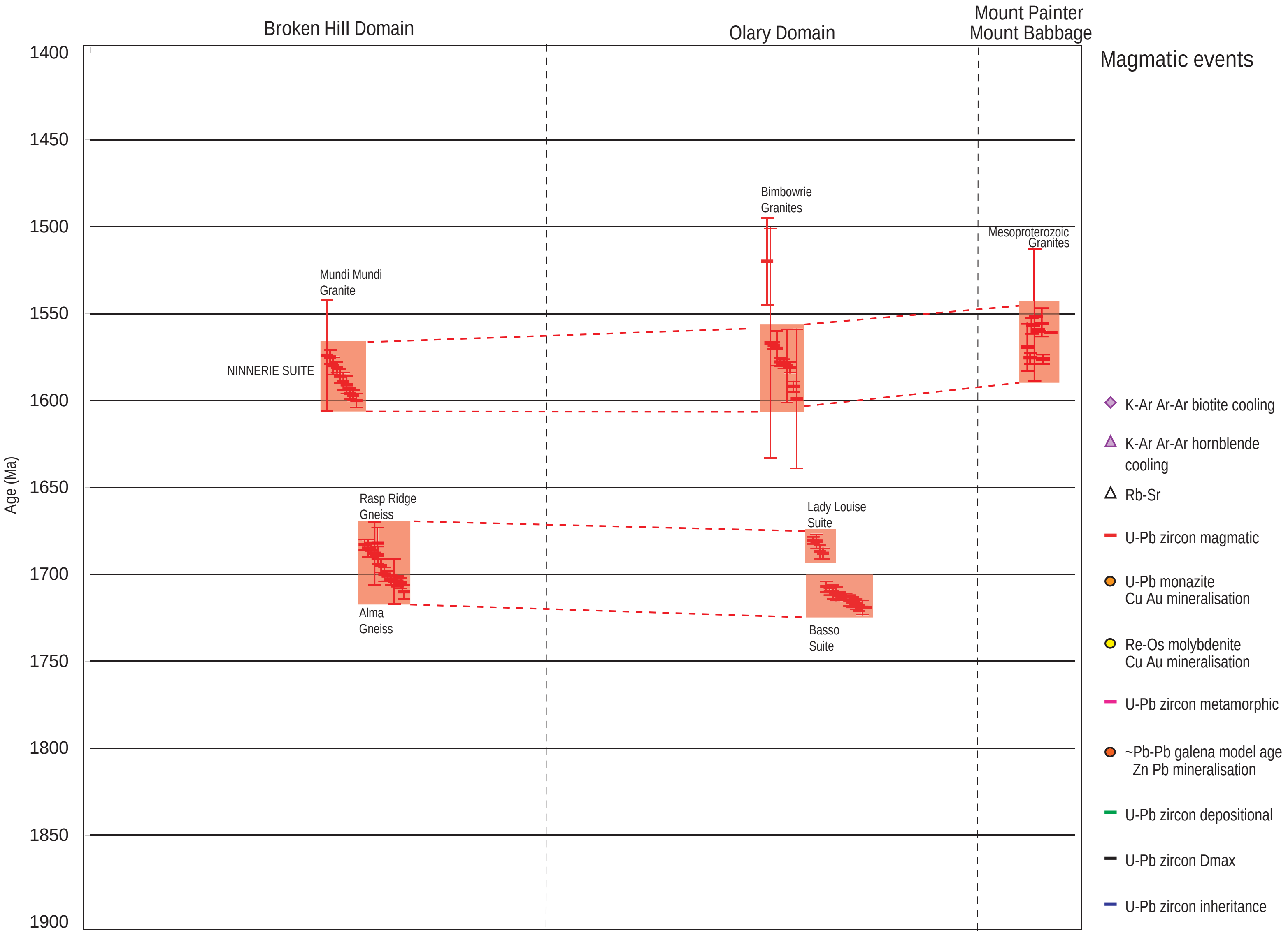
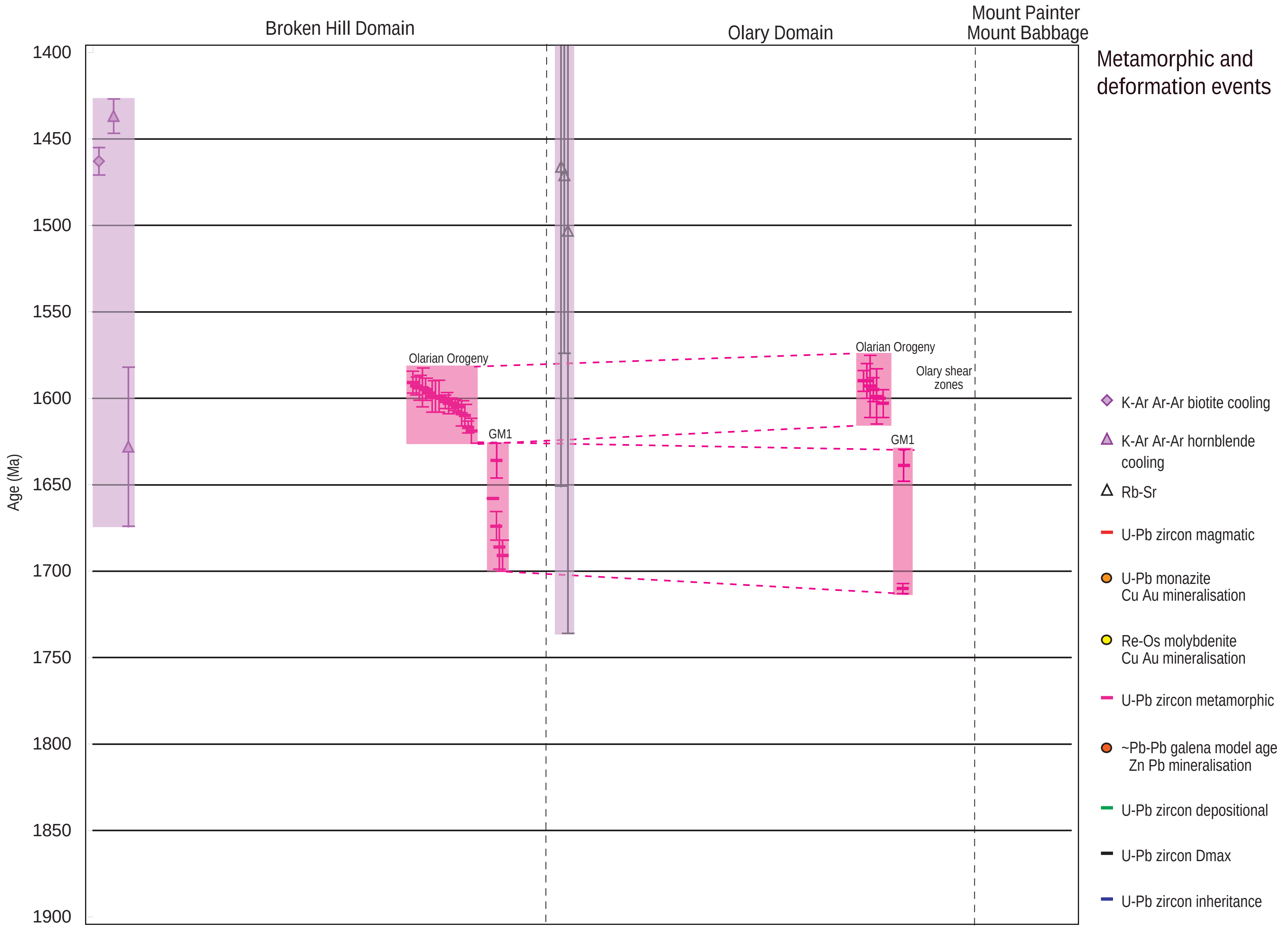
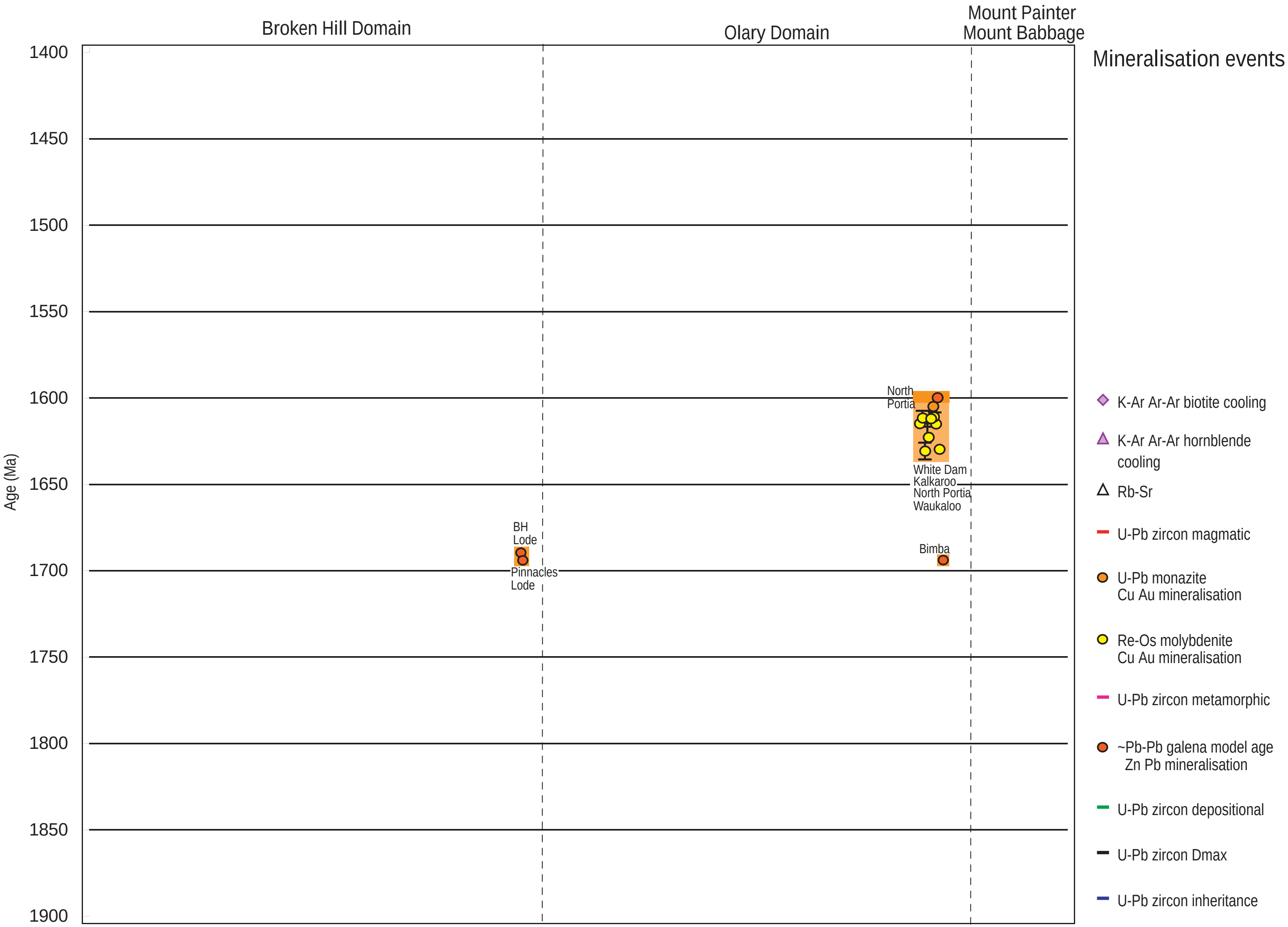

Broken Hill Domain
Olary Domain
Mount Painter
Mount Babbage
Sedimentary events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Willyama SG
Willyama SG
maximum
deposition
Willyama SG
Willyama SG
maximum
deposition
Radium
Creek
Metamorphics
K-Ar Ar-Ar biotite cooling
K-Ar Ar-Ar hornblende
cooling
Rb-Sr
U-Pb zircon magmatic
U-Pb monazite
Cu Au mineralisation
Re-Os molybdenite
Cu Au mineralisation
U-Pb zircon metamorphic
~Pb-Pb galena model age
Zn Pb mineralisation
U-Pb zircon depositional
U-Pb zircon Dmax
U-Pb zircon inheritance


Broken Hill Domain
Olary Domain
Mount Painter
Mount Babbage
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Mundi Mundi
Granite
NINNERIE SUITE
Bimbowrie
Granites
Mesoproterozoic
Granites
Rasp Ridge
Gneiss
Alma
Gneiss
Lady Louise
Suite
Basso
Suite
K-Ar Ar-Ar biotite cooling
K-Ar Ar-Ar hornblende
cooling
Rb-Sr
U-Pb zircon magmatic
U-Pb monazite
Cu Au mineralisation
Re-Os molybdenite
Cu Au mineralisation
U-Pb zircon metamorphic
~Pb-Pb galena model age
Zn Pb mineralisation
U-Pb zircon depositional
U-Pb zircon Dmax
U-Pb zircon inheritance



Metamorphic and deformation events


Broken Hill Domain
Olary Domain
Mount Painter
Mount Babbage
Mineralisation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
North Portia
White Dam
Kalkaroo
North Portia
Waukaloo
BH Lode
Pinnacles Lode
Bimba
K-Ar Ar-Ar biotite cooling
K-Ar Ar-Ar hornblende cooling
Rb-Sr
U-Pb zircon magmatic
U-Pb monazite Cu Au mineralisation
Re-Os molybdenite Cu Au mineralisation
U-Pb zircon metamorphic
~Pb-Pb galena model age Zn Pb mineralisation
U-Pb zircon depositional
U-Pb zircon Dmax
U-Pb zircon inheritance

Time-Space evolution of the Mount Isa Inlier and southern McArthur Basin

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OVERVIEW

The Mount Isa Inlier and southern McArthur of western Queensland and eastern Northern Territory consists of Proterozoic metasedimentary and igneous rocks which were deformed and metamorphosed during the ~1600 Ma Isan Orogeny (Figure 7). Blake and Stewart (1992) recognised two tectonostratigraphic cycles in the Western Succession of the Mount Isa Inlier. The early cycle is comprised of ~1900-1870 Ma basement rocks deformed and metamorphosed by the Barramundi Orogeny. The later cycle includes three cover sequences:

- cover sequence 1 (~1870-1850 Ma) comprises felsic intrusive and volcanic rocks,
- cover sequence 2 (~1790-1720 Ma) contains mixed siliciclastic and calcareous shallow-water sedimentary rocks and bimodal volcanics,
- cover sequence 3 (~1680-1625 Ma) includes the Mount Isa and McNamara Groups, and is dominated by fine-grained carbonate and siliciclastic rocks with minor volcanics.

The Isan Orogeny terminated sediment deposition in the upper tectonostratigraphic cycle.
Subsequent work refined the cover sequence terminology and defined a series of rift-sag basins within cover sequences 2 and 3 (Eriksson et al., 1993; O'Dea et al., 1997; Betts et al., 1998). More recently, sequence stratigraphic concepts integrated with facies analysis and SHRIMP geochronology have led to the development of a regional chronostratigraphic framework for the Western Fold Belt and the southern McArthur Basin (Southgate et al., 2000; Jackson et al., 2000; Page et al., 2000). Using the sequence approach, lithostratigraphic subdivisions for the region were revised to four superbasin phases: the ~1800 to 1750 Ma Leichhardt, ~1735 to 1690 Ma Calvert, ~1670 to 1575 Ma Isa and post-ca 1500 Roper Superbasins (Jackson et al., 2000). These sequence stratigraphic studies focused predominantly on the Isa Superbasin, as these sedimentary packages host the Mount Isa, Century and McArthur River (HYC) Pb-Zn-Ag deposits (e.g. Cooke et al., 2000; Betts et al., 2003).

Domain Subdivision

For this geochronology synthesis, the Mount Isa area has been divided into eight regions (Figure 7), based on the subdivisions of Blake (1987) and Southgate et al. (2000). The Southern McArthur region includes the area between the Urapunga Fault Zone and the Murphy Inlier. The Murphy Inlier includes both the stratigraphic units within this basement high, as well as the units which record an onlap relationship with the inlier on its northern and southern flanks. The Lawn Hill Platform includes the packages south of the Murphy Inlier to the boundary of the Mount Gordon Fault Zone. The Leichhardt River Fault Zone includes the packages south of the Mount Gordon Fault Zone plus the Sybella Batholith area and all the units east to the western boundary of the Kalkadoon-Leichhardt Belt. The Kalkadoon-Leichhardt Belt and units within the Mary Kathleen Block as far east as the Pilgram Fault and Coolullah Fault are included in the Mary Kathleen Belt. The Tommy Creek Block includes units east of the Pilgram Fault, as far south as the Mitakoodi Block, and to the area northeast of Cloncurry. The Mitakoodi, Marino and Stavely zones have been combined into one region, including outcrop as far east as the Mount Dore Fault Zone in the south (Selwyn area) and the Cloncurry Fault in the north (Snake Creek Anticline area). The Eastern Succession region includes units east of the Mount Dore Fault in the south and the Cloncurry Fault in the north, as far north as the Pumpkin Gully Syncline northeast of Cloncurry.

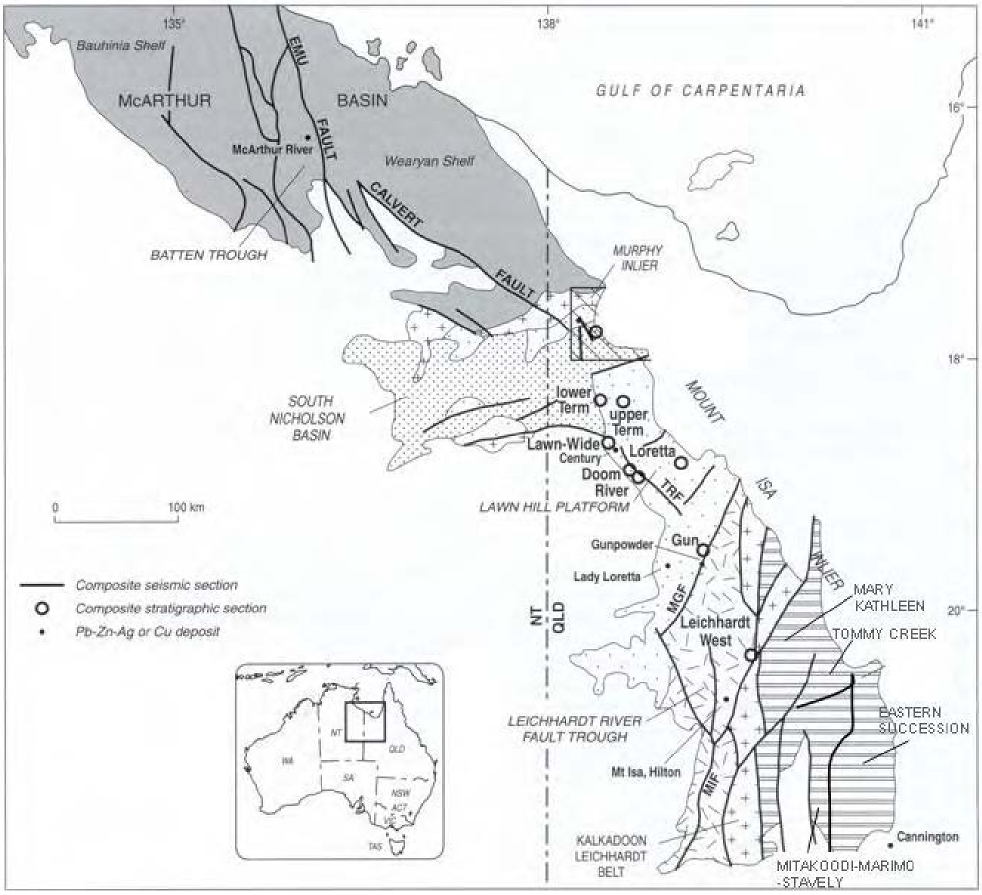


Figure 7: *Location and province divisions within the Mount Isa Inlier and southern McArthur Basin (modified from Southgate et al., 2000).*

Early papers documenting U-Pb zircon geochronology in the Mount Isa Area concentrated on the age of regional igneous units and the chronology of mineralisation (e.g. Page, 1983a,b; Wyborn et al., 1988; Pearson et al., 1992). More recently, U-Pb zircon SHRIMP geochronology has been integrated with sequence stratigraphy, focussing on the analysis of volcanics/peperites within the Calvert and Isa Superbasins (Page and Sweet, 1998; Page et al., 2000; Jackson et al., 2005) and detrital zircons within the Leichhardt and Calvert Superbasin (Neumann et al., 2006). The age of major Pb-Zn deposits in the Mount Isa area have been determined using Pb-Pb model ages (Carr et al., 2001). Ar-Ar geochronology has been used to constrain the timing of fluid flow, alteration and Cu mineralisation across the region (e.g. Perkins and Wyborn, 1998 and Perkins et al., 1999), and to determine the post-1500 Ma thermal history of the Mount Isa area (e.g. Spikings et al., 2001; Spikings et al., 2002.).

For the summary and Time-space plot (Figure 8) sedimentary units in each region have, where appropriate, been subdivided according to the superbasin and supersequence nomenclature of Jackson et al. (2000), Southgate et al. (2000) and Neumann et al. (2006). In detail, the stratigraphy includes three superbasins: the ~1800-1740 Ma Leichhardt, ~1730-1690 Ma Calvert and ~1670-1575 Ma Isan Superbasins. Within each superbasin, stratigraphic units have been subdivided based on geochronological constraints integrated with sequence stratigraphy. The Leichhardt Superbasin includes the Guide, Myally and Quilalar Supersequences, and the Calvert Superbasin includes the Big and Prize Supersequences. The overlying Isan Superbasin has seven supersequences: the Gun, Loretta, River, Term, Lawn, Wide and Doom Supersequences.

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Southern McArthur Basin

≥ 1850 Ma units

The oldest known unit in the southern McArthur Basin is the 1851 ± 7 Ma Scrutton Volcanics (Page et al., 2000), which is correlated with the Kalkadoon Suite.

Leichhardt Superbasin

The lower sedimentary and volcanic units which unconformably overlie the basement rocks have no age constraints. However, based on sequence stratigraphic correlations, Jackson et al. (2000) suggested the following relationships. The basal Yiyintyi Sandstone is thought to be equivalent to the ~1800-1780 Ma Guide Supersequence of the Leichhardt Superbasin in the Leichhardt River Fault Trough. The overlying mafic extrusives of the Seigal Volcanics, which have continental tholeiiite affinities, are correlated with the Eastern Creek Volcanics, and are therefore part of the ~1780-1760 Ma Myally Supersequence. The Sly Creek, Rosie Creek and McDermott Formations are poorly constrained and permit correlation with the Myally or Quilalar Supersequences.

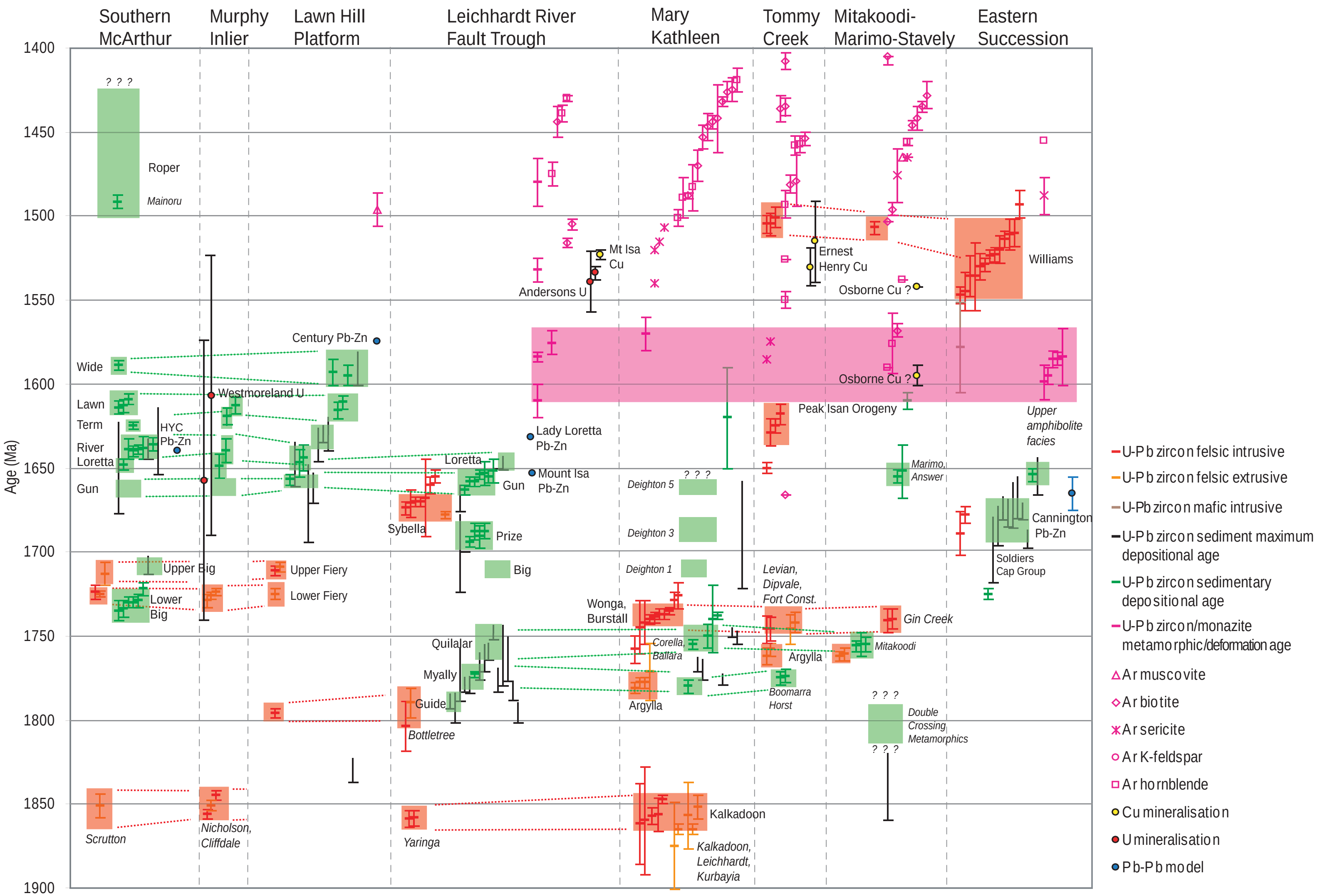
Calvert Superbasin

The ‘mid-Tawallah compression event’ was defined by Bull and Rogers (1996) as an east-west compression tectonic event, with the timing constrained to after deposition of the Quilalar Formation and the basal Wollogorang Formation. However, the regional significance of a compressive event is not clear. Following this tectonic event, deposition continued as recorded by the Wunummantyala Sandstone, the Aquarium Formation and the basal shales and carbonate-rich part of the Wollogorang Formation, which contain green ‘tuff’ horizons providing depositional ages between 1735 ± 6 and 1729 ± 4 Ma (Page et al., 2000), and one slightly younger age of 1722 ± 4 Ma. This younger age is within error of felsic volcanism in the region associated with the ~1725 Ma Packsaddle Granite and Hobblechain Rhyolite. This is followed by deposition of the upper Wollogorang Formation and the younger 1713 ± 7 Ma Tanumbirini Rhyolite. Jackson et al. (2000) also put the Nyanantu Formation within this group and, although the age of 1708 ± 5 Ma from felsic volcanic debris within the conglomeratic arkose is formally only a maximum depositional age, the unimodal age population suggests that it may be close to a depositional age for this unit (Page et al., 2000). The Parsons Range Group may also be part of the Prize Supersequence.

Isa Superbasin

The southern McArthur Basin contains a record of all seven supersequences of the Isa Superbasin, from the ~1660 Ma Gun Supersequence (upper Masterton, Mallapunyah Formations) through to the ~1585 Ma Doom Supersequence (Dungaminine Formation). Geochronological constraints on the stratigraphy within this superbasin includes an age for the Tatoolla Sandstone, where a tuffaceous siltstone contained a single zircon age population at 1648 ± 3 Ma (Page et al., 2000), interpreted to be part of the Loretta Supersequence. There are ages for three samples from the Barney Creek Formation (~1640-1638 Ma; Page et al., 2000), interpreted to constrain deposition of this unit as part of the River Supersequence. The Teena Dolomite (1639 ± 6 Ma) and the Lynott Formation (1636 ± 4 Ma) have similar ages, and are also correlated with the River Supersequence (Page et al., 2000).

Figure 8 **(overleaf):** *Geochronological data and summary Time-Space plot for the Mount Isa Inlier and southern McArthur Basin.*



Geochronological synthesis and time-space plots for Proterozoic Australia

Depositional ages for the Stretton Sandstone (1625 ± 2 Ma) indicate that it is part of the Term Supersequence, and that the Amos Formation (1614 ± 4 Ma) and lower Balbirini Dolomite (1613 ± 4 and 1609 ± 3 Ma) are part of the Lawn Supersequence (Page et al., 2000). A sample from the upper Balbirini Dolomite has a younger depositional age of 1589 ± 3 Ma, and is correlated with the Wide Supersequence (Page et al., 2000).

Mineralisation

Pb-Zn-Ag mineralisation at the HYC deposit has a Pb-Pb model age of ~1640 Ma (Carr et al., 2001).

Murphy Inlier and flanks

≥ 1850 Ma units

The oldest known unit in this region is the Murphy Metamorphics, which comprise metasedimentary rocks, volcanics and migmatites. This unit is suggested to be older than the ~1850 Ma Kalkadoon Suite (Blake, 1987) although there are no geochronological ages for the package.

The oldest dated units in the region are the ~1850 Ma granites and felsic volcanics, including the Nicholson Granite and the Cliffdale Volcanics, which form the ‘basement’ high of the Murphy Inlier. The two ages for the Nicholson Granite suggest minor age variation within the suite (1856 ± 3 and 1845 ± 3 Ma; Page et al., 2000).

Leichhardt Superbasin

Again, lower sedimentary and volcanic units in this region have no geochronological age constraints, but the correlations of Jackson et al. (2000) suggest that the basal Westmoreland Conglomerate on the northern flank of the inlier is equated with the Guide Supersequence of the Leichhardt Superbasin. The Wire Creek Sandstone crops out on the southern flank of the Murphy Inlier, and is correlated with the Guide Supersequence. The lower-most unit of the Buddawadda Basalt is correlated with the Seigal Volcanics and Eastern Creek Volcanics as part of the ~1780-1760 Ma Myally Supersequence. The McDermott Formation is correlated with the ~1755-1740 Ma Quilalar Supersequence.

Calvert Superbasin

On the southern flank of the Murphy Inlier, the Peters Creek Volcanics provide ages of 1729 ± 4 Ma to 1724 ± 2 Ma (Page and Sweet, 1998; Page et al., 2000), within error of felsic magmatism in the Southern McArthur basin. The lower Fish River Formation is correlated with the Prize Supersequence (Southgate et al., 2000).

Isa Superbasin

Most of the Isa Superbasin is preserved on the southern flanks of the Murphy Inlier. Stratigraphic units within the area include the upper Fish River Formation, which is interpreted to be part of the Gun Supersequence, and the Walford Dolomite, which has a depositional age of 1649 ± 7 Ma and is correlated with the Loretta Supersequence. The Mount Les Siltstone has a depositional age of 1640 ± 7 Ma, equating with the River Supersequence. The lower Doomadgee Formation has depositional ages of 1619 ± 5 Ma (part of the Term Supersequence) and 1613 ± 5 Ma (part of the Lawn Supersequence) and is overlain by the upper Doomadgee Formation (Page et al., 2000).

Mineralisation

Mineralisation associated with the Westmoreland U deposits is constrained to between 1665 Ma and 1606 Ma based on Ar-Ar ages from illite in diagenetic aquifers (Polito et al., 2006).

Lawn Hill Platform

Leichhardt Superbasin

In the Lawn Hill Platform, the oldest dated unit is the Yeldham Granite, which crops out in the Kamarga Dome, and has a xenotime TIMS age of 1796 ± 3 Ma, which is slightly younger than the ~1820 Ma zircon U-Pb TIMS age from the same sample (Wyborn et al., 1988). This granite intruded the Kamarga Volcanics, which include lower greenschist-facies basalts and feldspathic sandstones of unknown age (Wyborn et al., 1988). The mafic Mitchiebo Volcanics in the Carrara Range underlie the Top Rocky Rhyolite, and may also be correlated with the Eastern Creek Volcanics of the Myally Supersequence.

Calvert Superbasin

The Top Rocky Rhyolite from the Carrara Range has an age of 1725 ± 3 Ma (Page et al., 2000). Younger magmatism within the region includes the Weberra Granite (1711 ± 3 Ma; Neumann et al., 2006) and the mafic Fiery Creek Volcanics (1709 ± 3 Ma; Page and Sweet, 1998), which overlie the Bigie Formation. The lower Torpedo Creek Formation and low Gunpowder Creek Formation are also part of the Prize Supersequence, but there are no geochronology constraints for these units in this area.

Isa Superbasin

All supersequences of the Isa Superbasin are preserved in the Lawn Hill Platform. The Gun Supersequence includes the upper Gunpowder Creek Formation and Paradise Creek Formation, which in the Mellish Park area has a depositional age of 1657 ± 3 Ma (Page et al., 2000). There are depositional ages of 1647 ± 4 Ma for the Lady Loretta Formation (Loretta Supersequence) and 1644 ± 8 Ma for the Riversleigh Formation (River Supersequence). Depositional ages for the Lawn Hill Formation, integrated with sequence stratigraphy, allow subdivision of the unit, with unit Pmh1 indicating deposition at ~1636-1630 Ma (Term Supersequence). Unit Pmh2 has depositional ages between ~1616 and 1611 Ma, indicating transition between the Term and Lawn Supersequence, units Pmh3 and the lower parts of Pmh4 are also correlated with the Lawn Supersequence. A sample from the upper parts of Lawn Hill Formation unit Pmh4 has a depositional age of 1595 ± 6 Ma, and, together with unit Pmh5, is correlated with the Wide Supersequence; and unit Pmh6 with the Doom Supersequence (Southgate et al., 2000).

Mineralisation

Pb-Zn mineralisation at Century deposit has a Pb-Pb model age of ~1575 Ma (Carr et al., 2001).

Leichhardt River Fault Trough

≥ 1850 Ma units

The oldest units in this region are the Yaringa Metamorphics, Candover Metamorphics, Saint Ronans Metamorphics and Sulieman Gneiss, which are suggested to be pre-1850 Ma in age (Blake, 1987). Two gneissic samples of the Yaringa Metamorphics provided ages of 1900 ± 14 and 1885 ± 10 Ma from U-Pb zircon TIMS analysis (Page and Williams, 1988) which were interpreted as the age of amphibolite-facies metamorphism. These two constraints were combined to provide an age of 1890 ± 8 Ma, interpreted to record the age of high-grade metamorphism associated with the Barramundi Orogeny. However, more recent U-Pb zircon SHRIMP data for the Yaringa Metamorphics have interpreted magmatic crystallisation ages of ~1858 Ma (Bierlein et al., in press), suggesting that magmatism associated with this unit is earlier within the ~1860-1845 Kalkadoon Suite range. Whether the other units listed above are pre- or syn-1850 Ma is not known.

Leichhardt Superbasin

The Monoghans Granite (also known as the Big Toby Granite) intruded the Yaringa Metamorphics and has a U-Pb zircon TIMS age of 1805 ± 15 Ma (Wyborn et al., 1988), although there is some uncertainty about this age constraint given that the data have an imperfect discordia fit (MSWD = 11.6) and that the zircons have high common Pb. Other magmatism at this time is represented by felsic and mafic volcanics of the Bottletree Formation, which has U-Pb zircon multi-grain TIMS age of 1790 ± 15 Ma (Page, 1983), with a MSWD of 0.94 (5 fractions), suggesting that the data provide a good discordia.

This magmatism is synchronous with deposition of the Guide Supersequence, which in this region includes the Mount Guide Quartzite (zircon maximum depositional ages = 1793 ± 9 Ma and 1773 ± 19 Ma; Neumann et al., 2006). The May Downs Gneiss has a maximum depositional age of 1789 ± 4 Ma (Page, OZCHRON), and may also be part of this supersequence. Deposition of the Guide Supersequence is followed by extrusion of the Eastern Creek Volcanics (which have continental tholeiiite affinities) and associated deposition of the Lena Quartzite, Alsace Quartzite, Bortala Formation and Whitworth Quartzite. This succession is termed the Myally Supersequence, and its depositional age is constrained by a maximum depositional age of 1779 ± 4 for the Lena Quartzite and a depositional age from a volcaniclastic unit within the Bortala Formation at 1773 ± 3 Ma (Neumann et al., 2006).

Deposition of the overlying Quilalar Formation is constrained by a maximum depositional age of 1748 ± 3 Ma for the unit from the eastern margin of the Leichhardt River Fault Trough (Neumann et al., 2006).

Calvert Superbasin

The lower parts of this superbasin are represented by the Bigie Formation, and although maximum depositional ages are much older than deposition for this unit (~1760-1780 Ma), field relationships in the Lawn Hill Platform area suggest that it is coeval with the ~1710 Ma Fiery Creek Volcanics.

Overlying the Bigie Formation are the lower parts of the Surprise Creek Formation, Warrina Park Quartzite, Torpedo Creek Quartzite and Gunpowder Creek Formation (Southgate et al., 2000). Age constraints for these units are from peperites interpreted to be emplaced at the same time as sedimentation, providing depositional ages between 1694 ± 3 Ma and 1688 ± 5 Ma (Page et al., 2000; Jackson et al., 2005).

Sybella Event

Magmatism in the Leichhardt River Fault Trough, associated with the Gun unconformity, initiated at ~1690 Ma with the appearance of peperites within stratigraphic units of the Prize Supersequence. This is followed by volcanism recorded by the 1678 ± 2 Ma Carters Bore Rhyolite (Page and Sweet, 1998) and the major voluminous stage of intrusive magmatism associated with Sybella Batholith at 1675-1670 Ma (Page and Bell, 1986; Neumann et al., 2006). Ages from the Queen Elizabeth pluton of the Sybella Batholith record slightly younger ages of 1660 ± 5 and 1655 ± 4 Ma (Connors and Page, 1995), which are within error of ages from peperites within the Gun Supersequence (see below for details). This extensive record of magmatism from ~1690 Ma through to ~1655 Ma within the Leichhardt River Fault Trough suggests a long-lived thermal event.

Isa Superbasin

The age of the Gun Supersequence transgressive deposits have been constrained as older than ~1660 Ma, based on a maximum depositional age of 1668 ± 8 Ma for the Moondarra Siltstone and a depositional age of 1663 ± 3 Ma for the Breakaway Shale, both from the Paroo Range (Page et al., 2000). In the northern Leichhardt River Fault Trough, the Paradise Creek Formation (zircon depositional ages from peperites = 1658 ± 3 to 1653 ± 7 Ma) and the Esperanza Formation are also part of the Gun Supersequence, and constrain the supersequence highstand deposits. Farther south, in the Mount Isa valley, the upper part of the Gun Supersequence includes the Native Bee Siltstone, Urquhart Shale (depositional ages = 1655 ± 4 and 1652 ± 7 Ma; Page et al., 2000), and Spear Siltstone. The Kennedy Siltstone and Magazine Shale are correlated with the overlying Loretta Supersequence, which has a conformable contact with the underlying Gun Supersequence. Younger supersequences of the Isa Superbasin do not crop out in the Leichhardt River Fault Trough, either due to non-deposition or erosion.

Isan Orogeny

U-Pb zircon TIMS analyses from the Queen Elizabeth Granite of the Sybella Batholith give an age of 1610 ± 10 Ma (Page and Bell, 1986), which was considered to be a primary magmatic age for this part of the Sybella Granite. However, later SHRIMP results showed that the magmatic age for the granite is ~1660 Ma, and that the TIMS age may record a later thermal event.

In the Hazeldene region, monazite from cordierite-orthoamphibole gneisses provide a U-Pb SHRIMP age of 1575 ± 5 Ma (Hand and Rubatto, 2002), interpreted to represent peak metamorphism in this area. A pegmatite dyke within the May Downs Gneiss records a preliminary U-Pb SHRIMP monazite age of 1584 ± 3 Ma (Page, OZCHRON).

U-Pb zircon SHRIMP data from pegmatites recording different structural fabrics were analysed by Connors and Page (1995) to determine the timing of deformation associated with the Isan Orogeny. An age of 1532 ± 7 Ma for a pegmatite in the Queen Elizabeth Pluton region is regarded as close to the age of D_2 deformation in this region (Connors and Page, 1995). Data from a post D_3-pegmatite within the Queen Elizabeth Pluton is very scattered due to Pb loss from the high U zircon population, however, the most sub-concordant analyses give an age of 1480 ± 14 Ma, which is interpreted to provide a minimum age of for D_3 deformation (Connors and Page, 1995).

Mineralisation

Pb-Zn-Ag mineralisation at the Mount Isa deposit has a Pb-Pb model age of ~1653 Ma, with Pb-Pb model ages of 1635 Ma for the Lady Loretta deposit (Carr et al., 2001).

Biotite from carbonate-Fe oxide alteration associated with U mineralisation at Andersons Lode have Ar-Ar ages of ~1535 (Perkins et al., 1999).

Ar-Ar biotite data from alteration and tuff marker horizons are interpreted to constrain the age of Cu mineralisation at the Mount Isa mine at 1523 ± 3 Ma (Perkins et al., 1999).

Mary Kathleen Belt

≥ 1850 Ma units

The oldest mapped units within the Kalkadoon-Leichhardt Belt are the Kurbayia Migmatite and the Plum Mountain Gneiss. The Kurbayia Migmatite crops out in the southern Kalkadoon-Leichhardt Belt, and Page (OZCHRON) reported an igneous protolith age of 1857 ± 5 Ma for this felsic gneiss, based on 11 SHRIMP U-Pb zircon data points. Older ages within the sample were interpreted to represent inheritance (at ~1970 Ma but not a single population, plus ~3000 Ma, 2500-2400 Ma and ~2170 Ma). In contrast, McDonald et al. (1997) renamed the unit the Black Angel Gneiss and interpreted a primary igneous crystallisation age of the protolith of gneiss of ~2500 Ma to ~2420 Ma, with inherited ages up to 2970 Ma and rims and totally recrystallised grains at ~2040 Ma to ~1930 Ma, reflecting late thermotectonism. Another sample in the area, the Pothole Creek Gneiss was interpreted to have a crystallisation age of 1995 ± 20 Ma, with inheritance and metamorphic rims with ages of ~1940-1930 Ma and ~1870-1840 Ma (McDonald et al., 1997).

Other units within the Kalkadoon-Leichhardt Belt include the Kalkadoon Granite, which has a U-Pb zircon SHRIMP age of 1847 ± 3 Ma (Bierlein et al., in press) and U-Pb zircon TIMS ages of 1862 ± 24 Ma, 1860 ± 32 Ma and 1856 ± 10 Ma (Page, 1978; Wyborn and Page, 1983). Ages for the associated felsic Leichhardt Metamorphics (also called the Leichhardt Volcanics), include U-Pb zircon TIMS ages of 1875 ± 26 Ma, 1865 ± 3 Ma and 1852 ± 7 Ma (Page 1978; Page 1983), and a SHRIMP age of 1857 ± 20 Ma based on 7 analyses (Page, OZCHRON). Within this belt, the Ewen Granite has an age of ~1820 Ma (Wyborn and Page, 1983), with the very high initial common Pb in the zircons precluding a precise age determination.

Argylla Event

Overlying basement is the felsic intrusive-extrusive Argylla Formation. Age constraints indicate crystallisation at 1780-1775 Ma (Page, 1978; Page, OZCHRON; Neumann, unpublished), suggesting that it is coeval with extension associated with the Myally Supersequence in the Leichhardt River Fault Trough. This magmatic event may have a significant intrusive component, rather than being dominantly extrusive. Also, field relationships between Argylla Formation recording a strong mylonitic fabric and undeformed Wonga Granite (see below) can be used to constrain the timing of a deformational event in this area to between ~1780 Ma and ~1740 Ma (Neumann, unpublished).

Leichhardt Superbasin

The overlying Ballara Quartzite comprises quartzite and micaceous quartzite, and an age of 1755 ± 3 Ma from a sample described as tuffaceous quartzite. It is interpreted to represent a stratigraphic age for this unit (Page, OZCHRON), although the relationship between this outcroping block and the rest of the Mary Kathleen Belt is unclear. The Corella Formation overlies the Ballara Quartzite and comprises fine-grained sandstones and siltstones grading up into pelitic schists and calcareous limestone, overlain by a regionally continuous quartzite unit (mapped as Pkc_{2q}) and another calcareous package. A flow-banded porphyritic rhyolite within the Corella Formation from near the Dugald River deposit provides an age of 1750 ± 7 Ma (Page and Sun, 1998). This age is interpreted by the authors to be either a maximum depositional age, or the age of deposition if the rocks are of volcanic origin. In the Duchess area, three samples from mapped Corella Formation have been analysed. A tuffaceous sandstone near the Mount Morah mine provides a maximum depositional age of 1740 ± 20 Ma from the two youngest grains (Page, OZCHRON). Another sample from a rhyolite within the Corella Formation provides a crystallisation age of 1738 ± 2 Ma, and a metamorphic age of 1520 ± 2 Ma (Page, OZCHRON), while a hematised recrystallised rhyolite from this area has been interpreted to have an approximate crystallisation age of 1620 ± 30 Ma, calculated from 5 individual ages (Page, OZCHRON).

Wonga Event

The Wonga Batholith comprises bimodal intrusive rocks within the Mary Kathleen Belt which crop out along a north-south linear zone approximately 190 km long (Blake, 1987). These intrusives have been subdivided into two groups, based on the deformational style of the region: the Wonga Suite in the cental Wonga Belt and the Burstall and Mount Godkin Granites in the Eastern Zone (Pearson et al., 1992). Wyborn et al. (1988) and Pearson et al. (1992) interpreted magmatism in both domains as taking place during extension associated with the 1760-1720 Ma Wonga Extension Event.

The Wonga Suite comprises coarse-grained, foliated porphyritic granites and gneisses which intruded the Argylla Formation, Ballara Quartzite and Corella Formation. Within this suite, the Wonga Granite from Breakfast Creek has a SHRIMP age of 1758 ± 8 Ma, where-as the age for the Natalie Granite near Mary Kathleen has been interpreted to be 1729 ± 5 Ma for high-U zircon rims (Pearson et al., 1992). The Natalie Granite sample also contains a low-U zircon age population at 1778 ± 15 Ma, interpreted to record inheritance, possibly from felsic volcanics of the Argylla Formation, which this granite intruded. There is also a U-Pb TIMS age of 1742 ± 13 Ma for the Natalie Granite at the Wonga Waterhole. Although these ages are similar, the two SHRIMP ages are not within error of each other. Further, the Wonga Granite sample with the oldest measured age has the youngest cross-cutting relationships in outcrop (Pearson et al., 1992).

The Burstall Suite comprises a linear north-trending belt of granites and mafic rocks that occur in the Mary Kathleen Belt, and U-Pb TIMS ages for the Burstall Suite (Page, 1983a) suggests an age of ~1740 Ma for this magmatism, although the individual ages have large errors. New SHRIMP ages for these samples confirm a magmatic age of 1740-1735 Ma for the Burstall Granite and co-magmatic Lunch Creek Gabbro. Other units within this event include the Revenue Granite to the south of the Burstall pluton (U-Pb SHRIMP age = 1735 ± 2 Ma; Page, OZCHRON).

Calvert and Isa Superbasins

The Deighton Quartzite overlies the Corella Formation and has been mapped as five separate sub-units (Wilson et al., 1977). The contact with the underlying Corella Formation is interpreted to be stratigraphic. The basal unit of the Deighton Quartzite includes ~10m thick basaltic flows with massive bases and vesicular tops, interbedded with quartzite, and may be equivalent to the Fiery Creek Volcanics of the Lawn Hill Platform. Above these basalt flows is a ~50m thick package of massive pink-coloured, cross-bedded quartzite mapped as Deighton Quartzite unit 1. This quartzite is overlain/dissected by a conglomeratic unit comprising rounded quartzite, quartz and basaltic clasts. This conglomerate is overlain by thick-bedded coarse-to fine-grained sandstones which grade up into medium- to thickly-bedded, medium- to very fine-grained sandstones (units upper 1-4), and represent a deepening-upwards package deposited in fluvial to shallow marine environments. This package is correlated with the Prize Supersequence. The base of unit 5 consists of a sharp-based, ~70m thick polymict conglomerate unit which grades up into grey, medium-grained sandstones, and is correlated with the Gun Supersequence.

Isan Orogeny

In the Rosebud Syncline, monazite from a cordierite-orthoamphibole schist (sillimanite zone) yields a U-Pb SHRIMP age of 1570 ± 9 Ma with overgrowth ages of ~1540 Ma, while rutile from the same sample gives an age of ~1475 Ma (Hand and Rubatto, 2002). A cordierite-andalusite schist from the same region, but collected down-grade of the sillimanite-in zone, gives a monazite U-Pb SHRIMP age of ~1570 with overgrowths at ~1515 Ma, while a sample close to the sillimanite-in zone also gives a Sm-Nd garnet age of ~1570 Ma (Hand and Rubatto, 2002). Zircon overgrowths in a sample of the Corella Formation from the Duchess region provides a U-Pb SHRIMP age of 1520 ± 2 Ma (Page, OZCHRON).

Mineralisation

Pb-Zn-Ag mineralisation at the Dugald River deposit is interpreted to be hosted by Corella Formation and has a Pb-Pb model age of ~1665 Ma (Carr et al., 2001).

Tommy Creek Block

Leichhardt Superbasin

Sediments in the Boomarra Horst, originally mapped as Soldiers Cap Group, have depositional ages of 1775 ± 4 Ma and 1774 ± 4 Ma (Page and Sun, 1998), suggesting that they are equivalent to the Myally Supersequence in the Leichhardt River Fault Trough.

Argylla and Wonga Events

Rhyolites at ~1760 Ma (initially described as ‘Lalor Beds; Page, unpublished) are similar in age to the Argylla Formation of the Mitakoodi Block. Younger I- and S-type granitic intrusions including the Levian Granite and Dipvale Granite (Page and Sun, 1998; Davis et al., 2001) and iron-metasomatised latitic breccias in the Mount Fort Constantine area (Page and Sun, 1998) record ages between ~1745-1740 Ma, similar to the age of the Wonga Event in the Mary Kathleen Belt.

There are younger magmatic and associated sedimentary units in the Tommy Creek Block, including rhyolites dated at 1650 ± 3 Ma, 1629 ± 8 Ma, 1625 ± 4 Ma and 1618 ± 6 Ma (Page, OZCHRON; Hill et al., 1992; Page and Sun, 1998). Their relationship to the Isa Superbasin stratigraphy is unclear.
Granites in this region, including the Malakoff Granite and Mavis Granodiorite at 1505-1500 Ma (Page and Sun, 1998; Davis et al., 2001), are associated with the later parts of the Williams Batholith magmatism.

Mineralisation

The age of Fe-oxide Cu-Au mineralisation at the Ernest Henry deposit is constrained to between 1514 ± 24 Ma and 1529 +11/-8 Ma, based on U-Pb titanite ages within alteration cycles (Mark et al., 2006).

Isan Orogeny

Sm-Nd garnet data from two garnet-staurolite samples in the Tommy Creek Block have ages of 1585 Ma and 1575 Ma, interpreted to record an up-pressure evolution during the development of the regional foliation (Hand and Rubato, 2002), probably associated with the early stages of the Isan Orogeny.

Mitakoodi–Marimo-Stavely Zone

≥ 1850 Ma units

Possible basement in the Mitakoodi-Marimo-Stavely Zone is the Double Crossing Metamorphics, which crop out as sillimanite feldspathic gneisses west of the Selwyn mine. Page and Sun (1998) report a maximum depositional age of 1840 ± 20 Ma, based on the youngest individuals, although the MSWD permits an older maximum depositional age of 1863 ± 13 Ma (n=22; MSWD = 1.4). These age-constraints permit deposition of this unit to be either pre- or post-Kalkadoon magmatism.

Argylla Event and Leichhardt Superbasin

Argylla Formation magmatism in the Mitakoodi Anticline has crystallisation ages of ~1760 Ma (Page, OZCHRON), which is ~20 m.y. younger than samples of the Aryglla Formation from the Mary Kathleen Belt. In the Mitakoodi Anticline, the Argylla Formation is mapped as being overlain by a quartzite (Argylla Formation Pea5), the Marraba Volcanics (Cone Creek Basalt, Mount Start Member and Timberoo Member). The Marraba Volcanics are overlain by the Mitakoodi Quartzite and ages for volcanics within this unit from both sides of the Mitakoodi Anticline give depositional ages of ~1755 Ma (Page, OZCHRON). These age constraints would require very rapid deposition (<5 m.y.) of the Marraba Volcanics packages.

Wonga Event

There is some magmatism in the southern area of the zone (west of the Selwyn mine) associated with the ~1740 Ma event, including the Gin Creek Granite (1741 ± 7 Ma) and Double Crossing Metamorphics intrusive (1740 ± 6 Ma; Page and Sun 1998).

Calvert and Isa Superbasins

The Roxmere Quartzite has a maximum depositional age of ~1710 Ma (Neumann, unpublished) which would suggest that it represents a palaeo-shoreline at Prize Supersequence time. Facies-correlations suggest that the Answer and Marimo Slates may be deep-water equivalents of the Gun Supersequence. Repeated analyses of four zircons from a bedded, fine-grained cherty tuff and brecciated tuff from the Answer Slate provide an age of 1652 ± 16 Ma, interpreted to provide a constraint on the age of deposition of this stratigraphic unit (Page, OZCHRON). There are two samples with age constraints from the Marino Slate, sampled from the same outcrop region, and their ages are difficult to interpret. The first sample is a tuff, which has clear, euhedral zircons with prismatic faces which define a single group at 1655 ± 4 Ma (n=28; Page, OZCHRON). This age is within error of the ~1652 Ma age for the Answer Slate sample. The second sample is siltstone which includes some detrital ages ranging between ~1770 Ma and ~1623 Ma, and a weighted mean age of ~1610 Ma (n=20; Page, OZCHRON) from a population of euhedral, clear prismatic zircons. It is unlikely that the young age from the sediment is metamorphic in origin, given that the metamorphic grade in this area is greenschist facies. Perhaps these samples are from two different sedimentary packages.

Williams Event

The Wimberu Granite intruded stratigraphic units of the Mitakoodi Anitcline and Marimo-Stavely Zone, and has a magmatic crystallisation age of 1509 ± 4 Ma (Page and Sun, 1998). This indicates that this granite is part of the Williams Batholith magmatism.

Mineralisation

Cu-Au mineralisation associated with deposits of the Selwyn region (including the Starra, Mount Dore, Swan, and Mount Elliott deposits) are located along the Mount Dore Fault, which delineates the margin between the Mitakoodi-Marimo-Stavely Zone and the Eastern Succession domains defined in this synthesis. Ar-Ar alteration biotite ages of ~1503 Ma and 1496 ± 4 Ma from Starra and Mount Elliot are interpreted to have recorded flow of mineralising fluids (Perkins and Wyborn, 1998).

Eastern Succession

Leichhardt - Calvert Superbasin

The oldest known stratigraphic unit in the Eastern Succession is the Doherty Formation, which consists of calc-silicates and sands, and crops out in the south eastern part of the area. An igneous sample within the unit, interpreted to be volcanic, has an age of 1725 ± 3 Ma (n=44 of 45; Page and Sun, 1998). This is interpreted to be a reliable age for magmatic zircon crystallisation, and although this is possibly a high-level sill, this result should also be a meaningful stratigraphic age for the Doherty Formation (Page, pers. comm.). Alternatively, if the sample is intrusive, the age would provide a minimum constraint on depositional of the unit. Facies correlations would suggest a correlation with the Corella Formation (~1755 Ma Quilalar Supersequence).

Soldiers Cap Group

The Soldiers Cap Group forms a north-south belt in the eastern margin of the Mount Isa Inlier, and includes the Llewellyn Creek Formation, Mount Norna Quartzite and Toole Creek Volcanics. These mainly turbiditic sediments and mafic volcanics record a range in metamorphic grade from amphibolite-facies in the north, to granulite-facies in the south, near Cannington. Maximum depositional ages for the Soldiers Cap Group from the Cannington area (where it’s termed the Gandry Dam Gneiss) suggest depositional ages of between 1680 and 1660 Ma (Page and Sun, 1998; Giles and Nutman, 2003). Similar maximum depositional ages of ~1685 Ma are also identified from the Llewellyn Creek Formation and Mount Norna Quartzite further north (Page and Sun, 1998; Giles and Nutman, 2003; Neumann, unpublished), although a meta-rhyolite from undifferentiated Soldiers Cap Group in the Foxes Creek area does suggest a slightly younger depositional age of 1654 ± 3 Ma for the package in this area (Page and Sun, 1998). At the core of the Snake Creek Anticline, the Llewellyn Creek Formation is intruded by a tonalite which provides a upper intercept age of 1686 ± 8 Ma and a lower intercept age at ~530 Ma (Rubenach, 2005), suggesting non-zero Pb loss. The weighted mean $^{207}Pb/^{206}Pb$ age for the 14 analyses that are less that ~5% discordant is 1678 ± 5 Ma

(Rubenach, 2005). Given that this tonalite intruded the Soldiers Cap Group, the maximum depositional ages calculated for these turbidites are very close to the depositional age for this package.

Most samples from the Toole Creek Volcanics yielded only a few zircons, including detrital grains, and so determining a depositional age is difficult. One sample from southeast of Cloncurry has a cluster of ages around ~1657 Ma, but they do not form a single weighted mean population. The eight most concordant analyses provide an age of 1659 ± 10 Ma, which may be a stratigraphic age for the unit (Page, OZCHRON).

The Kuridala Formation crops out in the southern Marimo-Stavely Zone. Samples from turbiditic packages within the unit east of the Kuridala mine and east of the Sewlyn mine in the Mount Ulo area have maximum depositional ages of 1676 ± 4 Ma and 1676 ± 5 Ma (Neumann, unpublished; Page, OZCHRON). Given the similar facies and age constraints between the turbiditic part of the Kuridala Formation and the Mount Norna Quartzite, these two units are thought to be equivalent.

Isan Orogeny

Dating of metamorphic monazite, titanite and zircon rims from samples of the Eastern Succession constrains a high-grade metamorphic event in this area to between ~1600 Ma and ~1585 Ma (Giles and Nutman, 2002; Page and Sun, 1998), correlated with the Isan Orogeny.

Williams Event

Voluminous magmatism associated with the Williams Batholith has ages ranging over ~55 m.y., between 1547 ± 5 Ma for the Boorama Tank Gneiss and 1493 ± 8 Ma for the Yellow Waterhole Granite (Page and Sun, 1998).

Mineralisation

The Broken Hill-type Pb-Zn-Ag Cannington deposit has a Pb-Pb model age of ~1675 Ma (Carr et al., 2001). Other Pb-Zn systems in this region, including the Pegmont and Fairmile deposits, are also suggested to have similar mineralisation ages.

At the Cu-Au Osborne deposit, syn-metamorphic hydrothermal titanite associated with Cu mineralisation has an age of 1595 ± 6 Ma (Rubenach et al., 2001). The Eloise Cu-Au is located south-east of Cloncurry, and the main mineralisation is interpreted to be synchronous with D_3 deformation at ~1540-1500 Ma and emplacement of the Williams Batholith (Baker and Laing, 1998).

OUTSTANDING QUESTIONS AND SCOPE FOR FUTURE PROJECTS

Age and characteristics of pre-1850 Ma basement

As discussed above, the age and extent of pre-1850 Ma rocks in the Mount Isa Inlier are unclear. Older zircon ages and evolved Nd isotopic signatures identified from granites and gneisses within the Leichhardt River Fault Trough and Kalkadoon-Leichhardt Belt have been interpreted to represent either primary crystallisation ages (e.g. McDonald et al., 1997) or as inheritance (e.g. Page, OZCHRON). Further, the age and characteristics of ~1850 Ma deformation and metamorphism is also unclear. Initial geochronological constraints from the Yaringa Metamorphics were used to define metamorphism associated with the Barramundi Orogeny at 1890 ± 8 Ma, and to correlate this tectonothermal event across northern Proterozoic Australia (Page and Williams, 1988; Etheridge et al., 1987). However, more recent geochronological ages suggest crystallisation of this felsic magmatic unit at ~1855 Ma (Bierlein et al., in press). A detailed structural, metamorphic and geochemical study in conjunction with a targeted geochronological framework is required to determine the complete tectonothermal event history of these units.

Age of sedimentation in the Mitakoodi Anticline

There are no depositional ages for the Cone Creek Metabasalt Member, Mount Start Member and Timberoo Member of the Marraba Volcanics (Neumann, unpublished) as the youngest ages from detrital zircons are older than the underlying ~1760 Ma Argylla Volcanics (Page, unpublished). Also, as discussed above, the short time (<5 m.y.) permitted by the age constraints of the underlying Argylla Formation and overlying Mitakoodi Quartzite are difficult to reconcile with the range of sedimentary facies and thickness of the Marraba Volcanics packages. Further, the Marraba Volcanics have stratigraphic similarities with the Eastern Creek Volcanics and Myally Subgroup (the ~1780-1770 Ma Myally Supersequence) in the Leichhardt River Fault Trough, but the <1760 Ma age constraint from the underlying Argylla Formation suggests that they are younger than this package. Given these constraints, it is difficult to determine to which Leichhardt River Fault Trough supersequence the Marraba Volcanics are equivalent.

Age and characteristics of pre-Isan Orogeny metamorphism

There are a number of geochronological constraints for metamorphism in the Mount Isa Inlier associated with the Isan Orogeny, with ages between ~1600-1585 Ma recorded in the Leichhardt River Fault Trough, Mary Kathleen Belt and the Eastern Succession (Giles and Nutman, 2002; Page and Sun, 1998; Hand and Rubato, 2002). There is also an extensive and long-lived metamorphic and cooling history from ~1550 Ma to ~300 Ma recorded in Ar-Ar isotopic systems across the inlier (Perkins and Wyborn, 1998; Perkins et al., 1999; Spikings et al., 2001; Spikings et al., 2002). However, currently, there are no published geological constraints on the metamorphic history of the inlier prior to ~1600 Ma, although there is evidence for crustal-scale detachment structures being active during the development of the Leichhardt River Fault Trough, and syn-kinematic emplacement of the ~1740 Ma Wonga Batholith (e.g. Pearson et al., 1992).

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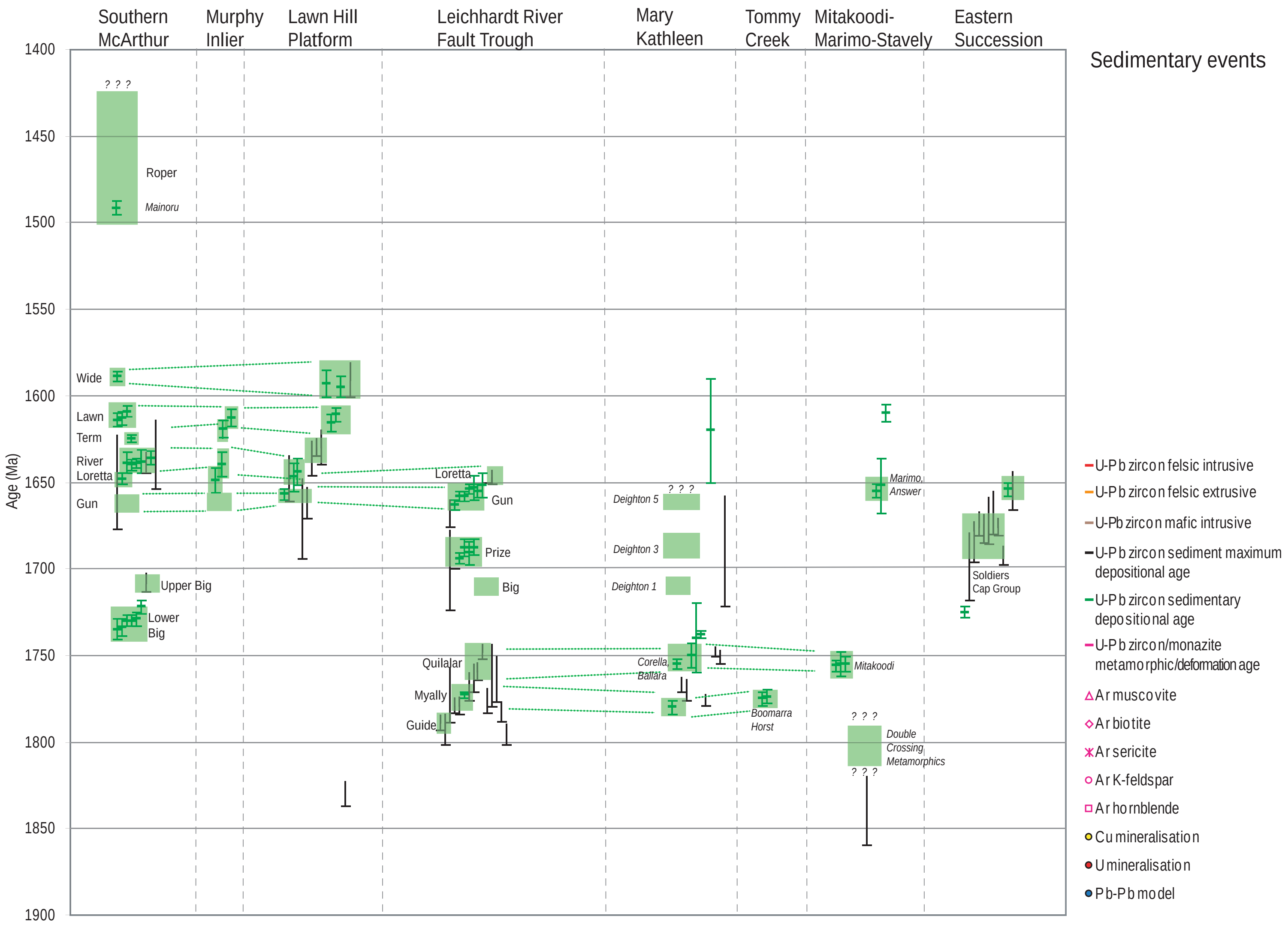
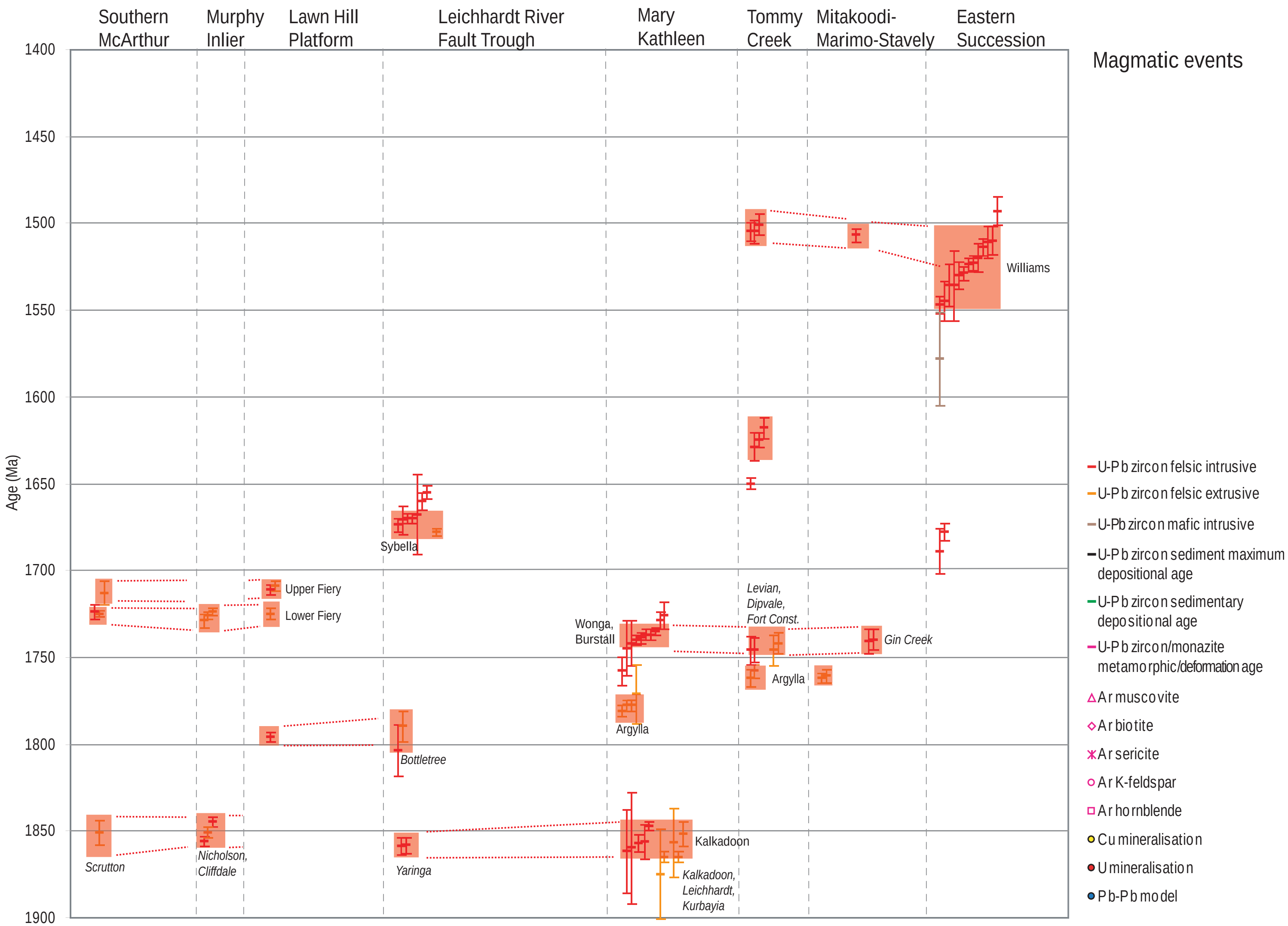
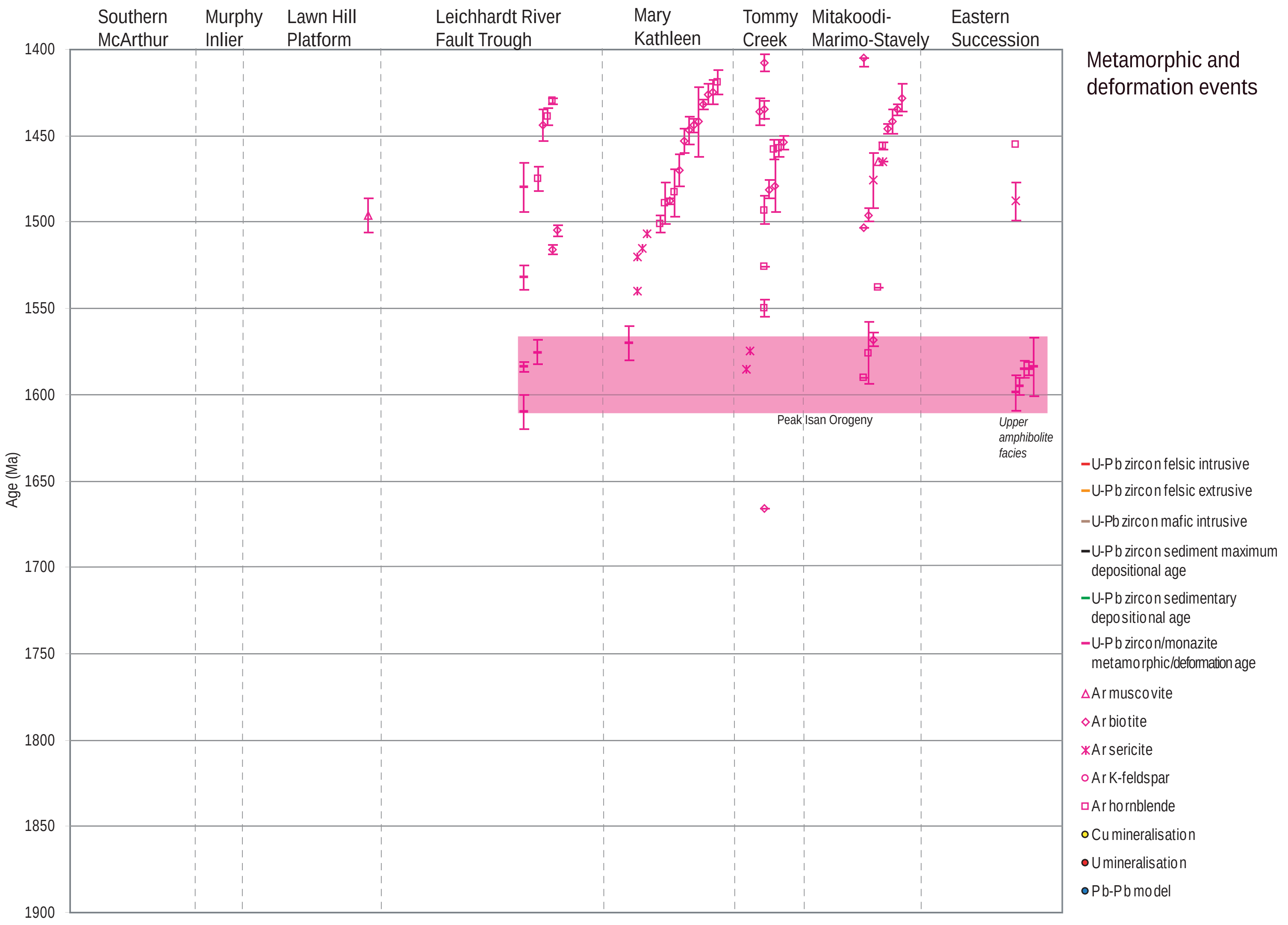
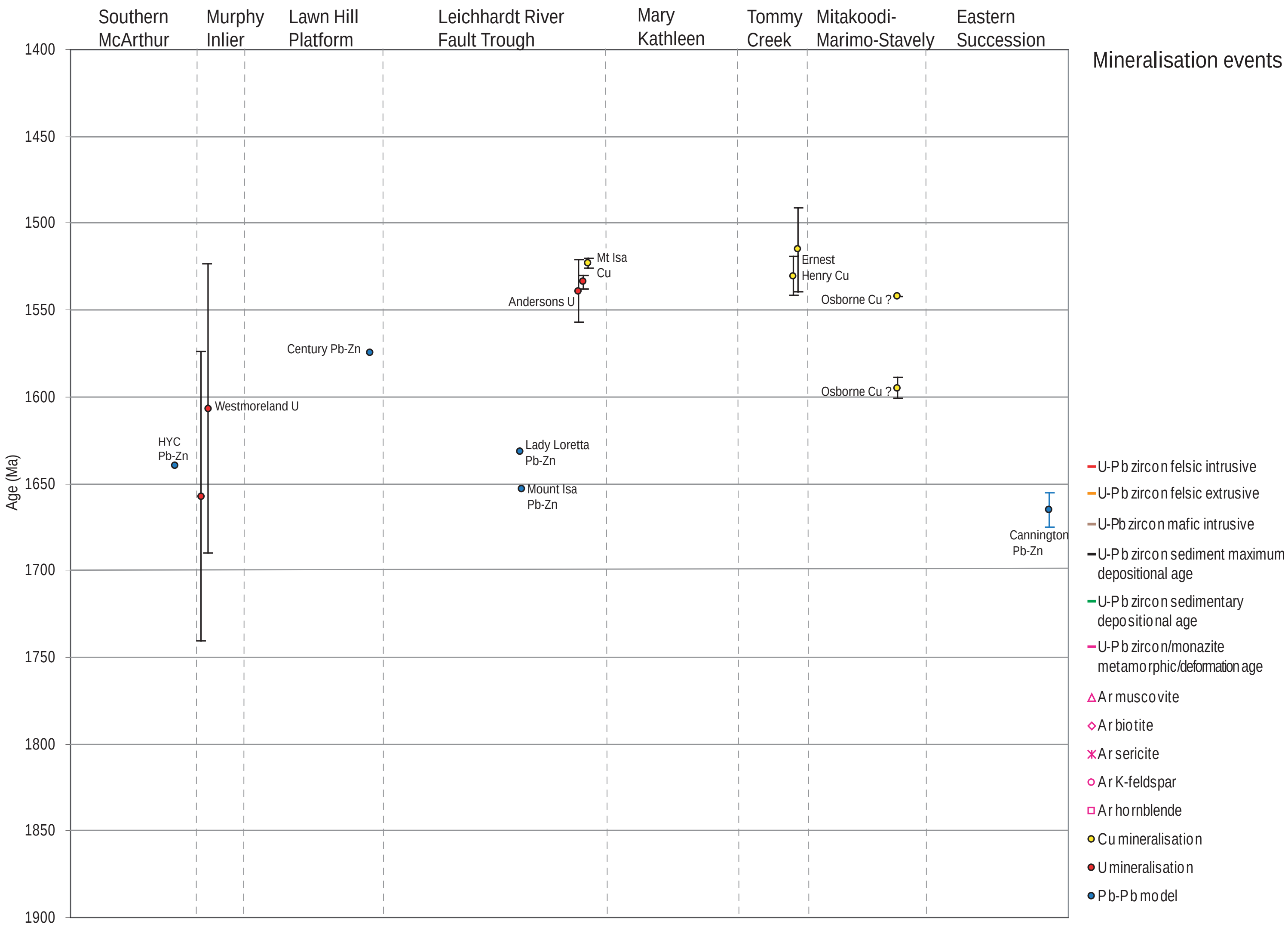

Southern McArthur
Murphy Inlier
Lawn Hill Platform
Leichhardt River Fault Trough
Mary Kathleen
Tommy Creek
Mitakoodi-Marimo-Stavely
Eastern Succession
Sedimentary events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
? ? ?
Roper
Mainoru
Wide
Lawn
Term
River
Loretta
Gun
Upper Big
Lower Big
Loretta
Gun
Prize
Big
Quilalar
Myally
Guide
Deighton 5
Deighton 3
Deighton 1
Corella, Ballara
Boomarra Horst
Mitakoodi
Marimo, Answer
Double Crossing Metamorphics
Soldiers Cap Group
U-Pb zircon felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb zircon sediment maximum depositional age
U-Pb zircon sedimentary depositional age
U-Pb zircon/monazite metamorphic/deformation age
Ar muscovite
Ar biotite
Ar sericite
Ar K-feldspar
Ar hornblende
Cu mineralisation
U mineralisation
Pb-Pb model


Southern McArthur
Murphy Inlier
Lawn Hill Platform
Leichhardt River Fault Trough
Mary Kathleen
Tommy Creek
Mitakoodi-Marimo-Stavely
Eastern Succession
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Williams
Sybella
Upper Fiery
Lower Fiery
Wonga, Burstall
Levian, Dipvale, Fort Const.
Gin Creek
Argylla
Argylla
Bottletree
Scrutton
Nicholson, Cliffdale
Yaringa
Kalkadoon
Kalkadoon, Leichhardt, Kurbayia
U-Pb zircon felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb zircon sediment maximum depositional age
U-Pb zircon sedimentary depositional age
U-Pb zircon/monazite metamorphic/deformation age
Ar muscovite
Ar biotite
Ar sericite
Ar K-feldspar
Ar hornblende
Cu mineralisation
U mineralisation
Pb-Pb model


Southern McArthur
Murphy Inlier
Lawn Hill Platform
Leichhardt River Fault Trough
Mary Kathleen
Tommy Creek
Mitakoodi-Marimo-Stavely
Eastern Succession
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Peak Isan Orogeny
Upper amphibolite facies
U-Pb zircon felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb zircon sediment maximum depositional age
U-Pb zircon sedimentary depositional age
U-Pb zircon/monazite metamorphic/deformation age
Ar muscovite
Ar biotite
Ar sericite
Ar K-feldspar
Ar hornblende
Cu mineralisation
U mineralisation
Pb-Pb model


Southern McArthur
Murphy Inlier
Lawn Hill Platform
Leichhardt River Fault Trough
Mary Kathleen
Tommy Creek
Mitakoodi-Marimo-Stavely
Eastern Succession
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
HYC Pb-Zn
Westmoreland U
Century Pb-Zn
Mt Isa Cu
Andersons U
Lady Loretta Pb-Zn
Mount Isa Pb-Zn
Ernest Henry Cu
Osborne Cu ?
Osborne Cu ?
Cannington Pb-Zn
Mineralisation events
U-Pb zircon felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb zircon sediment maximum depositional age
U-Pb zircon sedimentary depositional age
U-Pb zircon/monazite metamorphic/deformation age
Ar muscovite
Ar biotite
Ar sericite
Ar K-feldspar
Ar hornblende
Cu mineralisation
U mineralisation
Pb-Pb model

Time-Space evolution of the Georgetown and Coen regions

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OVERVIEW

The Proterozoic geology of northern Queensland includes the Georgetown, Coen, Yambo and Dargalong Inliers (e.g. Withnall et al., 1988; Bain and Draper, 1997; Black et al., 1998; Blewett et al., 1998; Figure 9). The region is bounded to the east by the Palaeozoic Tasman Line, and separated from the Mount Isa Inlier to the west by the Mesozoic Carpentaria Basin.

For this geochronological review and construction of the associated Time-Space plots (Figure 10), we have used the regional and stratigraphic subdivisions of Bain and Draper (1997), who divided the area into the Georgetown and Coen regions. The Georgetown Region also records an extensive Phanerozoic history, including magmatism during the early Palaeozoic, Silurian to Early Devonian, and Carboniferous to Permian. Likewise, the Coen Region also underwent Silurian-Devonian, Late Devonian to Early Carboniferous and Carboniferous-Permian magmatism. A summary of the Phanerozoic geological record in these regions can be found in Bain and Draper (1997).

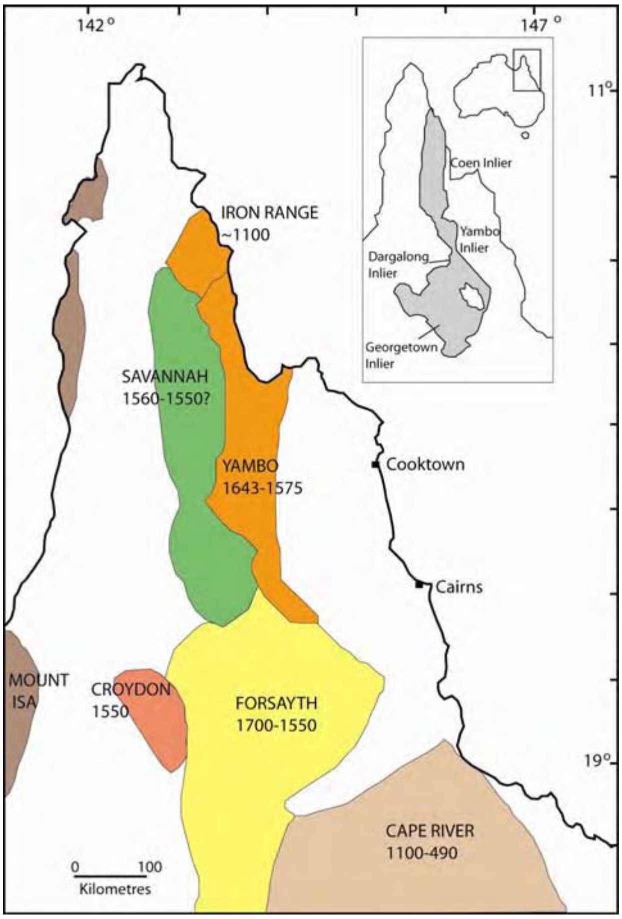


Figure 9: *Location and province divisions within the Georgetown and Coen regions, North Queensland (from Blewett et al., 1998). Main depositional and tectonothermal event ages given for each province.*

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Georgetown Region

The Georgetown region has been divided into two main structural units (Withnall et al., 1997) – the Etheridge Province and the Croydon Province. The Etheridge Province has been further divided into the Forsayth and Yambo Subprovinces, and the Croydon Province includes the Croydon Volcanic Group and the Esmeralda Supersuite. For this compilation, the geology and geochronology will be discussed according to these subprovince divisions.

Forsayth Subprovince

The Forsayth Subprovince includes the Etheridge and Langlovale Groups, McDevitt Metamorphics, unnamed mafic rocks and Mesoproterozoic granites of the Forsayth and Forest Home Supersuites.

Etheridge Group

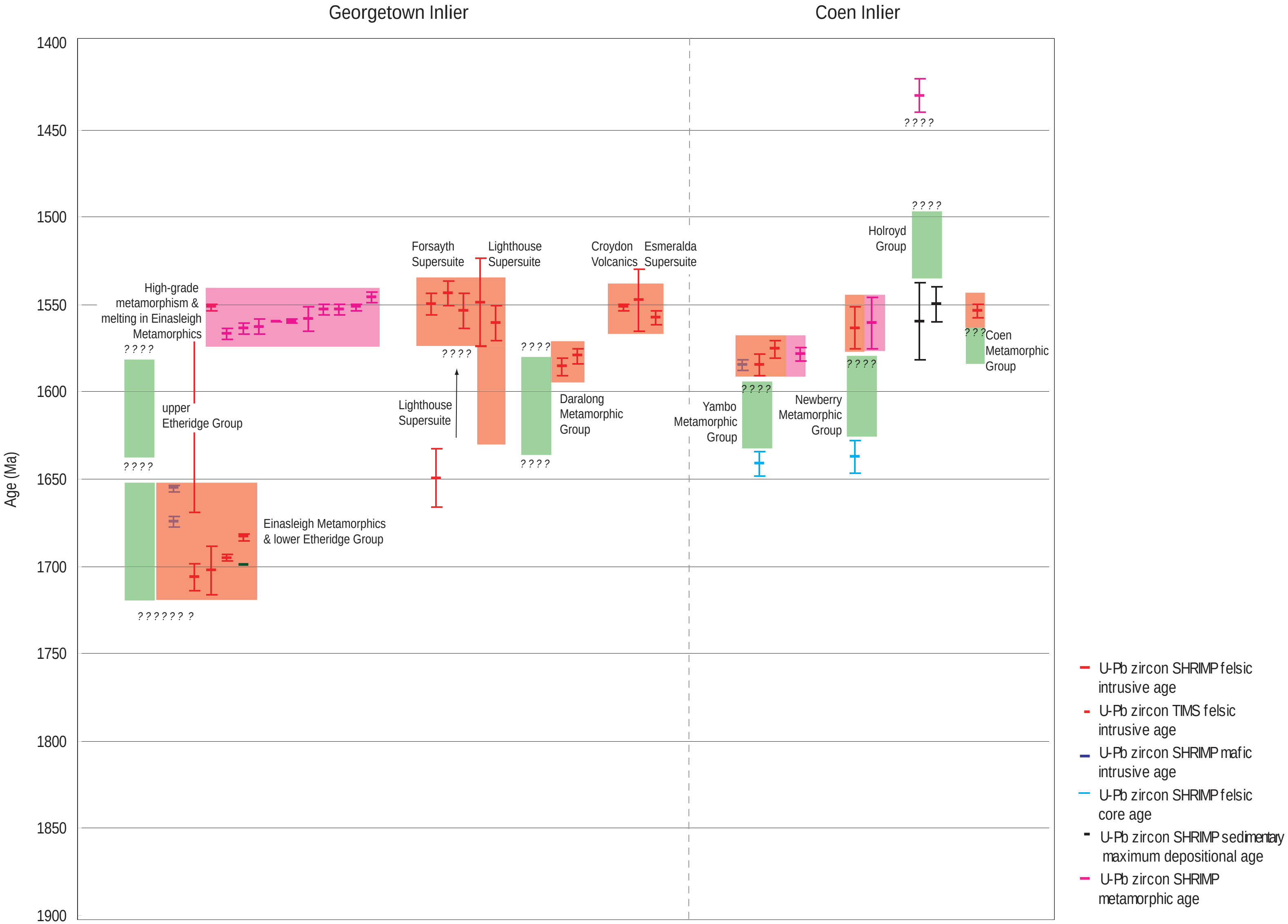
The Etheridge Group comprises a significant component of the Etheridge Province, and is interpreted to be at least 13km thick (Black et al., 1998). The metamorphic grade within the group increases eastward, but detailed stratigraphic correlations can be made in the low-grade rocks. The group includes a number of units and formations which have been separated into a lower and upper package. The base of the group is not exposed but suggested to be the Bernecker Creek Formation, although the Einasleigh Metamorphics may be stratigraphically lower (Withnall et al., 1997). Alternatively, the Einasleigh Metamorphics may be equivalent to the Bernecker Creek and Daniel Creek Formations, although the metamorphics contain leucogneiss, which has not been identified in low-grade equivalents (Withnall et al., 1997). The rest of the lower Etheridge Group includes the Daniel Creek Formation, Dead Horse Metabasalt, Corbett Formation and Lane Creek Formation, and are interpreted to represent an upward deepening basin package from shoreline to deep subtidal facies (Withnall et al., 1997).

The upper Etheridge Group includes stratigraphic units from the Townley Formation up to the Langdon River Mudstone, and is interpreted to represent, in general, a subtidal facies environment. Mafic rocks are common in the lower Etheridge Group, but have not been identified in the upper parts of the package.

The only age constraints for the development of the Etheridge Group come from dating of mafic bodies and granitic gneisses associated with this group and the Einasleigh Metamorphics. An amphibolite within the Einasleigh Metamorphics at Stockmans Creek records a U-Pb zircon SHRIMP age of 1675 ± 3 Ma and, based on stratigraphic correlations, suggests that mafics within the lower Etheridge Group also crystallised at that time (Black et al., 1998). There is also a U-Pb zircon SHRIMP crystallisation age of 1656 ± 2 Ma for a leucograbbro sill which intruded the Lane Creek Formation (top of the lower Etheridge Group) near Ironhurst, interpreted to approximate a depositional age for this part of the package. As indicated by Black et al. (1998), these two crystallisation ages are not within error, and suggest two periods of mafic magmatism associated with the lower Etheridge Group.

Granitic gneisses within the Einasleigh Metamorphics which are cross-cut by amphibolites have also been analysed from two locations (Black et al., 1998). Analysis of zoned zircons from a granite gneiss at Junction Creek North provides an age of 1684 ± 2 Ma, which is interpreted to represent crystallisation of the granitic precursor of this gneiss. The other sample from near the Kaiser Bill prospect records a crystallisation age of 1696 ± 2 Ma, also interpreted to represent crystallisation of an igneous precursor (Black et al., 1998).

Figure 10 **(overleaf):** *Geochronological data and summary Time-Space plot for the Georgetown and Coen regions.*


Georgetown Inlier
Coen Inlier
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
High-grade metamorphism & melting in Einasleigh Metamorphics
upper Etheridge Group
Einasleigh Metamorphics & lower Etheridge Group
Forsayth Supersuite
Lighthouse Supersuite
Lighthouse Supersuite
Daralong Metamorphic Group
Croydon Volcanics
Esmeralda Supersuite
Yambo Metamorphic Group
Newberry Metamorphic Group
Holroyd Group
Coen Metamorphic Group
U-Pb zircon SHRIMP felsic intrusive age
U-Pb zircon TIMS felsic intrusive age
U-Pb zircon SHRIMP mafic intrusive age
U-Pb zircon SHRIMP felsic core age
U-Pb zircon SHRIMP sedimentary maximum depositional age
U-Pb zircon SHRIMP metamorphic age

A felsic leucogneiss from the Einasleigh Metamorphics southwest of the Lynd Homestead has a U-Pb SHRIMP zircon age of 1707 ± 8 Ma which is interpreted to represent igneous crystallisation ages of the gneiss precursor (Black et al., 2005). Low Th/U zircons from this sample also record a younger age, associated with recrystallisation (see below). A similar rock-type from south of the Lyndhurst Homestead has a U-Pb SHRIMP zircon age 1703 ± 14 Ma, which is interpreted to record the crystallisation of this zircon, and, again, there is later recrystallisation of some grains (Black et al., 2005). A number of other leucogneisses from this region were also sampled during the study by Black et al. (2005), but these samples recorded a range of provenance ages as well as younger recrystallisation ages, and so a single crystallisation age was not reported for these samples. A felsic gneiss from the Daniel Creek Formation records a detrital zircon spectra with main age populations at about 1770 Ma, 2000-1900 Ma and 2600 Ma (Black, OZCHRON). When combined, these age constraints suggest deposition of the Einasleigh Metamorphics (and by correlation the lower Etheridge group) from ~1700 Ma to ~1655 Ma.

The Etheridge Group and Einasleigh Metamorphics were deformed, metamorphosed and intruded by granites (see below) between ~1560-1550 Ma. Regional metamorphic grade changes from lower greenschist facies in the southwest to granulite facies in the northeast. This metamorphism is recorded by zircon recrystallisation and rim growth within samples from the Einasleigh Metamorphics, with U-Pb SHRIMP ages ranging between 1568 ± 5 Ma and 1546 ± 3 Ma (Black et al., 2005; Black, OZCHRON). Another sample from the Einasleigh Metamorphics records a SHRIMP zircon U-Pb age of 1552 ± 2 Ma from grains that are interpreted to be of igneous origin, and are believed to have formed in situ in partial melts related to nearby pegmatites (Black et al., 2005).

Langlovale Group

The Langlovale Group unconformably overlies the Etheridge Group in the western Etheridge Province, and is overlain by the Croydon Volcanics. The group includes the Malacura Sandstone, which is interpreted to be deposited in a fluviatile environment, and Yarman Formation, which is suggested to represent turbiditic facies associated with a prodeltaic system (Withnall et al., 1997). There are no geochronological age constraints on the timing of deposition of this package.

McDevitt Metamorphics

The McDevitt Metamorphics comprise laminated to thin-bedded metapelites and subordinate meta-arenite, quartzite and mafic sills (Withnall et al., 1997). There are no geochronological age constraints for the McDevitt Metamorphics, but they are suggested to correlate with either the Etheridge or Dargalong Metamorphics Groups.

Forsayth Supersuite

The Forsayth Supersuite comprises peraluminous S-type granites, dominated by grey porphyritic biotite-muscovite granite (Bain and Champion, in Withnall et al., 1997). The suite includes the Aura, Delaney, Forsayth, Goldsmith, Mistletoe and Ropewalk granites, plus the Welfern Granite to the south. Other granites including the Mount Hogan, Fig Tree, and Mywyn Granite, and parts of the Digger Creek Granite are also probably part of this supersuite.

There are a number of U-Pb zircon multi-grain TIMS ages for granites from this supersuite: 1550 ± 6 Ma for the Forsayth Granite, and 1544 ± 7 Ma for the Mistletoe Granite which was derived from 3 of the 6 fractions with excess scatter (MSWD = 40) due to inheritance (Black and McCulloch, 1990). The U-Pb SHRIMP zircon age for a pink medium-to coarse-grained biotite granite from the Mount Hogan Granite is 1549 ± 25 Ma (Black, OZCHRON). A coarse pink garnetiferous muscovite sample from the Digger Creek Granite has a U-Pb SHRIMP zircon age of 1554 ± 10 Ma (Black, OZCHRON).

Lighthouse Supersuite

These small irregular-shaped gneissic to pegmatitic, garnetiferous, biotite-muscovite granites crop out along the eastern margin of the Forsayth Batholith. They were separated from the Forsayth Supersuite, as their geochemical signature suggests closer affinities with I-type Silurian granites in the region (Champion, 1991). Initial U-Pb zircon multi-grain TIMS analysis on a sample from the Lighthouse Granite contained a significant proportion of inheritance (Black and McCulloch, 1990). SHRIMP analysis of rims and single-phase zircon grains from this sample yields an age of 1561 ± 10 Ma, with rounded cores ranging in age from 1561 ± 10 Ma to more than 3100 Ma (Black, OZCHRON).

Forest Home Supersuite

This supersuite includes the Forest Home Trondhjemite, which crops out in the Black Gin Creek area, and Talbot Creek Trondhjemite, which occurs on the western side of the Newcastle Range. The Forest Home Trondhjemite is a medium- to fine-grained biotite trondhjemite and records no evidence of deformation, whereas the Talbot Creek Trondhjemite is equigranular, medium-grained muscovite-biotite leucotrondhjemite containing a weak foliation (Mackenzie in Withnall et al., 1997). SHRIMP zircon U-Pb analysis of the Forest Home Trondhjemite indicates that the majority of zircons have rounded cores of xenocrystic or restitic origin, which range in age from 2500 Ma to 1600 Ma. However, 19 of these cores have an age of 1650 ± 17 Ma, which is an older age limit for emplacement (Black, OZCHRON).

Yambo Subprovince

The Yambo Subprovince includes the Dargalong Metamorphic Group and occurs in the northern part of the province. The Dargalong Metamorphic Group comprises banded migmatitic gneiss, augen gneiss, amphibolite, with schist, quartzite and minor calc-silicate gneiss, and are suggested to be deposited after 1640 Ma (Withnall et al., 1997). Two mylonitised granodioritic to tonalitic gneisses from the Dargalong Metamorphics have been analysed for U-Pb zircon SHRIMP geochronology (Blewett et al., 1998). Zircon morphologies from both samples suggest an originally igneous zircon population which has been significantly modified by high-grade metamorphism. One sample (92836561) records an age of 1586 ± 5 Ma from zoned zircon grains and the other (92836559) provides an age 1580 ± 4 Ma. Both ages are interpreted to record crystallisation of the igneous precursor of these gneisses (Blewett et al., 1998).

The Halls Reward Metamorphics and mafic/ultramafic complexes occur further east in the Georgetown region, although the nature of their relationship with the Etheridge Province is unknown. There are no geochronological age constraints for these rock units.

Croydon Volcanic Group

In the western Georgetown Region, the Croydon Province comprises S-type Croydon Volcanic Group and granites of the Esmeralda Supersuite. The Croydon Volcanic Group includes rhyolitic ignimbrite and lesser porphyritic rhyolite with flow banding. There is also dacitic ignimbrite, quartzo-feldspathic sandstones and siltstones and minor andesite (Withnall et al., 1997). The group is estimated to be at least 1100-1500 m thick, and interpreted to be associated with a subaerial eruption. Geochronological age constraints for the Croydon Volcanic Group include a U-Pb zircon multigrain TIMS age for the Idalia Rhyolite of 1552 ± 2 Ma (Black and McCulloch, 1990), with the authors noting the presence of cores within the zircon separate. The same sample was analysed using SHRIMP techniques, yielding a crystallisation age of 1548 ± 18 Ma (Black and Withnall, 1993).

Esmeralda Supersuite

This supersuite crops out in the westernmost part of the Georgetown region and intruded the Croydon Volcanic Group, and the upper Etheridge and Langlovale Groups. Most units are coarse-grained biotite granite, have a S-type composition, and are characterised by high-carbon content (Withnall et al., 1997). A sample from the supersuite has a U-Pb zircon multi-grain TIMS age of 1558 ± 4 Ma (Black and McCulloch, 1990).

Inorunie Group

The Inorunie Group overlies the Croydon Volcanic Group and is preserved in a small partly fault-bounded basin (Withnall et al., 1997). The group includes four formations and consists of sandstones, siltstones and mudstones, possibly deposited in a fluviatile environment. The age of the group is unknown and could be Mesoproterozoic, Neoproterozoic or early Palaeozoic.

Known mineralisation and resources

Details regarding the characteristics of mineralisation in the Georgetown Region can be found in Denaro et al. (in Withnall et al., 1997) and include:

- Plutonic gold-quartz veins in the Croydon Province
- Polymetallic gold-quartz veins in the Etheridge Province
- Disseminated replacement gold deposits (Carlin-style) in the Etheridge Province
- Base-metal deposits in the Einasleigh Metamorphics and Etheridge Group
- Shear-hosted copper deposits in the Halls Reward Metamorphics
- Tin deposits in the Esmeralda Granite and Croydon Volcanic Group
- Nickel-cobalt laterites from mafic/ultramafic rocks and the Etheridge Province.

The age of many of these deposits and resources is unknown.

Coen Region

The Coen region is dominated by a north-south grain, and has been divided into two main Proterozoic provinces by Blewett et al. (1997); the Yambo Subprovince and the Savannah Province. The Yambo Subprovince includes the Yambo and Newberry Metamorphic Groups, and the Savannah Province includes the Coen, Holroyd and Edward River Metamorphics. For this compilation, the geology and geochronology will be discussed according to these divisions.

Yambo Subprovince

Yambo Metamorphic Group

The Yambo Metamorphic Group comprises high-grade metasedimentary and meta-igneous rocks, and crops out in the southern part of the region. It is faulted again the Palaeozoic Hodgkinson Province to the east along the Palmerville Fault and against the Savannah Province to the south along the Gamboola Fault (Blewett et al., 1997; Blewett and Black, 1998). The group has been divided into thirteen metamorphic units, although their thicknesses and contacts are difficult to establish due to high metamorphic grade, intense deformation, and poor exposure. Their sedimentary protoliths are interpreted to be fine-grained, even-grained, thin-bedded clastic rocks accumulated in an intracontinental basin after ~1640 Ma (Blewett et al., 1997).

Geochronological constraints on the age of the Yambo Metamorphic Group include analyses from a two-pyroxene mafic granulite, which contains complex internal zircon zonation interpreted to represent different growth phases (Blewett et al., 1998). Analysis of zoned zircon yields an age of

1586 ± 4 Ma, interpreted to represent igneous crystallisation of the mafic igneous precursor of this granulite (Blewett et al., 1998). A medium- to coarse-grained sericite-garnet gneiss from the Arkara Gneiss (a unit within the Yambo Metamorphic Group) has igneous zircon grains significantly modified by metamorphism. U-Pb SHRIMP analysis of zoned zircons from this sample provides an age of 1585 ± 6 Ma (Blewett et al., 1998).

Zircons from a granodioritic gneiss of the Arkara Gneiss also have complex internal zones and rims. Analyses from the exterior zircon yield an age of 1576 ± 5 Ma and are interpreted to record high-grade metamorphism, but are within error of the age from 8 core analyses at 1581 ± 8 Ma, interpreted to measure the age of crystallisation of the protolith (Blewett et al., 1998). This sample also has an age group at 1636 ± 13 Ma from zircon cores, interpreted to record the age of inheritance within the magma (Blewett et al., 1998).

A crenulated mylonitic granitic gneiss from another unit within the Yambo Metamorphic Group (the Annie Creek Schist) has a complex spectrum of zircon ages. The oldest rims give an age of 1579 ± 4 Ma, which is interpreted to record metamorphic zircon growth (Blewett et al., 1998). In contrast, the youngest group of cores provide an age of 1642 ± 7 Ma, which is interpreted to represent the maximum depositional age for this unit, and of the group (Blewett et al., 1998).

Newberry Metamorphic Group

This group is similar to the Yambo Metamorphic Group and includes high-grade (upper amphibolite-granulite) metamorphic rocks, which crop out poorly along the southeastern side of the region (Blewett et al., 1997). Three mappable units and three unnamed units are described, but again the thickness and boundary relationships of the rock types is unknown. The protolith and depositional environment of sedimentary units is unknown, although thick-bedded massive quartzite near Mount Newberry is suggested to possibly represent near-shore conditions (Blewett et al., 1997).

Geochronological constraints on the age of this group comes from two felsic gneisses. The first sample (Black, OZCHRON) has a U-Pb zircon SHIRMP age of 1564 ± 12 Ma, which is interpreted to represent the age of the precursor of this gneiss. This is slightly younger than ages from the Yambo Metamorphic Group. In contrast, the age of 1561 ± 15 Ma from zoned igneous rims in the second gneiss sample is interpreted to possibly date in situ partial metamorphism. In this sample, the 8 youngest cores yield a combined age of 1638 ± 9 Ma (Black, OZCHRON).

Savannah Province

Holroyd Group

This group crops out along the western side of the Coen Region and is faulted to the west by the Cattle Swamp Shear Zone. It comprises medium-grained clastic sediments, with ten mappable units identified. The sequence is about 10 km thick, becomes more pelitic to the east, and is interpreted to be deposited in a shallow-marine environment in an intracontinental or foreland basin setting (Blewett et al., 1997). There are also small volumes of high-temperature mafic magmas in the lower part of the package which have a MORB-like geochemical signature. Unlike the Yambo and Newberry Metamorphic Complexes, orthogneiss is rare in this group.

A light-grey, very fine-grained, laminated slate from the Astrea Formation (one of the units within the group) has a zircon maximum depositional age of 1560 ± 22 Ma, with a wide range of older ages up to ~3300 Ma (Black, OZCHRON). A phyllite from the Holroyd Group has a maximum depositional age of 1550 ± 10 Ma, with other age groups at ~1593 Ma, ~1639 Ma, ~1696 Ma and ~1746 Ma, although the interpreter noted that, due to the small size of the grains, the relevance of these ages is uncertain (Black, OZCHRON). Zircon rims in gneiss from another unit within the Holroyd Group (the Strathburn Formation) provide an age of 1430 ± 10 Ma, interpreted to have formed in situ in this rock (Black, OZCHRON).

Edward River Metamorphic Group

The Edward River Metamorphic Group consists of fine-grained clastic sediments, similar to the lower part of the Holroyd Group (Blewett et al., 1997). It crops out along the western edge of the Coen Inlier, and adjoins the Holroyd Group along the Cattle Swamp Shear Zone. The group includes five named units, and three concealed units. There have been no detailed sedimentary studies of the group, but by analogy to the Holroyd Group, it is suggested to be associated with a shallow marine environment in an intercontinental setting. Metamorphic grade ranges from sub-greenschist to middle greenschist facies, with increasing grade to the northwest (Blewett et al., 1997). There are no geochronological constraints on the age of the Edward River Metamorphic Group, but they are interpreted to be equivalent to the Holroyd Group (<1563 and >1433 Ma; Blewett et al., 1997).

Coen Metamorphic Group

This group comprises mid- to upper-amphibolite facies schist, gneiss and lesser quartzite, of unknown thicknesses. The group includes four metamorphic units with uncertain boundary relationships. Most of the group is structurally and metamorphically simpler than the Yambo and Newberry Metamorphic Group, and does not include the characteristic orthogneiss or mafic granulite of the Newberry Metamorphic Group (Blewett et al., 1997).

A feldspathic gneiss from the group has zoned, igneous, outer parts of zircon grains which crystallised at 1554 ± 4 Ma (possibly in situ partial melting), and three generations of core are present at ~1585 Ma, ~1699 Ma and ~1770 Ma (Black, OZCHRON).

Sefton Metamorphics

This group contains a range of rock types including fine-grained schist and quartzite, slate/phyllite, greenstone, limestone, marble and calc-silicate rock. They crop out in four main areas: around Mount Carter, between Pascoe River and the Iron Range, headlands of Temple Bay and in the Bowden area. A metaconglomerate from the group has a maximum depositional age of ~1200 Ma (Blewett et al., 1998), and organic matter in a limestone sample suggests that some for the group may be Palaeozoic (Trail et al., in Blewett et al., 1997).

Known mineralisation and resources

Details regarding the characteristics of mineralisation in the Coen Region can be found in Blewett et al. (1997) and include:

- Gold-quartz vein mineralisation in Proterozoic metamorphic rocks associated with Phanerozoic granites
- Base-metal mineralisation in the Holroyd Group
- Gold, tungsten, molybdenum and base metals in the Sefton Metamorphics.

The age of many of these deposits and resources is unknown.

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

Depositional age and nature of sedimentary units

The age of many sedimentary groups within both the Georgetown and Coen Regions are currently unknown; including the Langlovale Group, McDevitt Metamorphics, Inorunie Group, Edward River Metamorphic Group and Sefton Metamorphics. An integrated program of geochronology and basin analysis on these packages may permit closer correlations with the established stratigraphy (either Proterozoic or Phanerozoic). Also, the age of the upper Etheridge Group and the duration and significance of the break between this and the lower part of the package is unknown. This may also

permit a more detailed interpreted of the tectonic setting of these systems, their potential for mineralising systems (e.g. Broken Hill style Pb-Zn-Ag) and their relationship with the development of the Isa Superbasin of the Mount Isa Inlier to the west.
The age and characteristics of the Halls Reward Metamorphics, and their relationship to the Etheridge Province could be established through more detailed geochronological and stratigraphic work.

Age and characteristic of subprovince boundaries

Many of the groups within the Georgetown and Coen Regions record variations in metamorphic grade, suggesting major structural breaks between packages. Currently there are no isotopic data on the timing or duration of the structures which separate these groups. Ar-Ar data in the literature for the area only records Neoproterozoic and Phanerozoic thermal histories (Spikings et al., 2001).

Age of mineral systems

Currently the timing and duration of mineral systems in the regions using isotopic methods has not been undertaken, apart from relative timing associated with field relationships. Given the spatial overlap between Proterozoic and Phanerozoic magmatism, sedimentation, metamorphism and deformation within the Georgetown and Coen regions, many of the mineral systems discussed above may be younger than time-period considered in this study.

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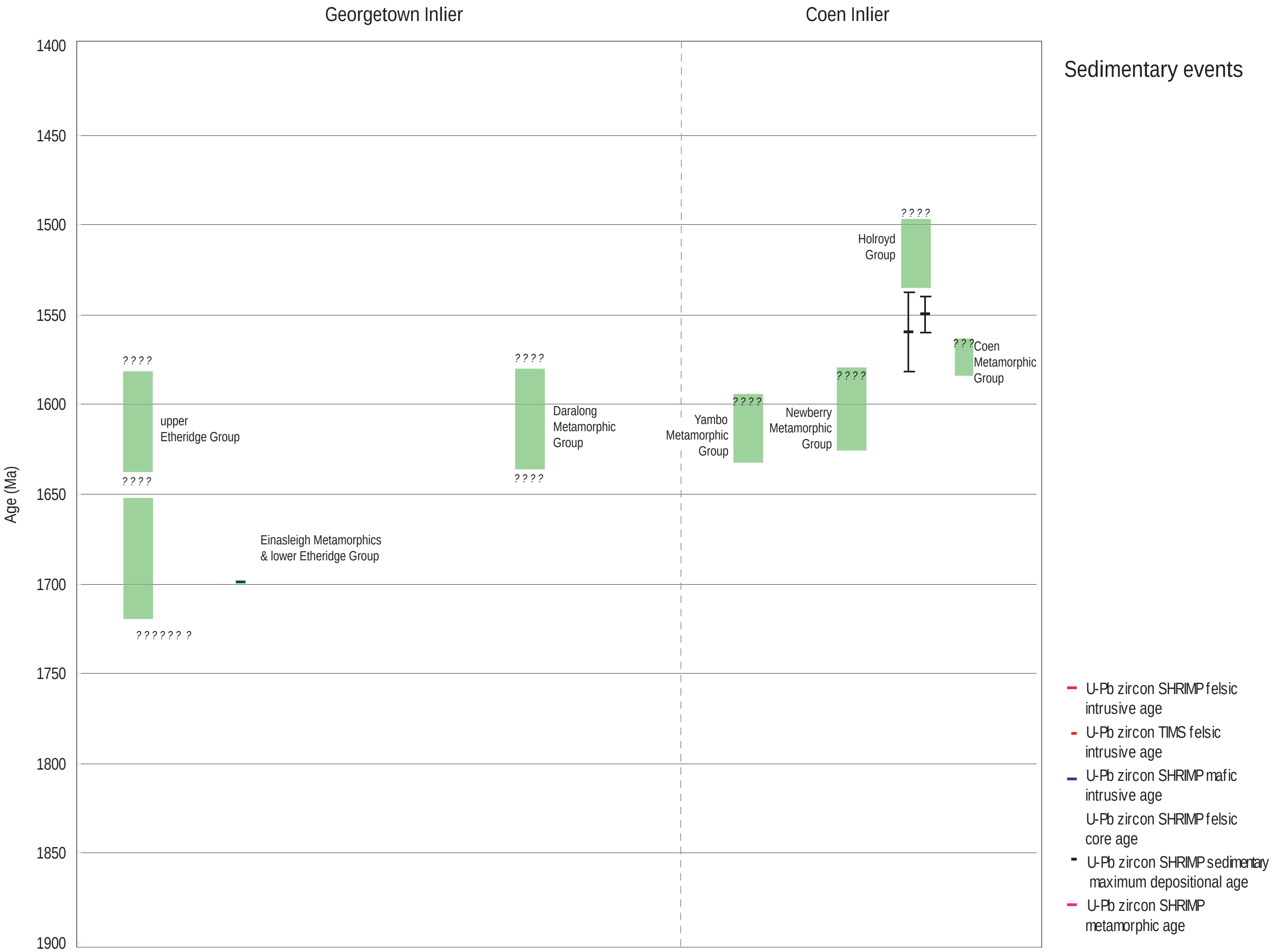
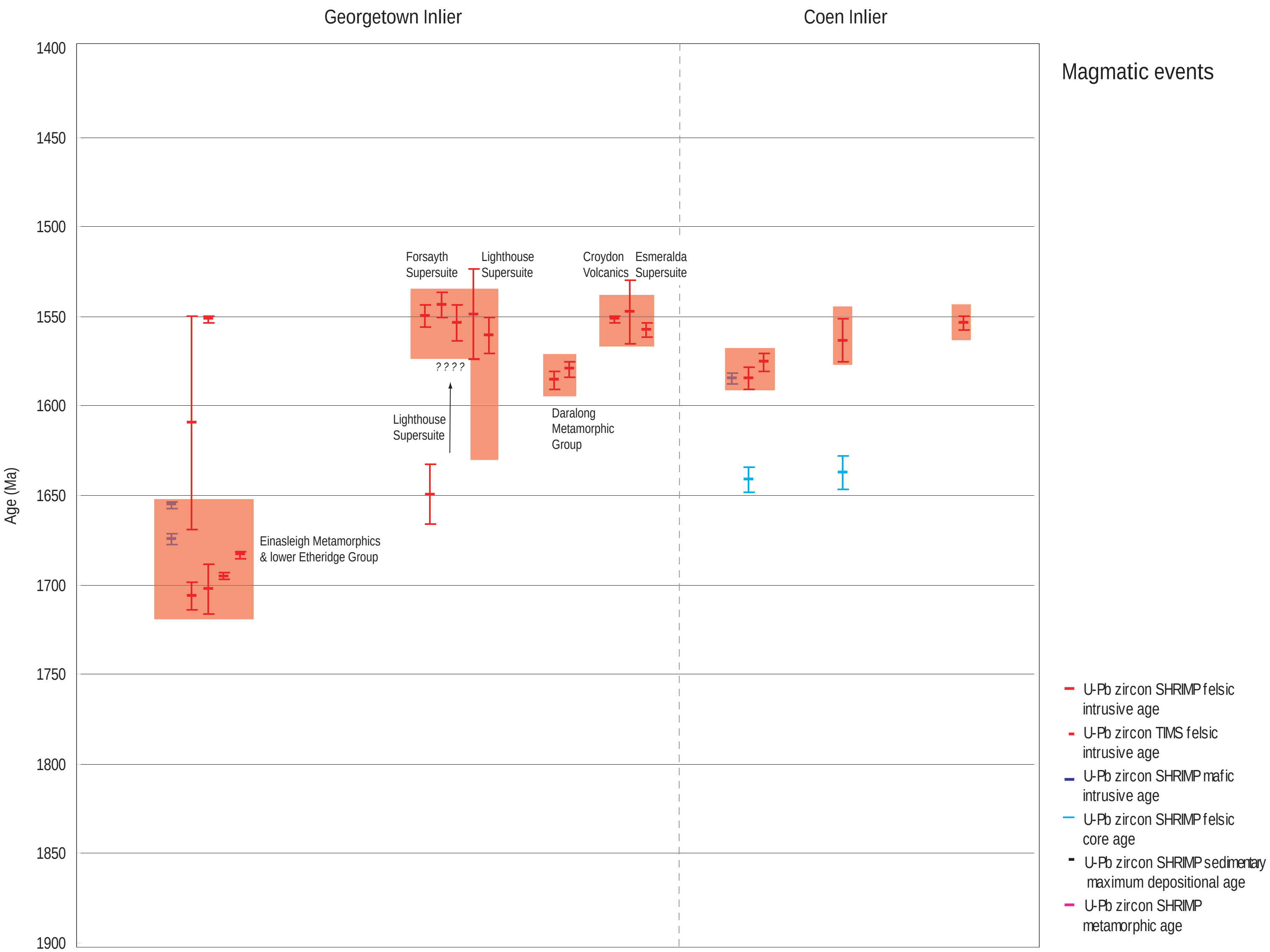
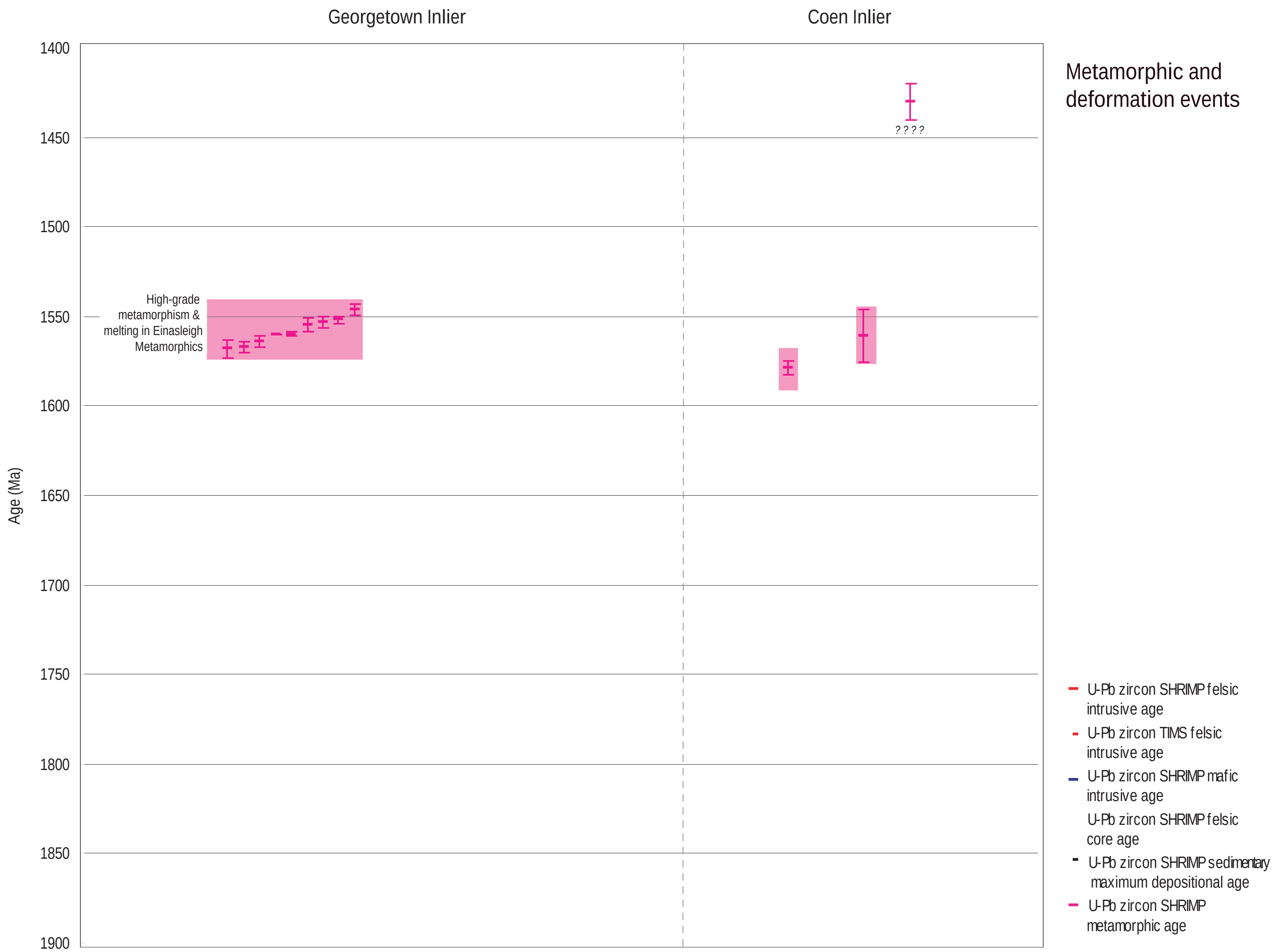

Georgetown Inlier
Coen Inlier
Sedimentary events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
upper Etheridge Group
Einasleigh Metamorphics & lower Etheridge Group
Daralong Metamorphic Group
Yambo Metamorphic Group
Newberry Metamorphic Group
Holroyd Group
Coen Metamorphic Group
U-Pb zircon SHRIMP felsic intrusive age
U-Pb zircon TIMS felsic intrusive age
U-Pb zircon SHRIMP mafic intrusive age
U-Pb zircon SHRIMP felsic core age
U-Pb zircon SHRIMP sedimentary maximum depositional age
U-Pb zircon SHRIMP metamorphic age


Georgetown Inlier
Coen Inlier
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Forsayth Supersuite
Lighthouse Supersuite
Croydon Volcanics
Esmeralda Supersuite
????
Lighthouse Supersuite
Daralong Metamorphic Group
Einasleigh Metamorphics & lower Etheridge Group
U-Pb zircon SHRIMP felsic intrusive age
U-Pb zircon TIMS felsic intrusive age
U-Pb zircon SHRIMP mafic intrusive age
U-Pb zircon SHRIMP felsic core age
U-Pb zircon SHRIMP sedimentary maximum depositional age
U-Pb zircon SHRIMP metamorphic age


Georgetown Inlier
Coen Inlier
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
High-grade metamorphism & melting in Einasleigh Metamorphics
????
U-Pb zircon SHRIMP felsic intrusive age
U-Pb zircon TIMS felsic intrusive age
U-Pb zircon SHRIMP mafic intrusive age
U-Pb zircon SHRIMP felsic core age
U-Pb zircon SHRIMP sedimentary maximum depositional age
U-Pb zircon SHRIMP metamorphic age

Time-Space evolution of the southern North Australia Craton

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OVERVIEW

The Arunta, Tennant and Tanami regions are among the most complex geological regions in Australia with a stratigraphic, igneous and tectonic history spanning the Palaeoproterozoic to the Palaeozoic (Figure 11). Prior to the mid-1990s the prevailing view of the tectonic evolution was a 'stabilist' view in which a single intact continent, stretching from the Arunta Region in the south to the Pine Creek Region in the north, was affected by synchronous intraplate processes (e.g. Etheridge et al., 1987). More recently tectonic models have invoked plate boundary processes analogous to modern systems (e.g. Myers et al., 1996; Betts et al., 2002). Clearly, detailed correlations substantiated by isotopic dating are fundamental to constraining this understanding.

Prior to this investigation, the regional event framework rested on the Arunta Region review by Collins and Shaw (1995), U-Pb and Ar/Ar dating in parts of the Tennant Region by Compston (1995), and relatively sparse dating coverage elsewhere in the Tanami and Tennant Regions. The knowledge base was dominated by younger systems which overprinted the Palaeoproterozoic rocks and early attempts to unravel the pre-1700 Ma evolution with SHRIMP U-Pb dating had not yet identified all of the major event systems and their scope. Post-1995 the increasing usage of cathodoluminescence (CL) to target specific zircon growth zones in SHRIMP U-Pb dating has led to the realisation that earlier dating had sometimes measured mixed ages. For this reason, the current review uses post-1995 CL-targeted SHRIMP U-Pb dating wherever possible, augmented by earlier dating studies where there is a lack of more recent work.

The Tennant, Tanami and Arunta regions comprise separate outcrop belts but this does not necessarily mean that they had separate evolutions and comprise distinct geological provinces. Myers et al. (1996) drew the southern boundary of their definition of the North Australian Craton to include the Arunta Region, whereas some subsequent authors (e.g. Scott et al., 2000) have regarded the metamorphosed and deformed Arunta 'belt' as possibly an orogen or mobile belt marginal to the craton, and suggested a boundary north of the Arunta Region. Correlations constrained by the new dating demonstrate northward continuity of the earliest evolution between much of the Arunta Region and the regions to its north: the major sector of the Arunta Region expressing this early continuity is now called the Aileron Province. The commonality is illustrated in the Time-Space plot by juxtaposing columns for the Aileron Province, Tennant Region and Tanami Region and clearly shows the shared evolution before ~1800 Ma. The main difference between the three regions is the local overprinting by later events which is largely confined to the Aileron Province. The Aileron Province combines the northern and central tectonic zones of the Arunta Region proposed earlier by Stewart et al. (1984).

Two fault-bound zones in the south of the Arunta Region do not share this common evolution. Stewart et al. (1984) had earlier proposed a distinct southern tectonic zone. The separate evolution has been confirmed by remapping and detailed isotopic dating and is now defined as the Warumpi Province, itself subdivided into the Haasts Bluff, Yaya and Kintore Domains (Scrimgeour et al., 2005). The Time-Space plot compares the Warumpi Province and Aileron Province evolutions.

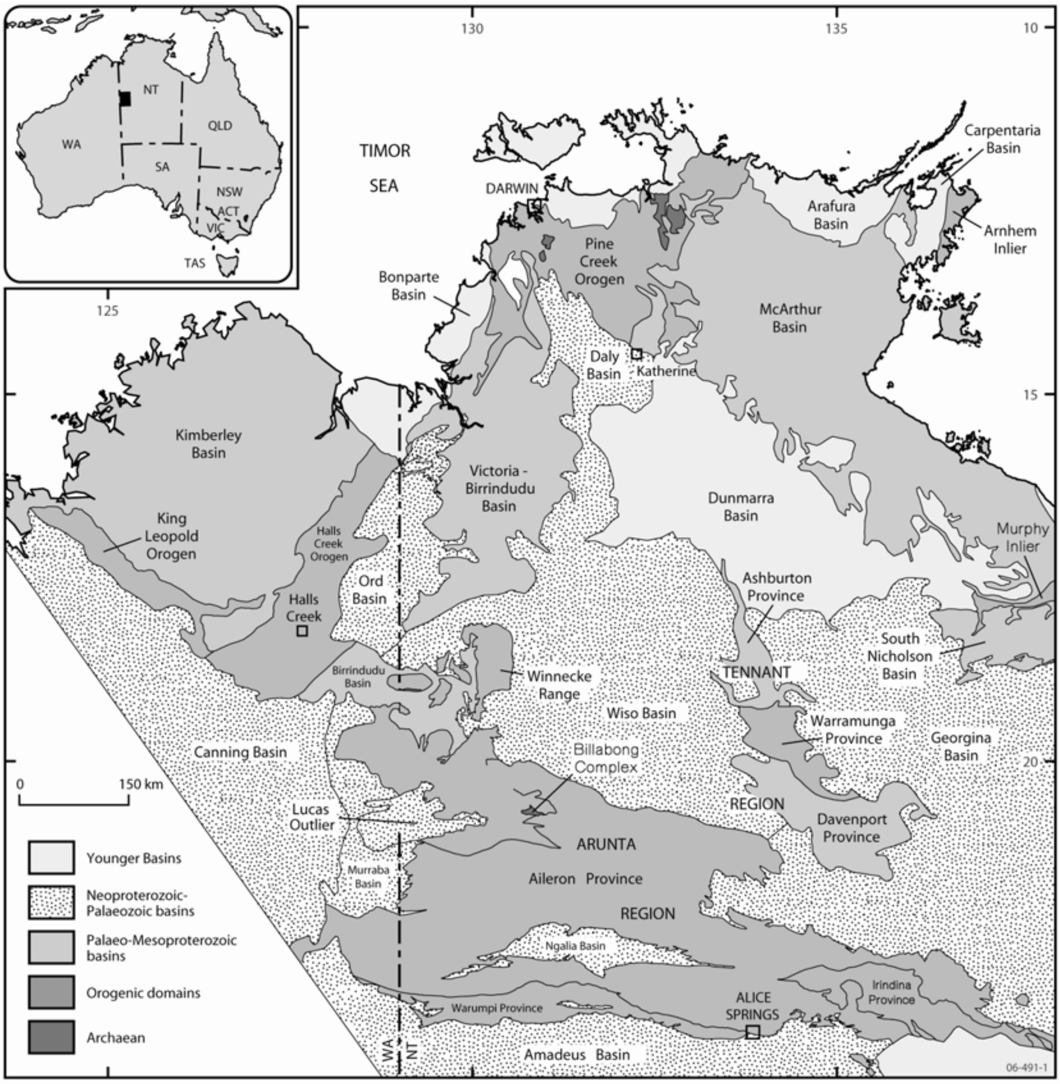


Figure 11: *Location and province divisions within the North Australia Craton.*

An unexpected discovery has been the recognition that high-grade metamorphic rocks in the Harts Range of the eastern Arunta Region are not Palaeoproterozoic, but represent Neoproterozoic and Palaeozoic successions metamorphosed in the Ordovician Larapinta Event (c.f. Scrimgeour, 2003). This fault-bound zone is now defined as the Irindina Province and its Neoproterozoic-Palaeozoic evolution is beyond the scope of this 1900-1500 Ma review.

The Time-Space plot for the Arunta-Tennant-Tanami Regions that accompanies this report (Figure 12) was produced from data available in September 2006. The major data source was the compilation by Huston et al. (2006), representing six years of study of these regions by Geoscience Australia and the Northern Territory Geological Survey within the 'North Australia' and 'Tanami' National Geoscience Accord Projects. These projects had a particular focus of isotopic dating accompanied by geophysical and geological remapping. The resulting isotopic dataset comprises nearly 300 U-Pb dates whose time-space construction was reviewed by Claoue-Long (2006), and a regional coverage of $^{40}Ar/^{39}Ar$ data overviewed by Fraser et al. (2006).

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Tennant Region

The key template for the early evolution is the Tennant Region where outcropping stratigraphic continuity is dated by intercalated volcanics and detrital zircons in sedimentary rocks.

Pre-1800 Ma

Three basin phases follow each other in rapid succession, separated by angular unconformities (Compston, 1995; Smith, 2001; Donnellan, 2005; Claoue-Long et al., 2005, Claoue-Long et al., in press b):

- **Basin Phase I:** Warramunga Group deep water sedimentary rocks and volcanics at ~1860 Ma;
- **Basin Phase II:** Ooradidgee Group bimodal volcanics and sedimentary rocks at ~1840 Ma; and
- **Basin Phase III:** Hatches Creek Group shallow-water sedimentary rocks and bimodal volcanics after ~1815 Ma.

Erupted volcanics in each successive basin phase are matched by the intrusion of subvolcanic plutons into underlying units, notably gabbros and granites intruding the Warramunga Group and correlatives of which many have been dated at ~1840-1855 Ma, and dolerites and granites intruding the Ooradidgee Group and correlatives at ~1810 Ma. The Time-Space diagram illustrates the prominence that has been given to dating the ~1850 Ma granite suite.

Detrital zircon ages in all three basin phases consistently infer basin development marginal to continental crust that was dominated by 1880-1850 Ma crystalline rocks.

The angular unconformity observed between Basin Phases I (Warramunga Group) and II (Ooradidgee Group) in the southern Tennant Region may not be present in the north where more continuity is mapped in the succession and the Flynn, Yunkulungu and Bernborough Groups have apparent deposition ages intermediate between ~1840-1860 Ma.

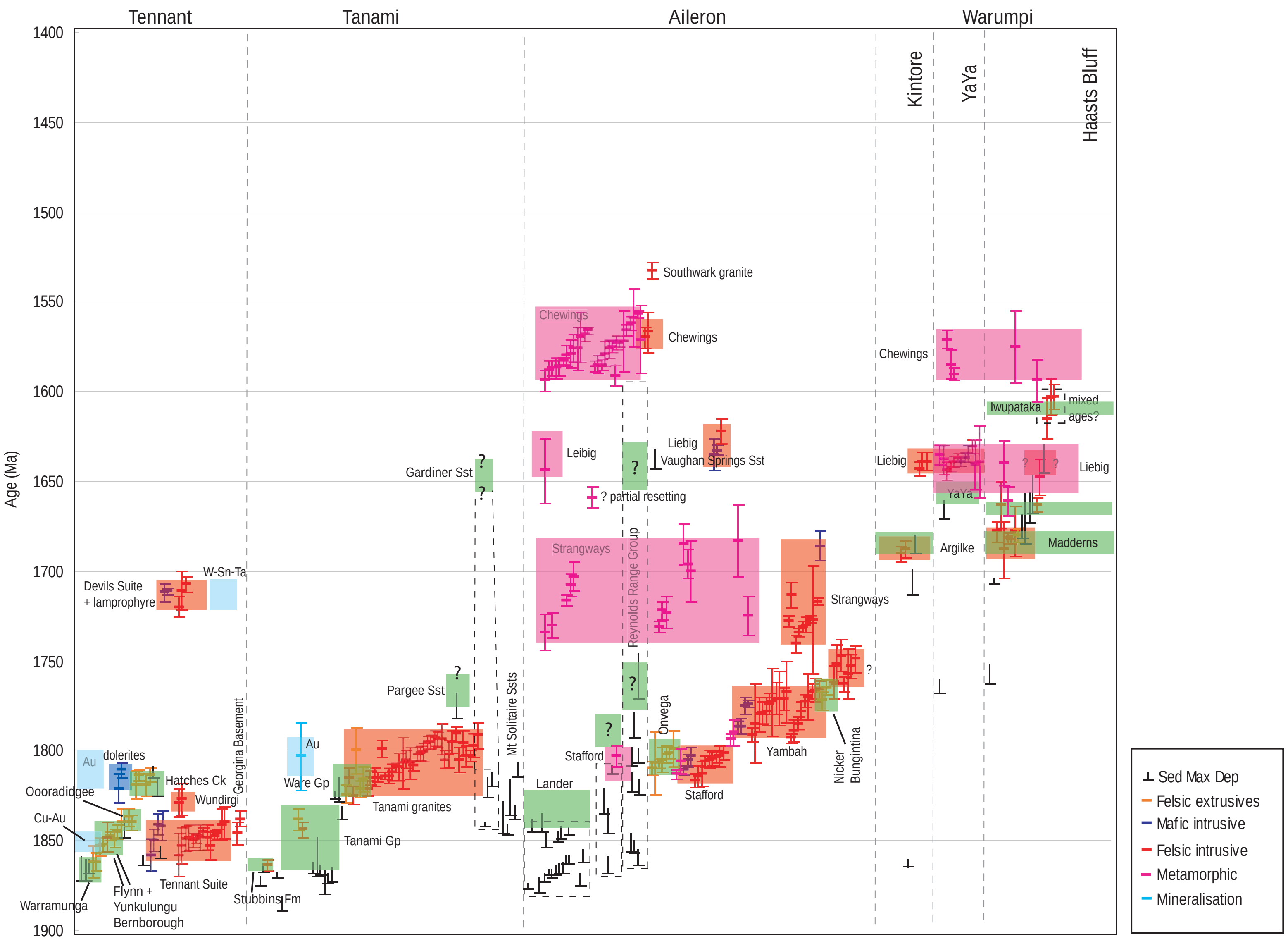
The first deformation of the Warramunga Group, the accompanying angular unconformity, and the thermal event registered by the Tennant Suite granites and minor gabbros, together define the ~1850 Ma Tennant Event. Later, undated, deformation at low metamorphic grade produced the distinctive ovoid folding pattern developed in Basin Phase III (Hatches Creek Group) sedimentary rocks.

Ar/Ar dating of sericites places the Tennant Region Cu-Au mineralisation within the Tennant Event (Compston, 1995; Fraser et al., 2006). A distinctly later phase of Au mineralisation is present in the Kurinelli goldfield which is hosted by Basin Phase II sedimentary rocks.

Post-1800 Ma

After a 100 Ma interval without recorded effects, Tennant region stratigraphy was still at shallow crustal depths (sub-greenschist facies) when it was intruded by ~1710 Ma Devils-Suite granites and mantle-derived lamprophyre dykes. The Time-Space diagram shows this shallow-level magmatism to be time-equivalent to the Strangways Event high grade metamorphism and magmatism in the Aileron Province several hundred km to the south. Tin-tungsten mineralisation in the south of the Tennant Region is associated with the ~1720 Ma Devils suite granites.

Figure 12 **(overleaf):** *Geochronological data and summary Time-Space plot of the southern North Australia Craton.*



Tennant
Tanami
Aileron
Warumpi
Kintore
YaYa
Haasts Bluff
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Southwark granite
Chewings
Chewings
Chewings
Iwupataka
mixed ages?
Leibig
Liebig
Vaughan Springs Sst
Gardiner Sst
? partial resetting
Liebig
Liebig
YaYa
Argilke
Madderns
Strangways
Reynolds Range Group
Strangways
Devils Suite + lamprophyre
W-Sn-Ta
Pargee Sst
Mt Solitaire Ssts
Önvega
Yambah
Nicker
Bungintina
Stafford
Stafford
Lander
Au
dolerites
Hatches Ck
Oooradidgee
Wundirgi
Cu-Au
Georgina Basement
Au
Ware Gp
Tanami granites
Tanami Gp
Warramunga
Flynn + Yunkulungu Bernborough
Tennant Suite
Stubbins Fm
Sed Max Dep
Felsic extrusives
Mafic intrusive
Felsic intrusive
Metamorphic
Mineralisation

Tanami Region

Pre-1900 Ma

The Tanami region preserves evidence of the presence of small areas of late Archaean basement, either under the region or nearby. Certain intrusions and some sedimentary units are dominated by ~2500 Ma inheritance, probably locally derived. Outcrops of granite and orthogneiss in the De Bavay Hills in the southeast Tanami Region ("Billabong Complex") contain late Archaean zircons (Page et al., 1995) which could be similar inheritance or could identify a remnant Archaean inlier.

1900-1800 Ma

Stratigraphic and isotopic dating constraints are patchy in the poorly outcropping Tanami Region where unconformity surfaces are yet to be delineated, but an evolution closely similar to the Tennant Region can be constructed from recent evidence (Cross and Crispe, 2007).

The earliest stratigraphic constraint of ~1860 Ma for the Stubbins Formation is identical to that of Tennant region Basin Phase I (D. Maidment, unpublished). Detrital zircon ages in the widespread Killi Killi Formation sandstones, and an interpreted tuff age of ~1840 Ma in the underlying Dead Bullock Formation, together support correlation of the Tanami Group with Tennant Region Basin Phase II (Cross and Crispe, 2007). Dated bimodal volcanics and maximum deposition ages from detrital zircons in sandstones link the Tanami region Ware Group with Tennant region Basin Phase III (Smith, 2005).

The Time-Space diagram shows the prominence that has been given to dating Tanami Region granites (c.f. Smith, 2001), all of which intruded ~1820-1795 Ma, broadly coincident with the development of Basin Phase III and coeval with the late bimodal magmatism in the Tennant Region.

Limited U-Pb dating evidence suggests that the major Tanami Region gold mineralisation, which is hosted in Tanami Group sedimentary rocks, occurred late during the thermal event represented by the ~1820-1790 Ma Tanami granites.

Post-1800 Ma

The Tanami region also preserves components of younger basins, including the Pargee Group, itself overlain by the basal Birrindudu Group of the north Australian Platform Cover (Victoria-Birrindudu Basin). Detrital zircons as young as ~1760 Ma in Pargee Group sandstone (Cross and Crispe, 2007) require this unit to have been deposited long after deposition of the earlier stratigraphy and the intrusion of the ~1820-1790 Ma Tanami granites. The opening phase of the Birrindudu basin (Gardiner Sandstone) is not dated directly, but the overlying Limbunyah Group is dated at ~1635 Ma by intercalated volcanics (Smith, 2001), so it is probable that this basin phase commenced after ~1700 Ma.

Ar/Ar ages in Tanami region granites are consistent with regional cooling after their ~1820-1795 Ma emplacement. Later thermal overprinting is registered cryptically, in the form of ~1700-1730 Ma Ar/Ar ages for micas in certain vein systems (Fraser, 2003), coeval with the Aileron Province Strangways Event and shallow-level magmatism in the Tennant Region.

Aileron Province

As the Time-Space diagram makes clear, the Aileron Province has experienced significant overprinting by later thermal events which are not important in regions to the north.

Pre-1800 Ma

The earliest rocks of the Arunta region are widespread clastic sedimentary rocks collectively known as the Lander Package, which comprise more than 60% of the known outcrop. Before dating evidence became available, these sedimentary rocks were tentatively considered to correlate with

Tennant Region Basin Phase I (Warramunga Group). The Lander Package is deformed and overlain with a major regional angular unconformity by the Reynolds Range Group, which is preserved in keel-like synclines produced by a later deformation. Prior to recent dating the Reynolds Package was regarded as a possible correlative of the Tennant Region Hatches Creek Group (now Basin Phase III).

However, new dating coverage in the Aileron Province (e.g. Claoue-Long, 2003, Cross et al., 2004; Cross et al., 2005a,b,c; Claoue-Long and Edgoose, in press; Claoue-Long et al., in press a) has so far failed to identify Basin Phase I of the Tennant and Tanami regions. Detrital zircons regionally in the Lander Package correlate it instead with Basin Phase II, with a widespread prevalence of detrital zircons as young as ~1840 Ma, similar to the Tennant Region Ooradidgee Group and the Tanami Region Killi Killi Formation.

The earliest magmatic intrusions in the Lander Package are dated to the ~1810-1800 Ma Stafford Event (c.f. Claoue-Long and Hoatson, 2005). Magmatism older than ~1810 Ma is not known from the Aileron Province. The 1806 ± 6 Ma age of the anatectic Ngadarunga Granite, which is undeformed but includes enclaves of deformed Lander Package sedimentary rocks, constrains the earliest metamorphism and deformation of the Lander Package to the Stafford Event (Claoue-Long and Edgoose, in press).

The Ongeva Package in the east of the Aileron Province comprises marine sedimentary rocks and bimodal magmatism, much of it now granulite facies protoliths to the Strangways Metamorphic Complex. U-Pb zircon ages in the range ~1810-1800 Ma, for interpreted volcaniclastic protoliths, link these units to Basin Phase III and to the intrusion of ~1810-1800 Ma Stafford Event plutons in the earlier Lander Package (Hussey et al., 2005). This coeval volcanic-subvolcanic association is a link with the Basin Phase III sequence in both the Tennant Region (Hatches Creek Group) and Tanami Region (Ware Group) where bimodal volcanics in the supracrustal successions are similarly matched by coeval subvolcanic intrusions into the earlier Basin Phase II. The nature of any contact between the Lander and Ongeva Packages is obscure.

Post-1800 Ma

Locally within the Reynolds Range an enigmatic (so far unnamed) sandstone package, immediately below the regional unconformity, has been identified by detrital zircon ages as belonging to neither the Lander nor Reynolds Packages (Claoue-Long et al., in press a). Originally mapped as Lander Rock Formation, detrital zircons as young as ~1790 Ma constrain its deposition to postdate the 1810-1800 Ma Stafford Event plutons that intrude the Lander Package, so it potentially postdates the Ongeva Package and Basin Phase III.

The stratigraphic position and regional significance of the Reynolds Package of sedimentary rocks, preserved as inliers in the keels of major synclines, is not clear. The base of the package overlies the regional unconformity and the unnamed sandstones noted above. Detrital zircons in the basal Mount Thomas Quartzite are as young as ~1800 Ma and permit the unit to correlate higher than Basin Phase III, to one of the several younger sedimentary systems seen elsewhere (Claoue-Long et al., in press a).

The south Aileron Province is characterised by younger thermal activity not seen elsewhere. ~1780-1760 Ma granites and gabbros are widespread in a belt within 150 km of the southern margin. To some extent these are a timing continuum with 1810-1790 Ma magmatism further north and there is a sense of diachronous migration of a thermal system southwards, but a cluster of ages permits reference to a separate ‘Yambah’ thermal event. The preservation of a small ~1775-1765 Ma volcano-sedimentary belt in the southeast is evidence of local basin development at the same time (Scrimgeour, 2003).

Commencing at ~1740 Ma a restricted area in the southeast (Strangways Metamorphic Complex) experienced the Strangways Event, a major thermal and deformation system with a prolonged series of effects over 50 m.y. (Claoue-Long et al., in press c). Protoliths were buried to 10 kbar producing granulite facies rocks. Northwards the metamorphic grade becomes lower (amphibolite facies) with higher grade effects spatially associated with certain intrusions. Time equivalents in the Tennant region, distal from the Strangways Metamorphic Complex, are granite stocks and lamprophyre dykes emplaced in (sub)greenschist facies country rocks at shallow crustal levels. Cryptic ~1720 Ma Ar/Ar ages are present in micas in certain Tanami Region vein systems (Fraser, 2003). Termination of the Strangways Event at ~1690 Ma in the Ailerion Province coincided with the local intrusion of N-trending dolerite dykes.

Two further Aileron Province thermal episodes are restricted to the southern part and are shared with the fault-bound Warumpi Province to the south. There are two dated magmatic intrusions into Lander Package country rocks coeval with the Warumpi Province Liebig Event: the Andrew Young Hills Gabbro at ~1635 Ma; and the Ennugan Mountain Granite which has a similar age of ~1625 Ma. The ~1590 Ma Chewings Event is recorded as distinctive low-pressure/high-temperature metamorphism locally in the southeast Reynolds Range, together with local felsic magmatism; and as the age of a geographically widespread granite suite in the western Aileron Province.

Warumpi Province

The Warumpi Province is an east-trending 1690-1590 Ma terrane which extends for >500 km along the southwestern margin of the Arunta Region (Scrimgeour et al., 2005). It has been interpreted as an exotic terrane accreted onto the southern Aileron Province during the ~1640 Ma Liebig Event. The Warumpi Province has been subdivided into three domains that have differing protolith ages and structural and metamorphic histories, but which nevertheless share effects of the ~1640 Ma Liebig and ~1590 Ma Chewings Events. The domains are the amphibolite facies Haasts Bluff Domain in the south and west, the granulite facies Yaya Domain in the north, and the greenschist facies Kintore Domain in the west.

1700-1600 Ma

The earliest dated evolution within the Warumpi Province is the 1690-1660 Ma Argilke Event of voluminous felsic intrusive and extrusive magmatism in the Haasts Bluff Domain (Cross et al., 2004). This may represent a volcanic arc outboard of the Aileron Province. At ~1660 Ma parts of these protoliths may have been exposed because detritus with 1690-1660 Ma detrital zircons was shed into a basin, coeval with mafic magmatism, to produce the protoliths to the Yaya Metamorphic Complex.

The Liebig Event is interpreted by Scrimgeour et al. (2005) as oblique sinistral collision of the Warumpi Province onto the Aileron Province at ~1640 Ma. This process metamorphosed Yaya Domain protoliths to granulite facies and was accompanied by voluminous mafic and felsic magmatism. The Kintore Domain comprises 1690-1670 Ma granites and ~1630 Ma volcanics, deformed under greenschist facies conditions. The Liebig event in the Warumpi Province was synchronous with the intrusion of the large Andrew Young Hills Gabbro within the adjoining Aileron Province.

Exhumation of the Yaya and Haasts Bluff Domains is indicated by deposition of a sediment package at ~1630-1610 Ma, forming protoliths to the Iwupataka Metamorphic Complex.

Post-1600 Ma

The Yaya and Haasts Bluff Domains were subsequently subjected to amphibolite facies deformation and metamorphism during the 1590-1570 Ma Chewings Event, which produced no magmatism within the Warumpi Province, but was coeval with local magmatism and high-temperature/low-pressure metamorphism within the Aileron Province to the north.

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

The coverage of detailed geochronology in the Tennant, Tanami and Arunta Regions is at an early stage and many basic aspects of the geological framework remain unresolved. Major surprises remain possible, as witness the very recent recognition of Palaeozoic granulite facies gneisses in the newly-defined Irindina Province.

A fundamental unresolved issue is the nature and whereabouts of basement to the earliest sedimentary rocks that have been recognised in each region (Basin Phase I in the Tanami and Tennant Regions, Basin Phase II in the Arunta Region). Detailed research on the nature and age of the Billabong Complex in the southeast Tanami Region should establish whether these granitoid exposures are a rare (and valuable) exposure of late Archaean basement or represent Proterozoic rocks containing Archaean inheritance.

The deep seismic traverse across the Tanami Region presents targets for shallow drilling beneath the regolith to test basic stratigraphic and structural relationships between the basin packages that have been identified. Coupled with sampling for geochronology to identify sedimentary packages, the relationship between Basin Phases I and II in the Tanami Region can potentially be constrained, and lead to a geodynamic evolution of that region from the links between stratigraphic timing and imaged structures. The time-space understanding of the Tanami Region is constrained mostly by detrital zircon studies and by very few direct stratigraphic dates for intercalated volcanics, so a much more detailed coverage of geochronology is needed to support the relationships that have been proposed.

In the Arunta Region there exists no basic stratigraphic framework for the Lander Package sedimentary rocks, which comprise more than 60% of the exposure. This is owed in part to lack of outcrop and the complexities of deformation, but in some locations of the western Aileron Province the successions are little-metamorphosed and less deformed and potential exists to attempt primary stratigraphic studies.

A prominent stratigraphic and tectonic issue in the Aileron Province is the stratigraphic correlation of the Reynolds Range Group, which is preserved in keel-like synclines in the Reynolds Range and elsewhere, and of the regionally extensive unconformity that underlies it. In the absence of age determinations, the unconformity has long been supposed to be equivalent to the Tennant Event and the Warramunga Group - Hatches Creek Group unconformity in the Tennant Region, but, as described above, detrital zircon ages now question this view. This question is linked to the stratigraphic assignment of the newly-recognised unnamed sandstone sequence underlying the unconformity within the Reynolds Range, which may post-date the Stafford Event and could require the overlying Reynolds Package to be younger. A related question is the nature of the contact between the Lander Package (Basin Phase II) and Ongeva Package (Basin Phase III) in the Aileron Province, and the relationship of both Packages to small occurrences of later basin phases.

Of wider interest is the tectonic relationship, if any, between the different regions and provinces described here. This Time-Space construction points to broad time equivalence of the evolution in the now-separate Tanami, Arunta and Tennant Regions, but this does not imply direct correlations or a single geological system: these could be time-equivalent but separate evolutions. Further work on stratigraphic, lithological, geochemical and thermal correlations is needed to further test the basic equivalences that are indicated by geochronology alone. Apart from the relationship between these three regions, there are many other questions under this heading: the relationship, if any, between the Warumpi and Aileron Provinces during their development; the northward relationship, if any, between the Tennant/Tanami regions and the time-space evolution observed in Pine Creek; and the geographic extent of prominent thermal events such as the Strangways Event which appear to have resulted in different, but time-equivalent, effects in different places. Better understanding of all these issues is a prerequisite for constraining the tectonic environments that are represented.

Perhaps the most immediately rewarding future study that can be identified is adding detail and tighter precision to the basic geochronology framework now established in the Tennant Region. The benefits of low metamorphic grade, relatively uncomplicated deformation, relatively good exposure and stratigraphic continuity, with intercalated volcanics amenable to age dating, make this region a unique template in which to establish detailed timing control on the geological evolution. The recent realisation that time equivalence of both stratigraphy and thermal events can be recognised as far away as the Tanami and Arunta Regions mean that timing detail established in the Tennant Region may potentially constrain understandings elsewhere in regions that are more difficult to study.

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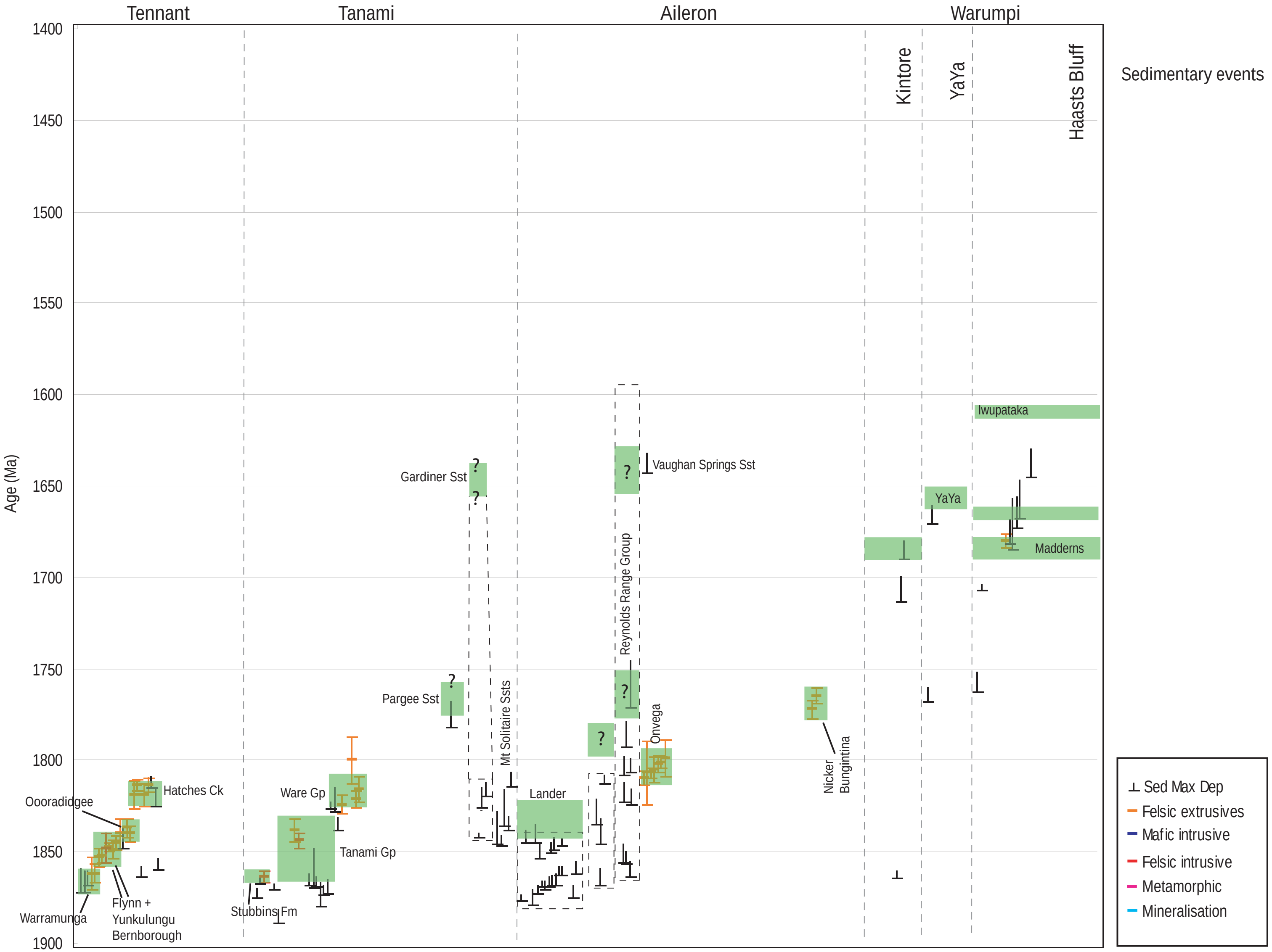
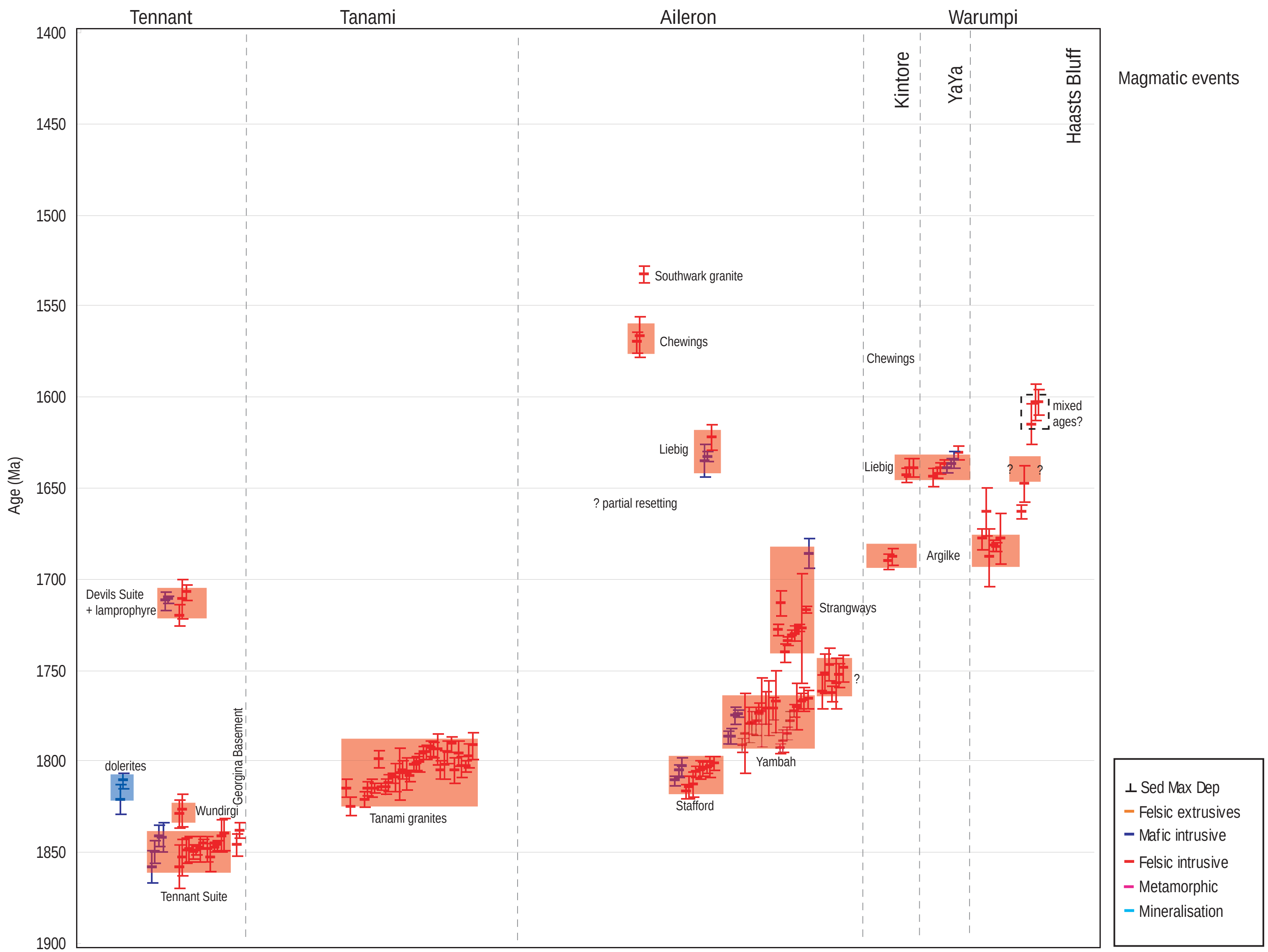
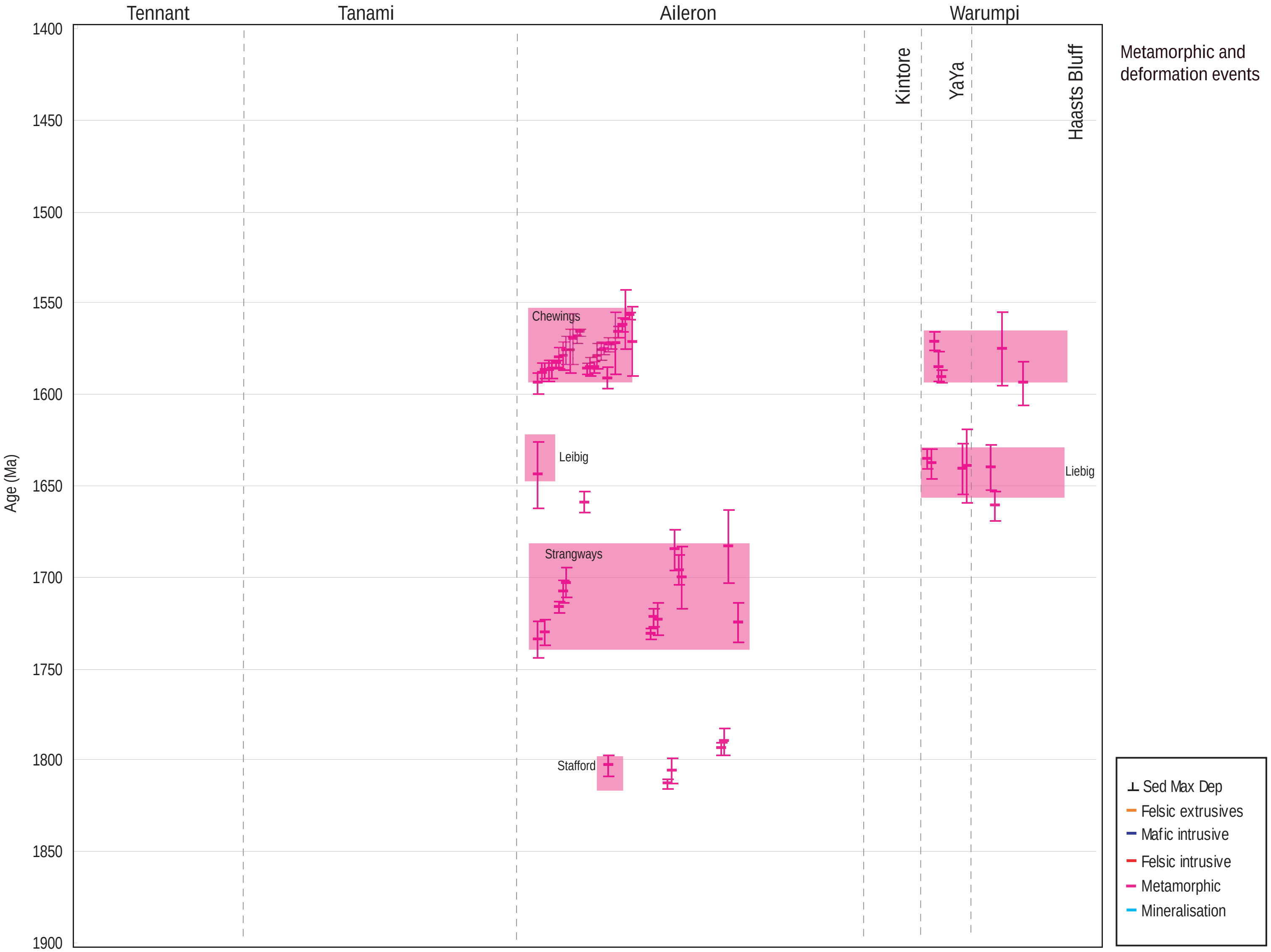
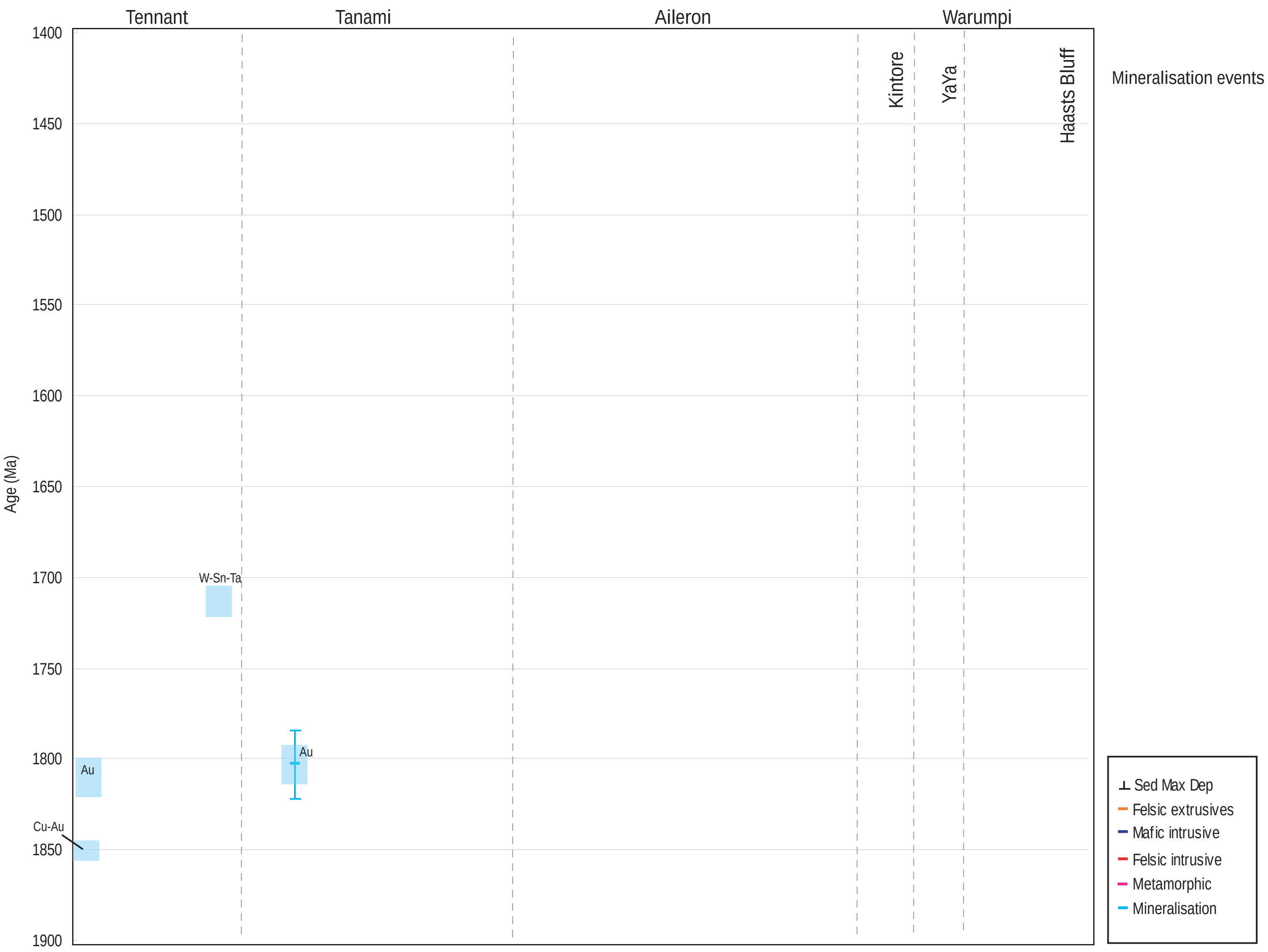


Tennant
Tanami
Aileron
Warumpi
Kintore
YaYa
Haasts Bluff
Sedimentary events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Iwupataka
Gardiner Sst
Vaughan Springs Sst
YaYa
Madderns
Reynolds Range Group
Pargee Sst
Mt Solitaire Ssts
Onvega
Nicker
Bungintina
Hatches Ck
Ooradidgee
Ware Gp
Lander
Tanami Gp
Stubbins Fm
Warramunga
Flynn +
Yunkulungu
Bernborough
Sed Max Dep
Felsic extrusives
Mafic intrusive
Felsic intrusive
Metamorphic
Mineralisation



Geochronological synthesis and time-space plots for Proterozoic Australia


Tennant
Tanami
Aileron
Warumpi
Kintore
YaYa
Haasts Bluff
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Chewings
Leibig
Strangways
Stafford
Liebig
Sed Max Dep
Felsic extrusives
Mafic intrusive
Felsic intrusive
Metamorphic
Mineralisation


Tennant
Tanami
Aileron
Warumpi
Kintore
YaYa
Haasts Bluff
Mineralisation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
W-Sn-Ta
Au
Au
Cu-Au
Sed Max Dep
Felsic extrusives
Mafic intrusive
Felsic intrusive
Metamorphic
Mineralisation

Time-Space evolution of the Pine Creek Orogen, northern McArthur Basin, and Arnhem Inlier

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OVERVIEW

The Pine Creek Orogen forms the northern margin of the North Australian Craton (Plumb, 1979). Broadly, it comprises sequences of carbonaceous, clastic, and volcanogenic sedimentary rocks deposited upon rifted Archaean crystalline basement, which were subsequently deformed, metamorphosed, and intruded by syn- to post-orogenic granitoids and mafic bodies (Figure 13). The Pine Creek Orogen forms basement to the siliciclastic and carbonaceous sedimentary and volcanic rocks of the composite Palaeoproterozoic-Mesoproterozoic platform cover of the McArthur Basin, which stretches from the north coast of Arnhem Land to the Mount Isa region. The Arnhem Inlier is unconformably overlain by the McArthur Basin stratigraphy, and is exposed at its north-eastern margin.

This chapter details the time-space evolution of the Pine Creek Orogen, the northern McArthur Basin, and the Arnhem Inlier during the interval 1900-1400 Ma, as plotted in the accompanying Time-Space plots (Figure 14). A brief description of the geological history not encompassed in this time interval is provided where applicable.

Domain subdivision

The Pine Creek Orogen can be divided into three distinct domains (Figure 13), reflecting different deformational, metamorphic, and stratigraphic attributes (e.g. Worden et al., in press). These are, from west to east: the Litchfield Province, the Central Domain, and the Nimbuwah Domain. The Litchfield Province-Central Domain boundary has been arbitrarily defined as passing along the western flank of the Rum Jungle Complex to the Giants Reef Fault. It follows the Giants Reef Fault, and includes rocks of the Wingate Plateau. Its southern boundary is aligned with the Victoria River Fault system. The Central Domain stretches east to the South Alligator River, and follows the Jim Jim Fault Zone in a southeast direction to include the South Alligator Valley region. The Nimbuwah Domain lies to the east and northeast of this zone, and is largely overlain by stratigraphy of the McArthur Basin.

The northern McArthur Basin includes sequences of sedimentary and lesser volcanic rocks, and is broadly subdivided into several elements: the Arnhem Shelf (which covers the Nimbuwah Domain and south-eastern parts of the Central Domain), the Walker Fault Zone, and the Caledon Shelf. It is bounded to the south by the east-west trending Urapunga Fault Zone in the vicinity of the Roper River. The Arnhem Inlier is exposed at the north-eastern margin of the McArthur Basin, north of the Caledon Shelf.

The stratigraphy of the McArthur Basin in each of these areas has been subdivided into the Superbasin terminology developed from the southern McArthur-Mount Isa region (e.g. Southgate et al., 2000; Jackson et al., 2000; Abbot and Sweet, 2000). This has been done to ensure continuity with the southern McArthur Basin-Murphy Inlier-Mount Isa Time-Space diagrams and accompanying discussion compiled by Neumann in this record.

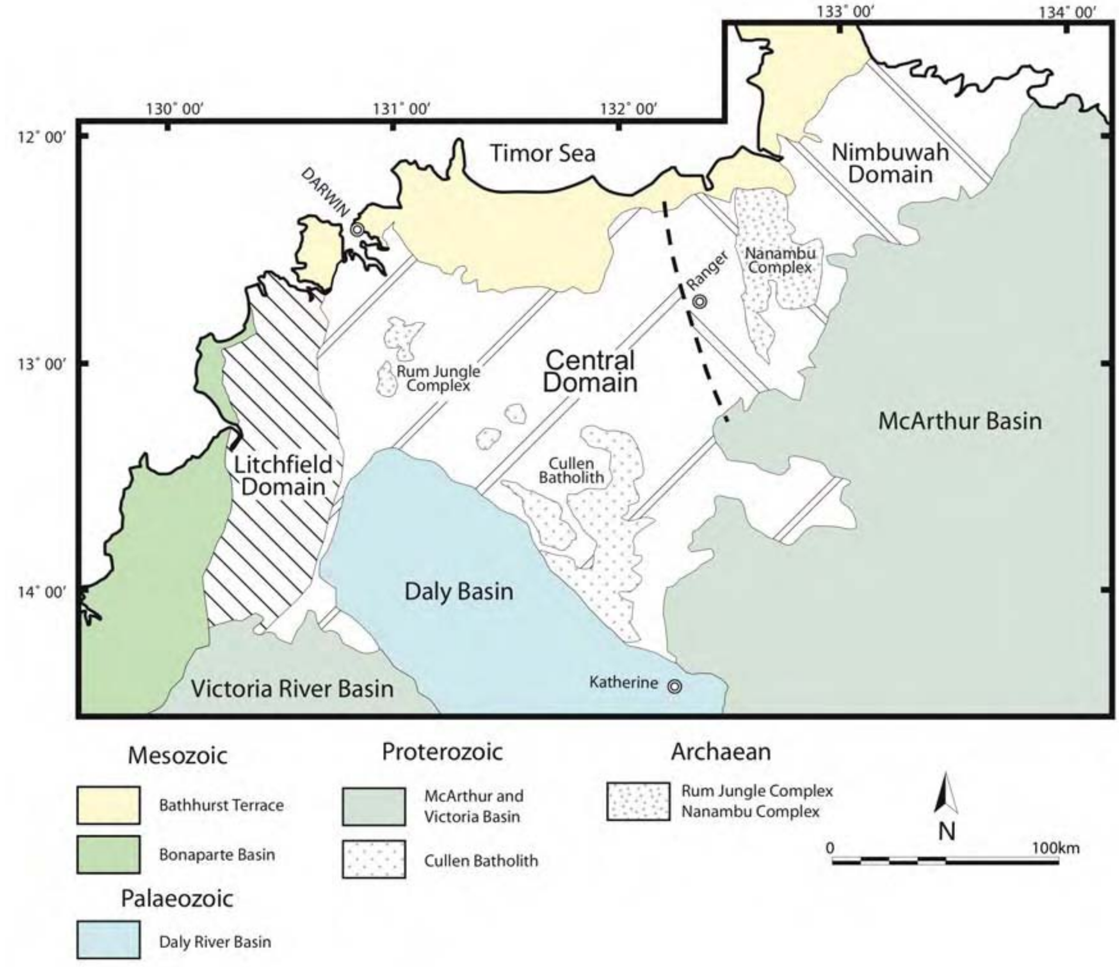


Figure 13: Domains and regional geology of the Pine Creek Orogen, northern McArthur Basin, and Arnhem Inlier (from Worden et al., in press).

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

The Litchfield Province

>1900 Ma

Archaean basement has not been detected in the Litchfield Province. Early stratigraphy includes graphitic siliciclastic and mafic volcanogenic sedimentary rocks of the Fog Bay Metamorphics, known only from drillcore. Among the initial isotopic age determinations for this region is a Rb-Sr whole-rock isochron age of 2002 ± 42 Ma (de Laeter 1983 in Hickey, 1985) for the Fog Bay Metamorphics, which may represent an early metamorphic episode (Carson et al., in press). This is a 'best fit' determination, and evidence exists for further resetting at 1792 ± 197 Ma (Hickey, 1985).

1900-1400 Ma

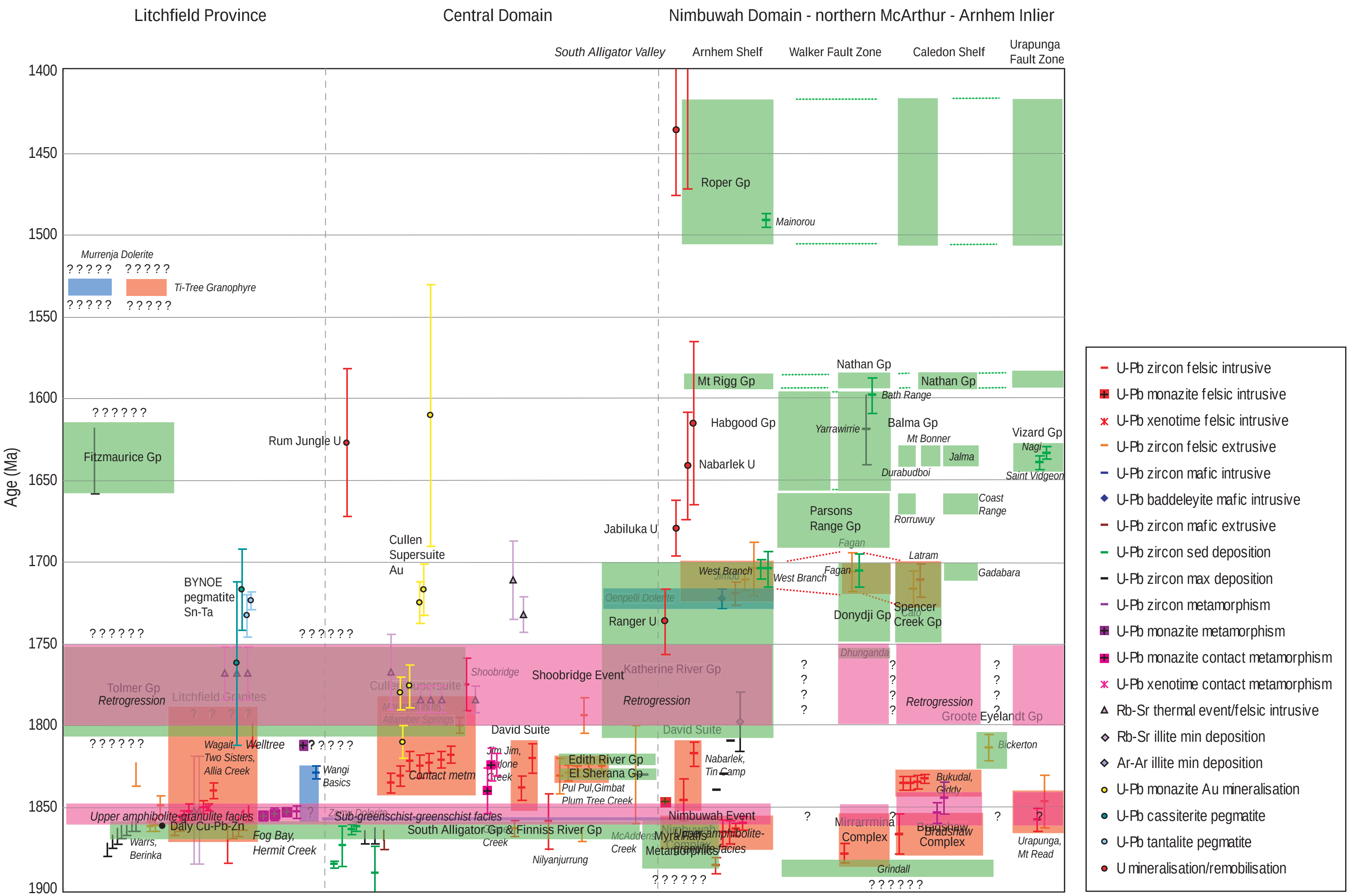
The semi-pelitic sedimentary and intercalated mafic igneous protoliths of the Hermit Creek Metamorphics and the psammopelitic-dominated protoliths of the Welltree Metamorphics, together with the predominantly turbiditic metasedimentary rocks of the Finniss River Group have maximum deposition ages between ca 1876-1861 Ma (Worden, et al. 2006a; Worden, et al. 2006b; Worden et al., in review). An unnamed volcanic within the Chilling Sandstone contains a largely inherited zircon population, with the youngest population at 1830 ± 7 Ma defining a maximum age of extrusion (Worden et al., 2006b). Included in the plot for comparison is a Halls Creek Group sample, collected from Keep River National Park (Worden et al., in review).

Lithostratigraphic correlations in the Litchfield Province are ambiguous given the lack of contiguous outcrop**.** Of the metasedimentary rocks mentioned above**,** Pietsch (1986) notes that the Welltree Metamorphics occur west of the Burrell Creek Formation in an apparent metamorphic gradational contact, and the two units are considered equivalent.

Following deposition of these units, the Litchfield Province was deformed, regionally metamorphosed, and intruded by a series of ca 1863-1806 Ma granites and mafic bodies. The oldest isotopically-dated granites in the Litchfield Province are the Wagait Granite and the Koolendong Granite, which have crystallisation ages of 1863 ± 4 Ma and 1860 ± 5 Ma respectively (Worden et al., 2006b; Worden et al., in review). This new age information is consistent with early Rb-Sr ages of 1852 ± 33 Ma for the Wagait Granite and Murra-Kamangee Granodiorite (Page et al., 1985). Contemporaneous felsic volcanics were extruded at the base of the Finniss River Group and include the Warrs Volcanic member and Berinka Volcanics, which have crystallisation ages of 1862 ± 3 Ma and 1861 ± 4 Ma respectively (Worden et al., in press).

A number of granitic rocks in the Litchfield Province have ca 1850 Ma emplacement ages. These include the Fish-Billabong Adamellite which intruded at 1850 ± 4 Ma (Worden et al., in review), an unnamed granite from FOG BAY interpreted to intrude the Fog Bay Metamorphics at 1855 ± 3 Ma (Worden et al., in review), and ca 1850-1840 Ma ID-TIMS emplacement ages determined for the Murra-Kamangee Granodiorite using zircon and xenotime separates (Page et al., 1985). From the Keep River National Park, the Bow River Granite has a crystallisation age of 1853 ± 5 Ma, and a sample of the co-magmatic Whitewater Volcanics crystallised at 1849 ± 6 Ma (Worden et al., in review).

Figure 14 **(overleaf):** *Geochronological data and summary Time-Space plot for the Pine Creek Orogen, northern McArthur Basin, and Arnhem Inlier.*



Litchfield Province
Central Domain
Nimbuwah Domain - northern McArthur - Arnhem Inlier
South Alligator Valley
Arnhem Shelf
Walker Fault Zone
Caledon Shelf
Urapunga Fault Zone
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Murrenja Dolerite
Ti-Tree Granophyre
Fitzmaurice Gp
Rum Jungle U
Cullen Supersuite Au
BYNOE pegmatite Sn-Ta
Tolmer Gp
Retrogression
Litchfield Granites
Cullen Supersuite
Shoobridge
Shoobridge Event
Katherine River Gp
Retrogression
David Suite
Wagait, Two Sisters, Allia Creek
Welltree
Wangi Basics
Contact metm
Jim Jim, Stone Creek
Edith River Gp
El Sherana Gp
Pul Pul, Gimbat
Plum Tree Creek
Nabarlek, Tin Camp
Upper amphibolite-granulite facies
Daly Cu-Pb-Zn
Fog Bay, Hermit Creek
Warrs, Berinka
Sub-greenschist-greenschist facies
South Alligator Gp & Finniss River Gp
Nilyanjurrung
McAddens Creek
Nimbuwah Event
Myra Falls Metamorphics
Upper amphibolite-granulite facies
Roper Gp
Mainorou
Mt Rigg Gp
Nathan Gp
Bath Range
Habgood Gp
Yarrawirrie
Balma Gp
Mt Bonner
Jalma
Nabarlek U
Durabudboi
Vizard Gp
Nagi
Saint Vidgeon
Jabiluka U
Parsons Range Gp
Fagan
Rorruwuy
Coast Range
Latram
Gadabara
West Branch
Oenpelli Dolerite
Ranger U
Donydji Gp
Spencer Creek Gp
Dhunganda
Retrogression
Groote Eylandt Gp
Bickerton
Bukudal, Giddy
Mirrarmina Complex
Bradshaw Complex
Grindall
Urapunga, Mt Read
U-Pb zircon felsic intrusive
U-Pb monazite felsic intrusive
U-Pb xenotime felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb baddeleyite mafic intrusive
U-Pb zircon mafic extrusive
U-Pb zircon sed deposition
U-Pb zircon max deposition
U-Pb zircon metamorphism
U-Pb monazite metamorphism
U-Pb monazite contact metamorphism
U-Pb xenotime contact metamorphism
Rb-Sr thermal event/felsic intrusive
Rb-Sr illite min deposition
Ar-Ar illite min deposition
U-Pb monazite Au mineralisation
U-Pb cassiterite pegmatite
U-Pb tantalite pegmatite
U mineralisation/remobilisation

The emplacement ages for these granites overlap the timing of regional metamorphism within the Litchfield Province. Recent in situ analysis of monazite within upper amphibolite-granulite grade rocks of the Hermit Creek Metamorphics (1856 ± 2 Ma, 1854 ± 4 Ma) and the Fog Bay Metamorphics (1853 ± 3 Ma) establish the timing of regional metamorphism at ca 1855 Ma (Carson et al., in press). For the Fog Bay Metamorphics this is supported by analysis of metamorphic overgrowths on zircon, which crystallised at 1853 ± 4 Ma (Carson et al., in press). Monazites within the Welltree Metamorphics record a second phase of metamorphism at 1812 ± 3 Ma (Carson et al., in press). This has not been detected in the high grade rocks, and its significance is not yet understood.

Attempts have been made to determine the emplacement ages of other syn-post tectonic granitic rocks of Litchfield Province, including the Jammine Granite, Soldiers Creek Granite, Two Sisters Granite, Allia Creek Granite, and various samples of Murra-Kamangee Granodiorite. Inherited zircon is present in all of these granites, and they may not contain magmatic zircon recording their emplacement. This is evidenced by the fact that the Soldiers Creek Granite, Two Sisters Granite, and a sample of Murra-Kamangee Granodiorite (which may be a roof pendant of Hermit Creek Metamorphics) all have youngest populations between ca 1872-1862 Ma. These are interpreted as maximum ages of intrusion, as the stratigraphy they intrude (Hermit Creek Metamorphics, Burrell Creek Formation) is equivalent in age or younger. The youngest zircons in the Jammine Granite yield a maximum emplacement age of 1858 ± 6 Ma, while Murra-Kamangee Granodiorite *sensu stricto* has a youngest population at 1854 ± 5 Ma (Worden et al., in review). The latter sample is affected by significant non-zero age lead loss, and it also contains inherited zircon, making identification of a possible magmatic population difficult (Worden et al., in review). The Allia Creek Granite contains high U zircons, and the compositions are spread along concordia. It has a maximum intrusion age of 1806 ± 7 Ma (Worden et al., in review).

Mafic magmatism in the Litchfield Province is constituted by two recognised episodes of dolerite intrusion and intrusion of mafic-ultramafic plutons. The Zamu Dolerite is present in the eastern Litchfield Province, although its predominant occurrence is in the Central Domain. It intrudes stratigraphy of the Finniss River Group and the two units were folded together during regional deformation. It has a ca 1870 Ma intrusion age, which is discussed in detail below. The Wangi Basics are a loosely-defined group of mafic-ultramafic plutonic rocks that appear to intrude the Litchfield Province at various times. One stock has a post-tectonic emplacement age of 1829 ± 4 Ma (Worden et al., in review), while others appear to have been regionally metamorphosed at ca 1855 Ma. Parts of the Wangi Basics have been correlated with the Zamu Dolerite (e.g. Ahmad et al., 1993).

Unconformably overlying these rocks in restricted outcrop are the sedimentary rocks of the Tolmer Group, which are relatively flat lying and considered possible equivalents to stratigraphy of the Katherine River Group to the east. Based on this, they have an inferred maximum depositional age of ca 1800 Ma, although this has not been isotopically determined.

Rb-Sr systematics of various intrusions across the Pine Creek Orogen record an event at ca 1780 Ma. This has been assigned to the Shoobridge Event in the Cental Domain, and is interpreted to reflect widespread retrogression (Needham et al., 1988). Combined Rb-Sr measurements of several Litchfield Province granites including the Mount Litchfield Granite, the Two Sisters Granite, and the Murra-Kamangee Granodiorite record an age of 1768 ± 16 Ma which may be attributed to this event (Page et al., 1985).

The Shoobridge Event also broadly coincides with Sn-Ta mineralisation associated with S-type granites of the BYNOE region in the Litchfield Province. SHRIMP U-Pb analysis of cassiterite and tantalite from a number of greisens and pegmatites intruding Burrell Creek Formation yielded several ca 1730 Ma intrusions ages, and an older, more imprecise age determination at ca 1760 Ma (Kinny, P.D and Wartho, J., unpublished data). These age determinations constitute the only directly dated mineralisation within the Litchfield Province; ages of other deposits, such as the stratiform VMS Cu-Pb-Zn mineralisation in the Daly Mineral Field, are inferred from crystallisation ages of the host units (in this case, the 1862 ± 3 Ma Warrs Volcanic member: Worden et al., in press).

Mesoproterozoic stratigraphy is also present in the Litchfield Province. The Fitzmaurice Group has a maximum deposition age of ca 1635 Ma, obtained from the Moyle River Formation (Carson, C.J., unpublished data). Also present in this sample is a single zircon with a ca 1300 Ma age. However, given the presence of other ca 1650 Ma zircons in the Moyle River Formation, the conservative maximum depositional age is plotted.

Mesoproterozoic bimodal magmatism is recorded by intrusion of the Murrenja Dolerite and the Ti-Tree Granophyre. These units are constrained by their field relationships; they have not been directly dated. The Murrenja Dolerite intrudes the Moyle River Formation, while the Ti-Tree Granophyre forms sills in the Finniss River Group, and also intrudes the Fitzmaurice Group.

<1400 Ma

Overlying the Fitzmaurice Group is the Auvergne Group, for which a maximum deposition age of ca 1050 Ma has been determined (Carson, C.J., unpublished data).

The final Proterozoic sedimentary unit deposited in the Litchfield Province is the Neoproterozoic Uniya Formation. This is a package of glacial sedimentary rocks that crops out south of Daly River and on the eastern edge of the Wingate Plateau. It overlies the Tolmer Group with angular unconformity (Dundas et al., 1987), and also overlies the Auvergne Group (Edgoose et al., 1989).

Proterozoic rocks of the Litchfield Province are variably covered by the Cambrian Antrim Plateau Volcanics and Daly River Group, the Early Permian Port Keats Group of the Bonaparte Basin, the Jurassic-Cretaceous Petrel Formation, and the Cretaceous Bathurst Island Formation.

Central Domain

>1900 Ma

Archaean basement is exposed in the Central Domain. In the Rum Jungle region, two exposed granite-gneiss complexes (Rum Jungle and Waterhouse) with crystallisation ages of ~2545-2520 Ma (Cross et al., 2005) are intercalated with the Stanley Metamorphics (Lally, 2002). Also in the Central Domain, drillcore has intersected the Woolner Granite (2675 ± 15 Ma: McAndrew et al., 1985) and the overlying Archaean Dirty Water Metamorphics (Pietsch and Stuart-Smith, 1987).

The Archaean basement is overlain by the Manton and Namoona Groups, which are stratigraphically equivalent. Detrital zircons within the basal conglomerates of the Beestons Formation yield a maximum age of deposition of 2506 ± 14 Ma (Cross et al., 2005), although this figure was determined on the youngest six analyses from a dispersed population with ages ranging from ca 2500-2575 Ma. Sedimentary rocks in the Namoona Group are capped by the basaltic-andesitic Stag Creek Volcanics, which contain a youngest zircon population with an age of 2021 ± 10 Ma (Worden et al., in press). Zircons with a mean age of 2048 ± 13 Ma have also been reported from the Stag Creek Volcanics (Page, OZCHRON).

These initial basins are unconformably overlain by the Mount Partridge Group. Volcanic zircons separated from a tuffaceous siltstone within the Wildman Siltstone at the top of the Mount Partridge Group yielded a crystallisation age of 2019 ± 4 Ma (Worden et al., in press). Deposition of the Mount Partridge Group was followed by a major hiatus, resulting in removal of up to 160 m.y. of the rock record.

1900-1400 Ma

Within the Central Domain, deposition of the South Alligator Group represents the first event in this time interval. Initial ID-TIMS dating of the Gerowie Tuff and a tuffaceous component of the Mount Bonnie Formation provided depositional constraints of 1884 ± 3 Ma and 1877 ± 11 Ma respectively (Needham et al., 1988). Recent SHRIMP analysis of two Gerowie Tuff samples have refined the timing of South Alligator Group deposition, with ages of 1864 ± 3 Ma and 1862 ± 4 Ma (Worden et al., in press).

The South Alligator Group is conformably overlain by the Finniss River Group, a widespread sedimentary package dominated by turbiditic sedimentary rocks and minor basal felsic volcanics. These volcanics have ca 1863 Ma crystallisation ages (see Warrs Volcanic Member and Berinka Volcanics described above), which reflect the ca 1868 Ma maximum depositional age for the Burrell Creek Formation in the Central Domain. In the eastern Central Domain, the Burrell Creek Formation is overlain by the Tollis Formation, which is correlated with the Chilling Sandstone in the Litchfield Province. Recent dating of the Tollis Formation provides a maximum deposition age of 1868 ± 5 Ma (Worden et al., in review), revising the previously published age of 1890 +18/-15 Ma (Page and Williams, 1988).

Following deposition of the South Alligator and Finniss River Groups, the Zamu Dolerite was intruded throughout the Pine Creek Orogen. SHRIMP analysis of zircons within the Zamu Dolerite yielded an age of 1870 ± 6 Ma (Page, OZCHRON). However, this is likely to constitute a maximum age of intrusion, as the sample contains a significant component of inherited zircon. The Zamu Dolerite is considered equivalent to parts of the Wangi Basics in the Litchfield Province (Ahmad et al., 1993).

After intrusion of the Zamu Dolerite, compression during the Nimbuwah Event tightly folded the stratigraphy, although the regional metamorphic grade in the Central Domain did not exceed sub-greenschist-greenschist facies. This period of deformation is constrained by a post-tectonic pegmatite at the Ranger uranium mine, which has an emplacement age of 1847 ± 1 Ma, based on ID-TIMS analyses of monazite (Annesley et al., 2002).

Deformation and metamorphism were both accompanied by, and followed by, emplacement of granitic rocks across the Pine Creek Orogen. In the Central Domain, these are post-tectonic, predominantly I-type in composition, and comprise the 23 identified plutons of the Cullen Supersuite (Stuart-Smith et al., 1993) and several plutons grouped within the David Suite (Ferenczi and Sweet, 2005). Various SHRIMP U-Pb, ID-TIMS U-Pb, and Rb-Sr age determinations exist for Cullen Supersuite granites. Where SHRIMP and ID-TIMS data exist for the same sample, the published SHRIMP data are generally more precise, and are preferentially included in the Time-Space plot. All data for these intrusions are published by Stuart-Smith et al. (1993), except where otherwise acknowledged.

The oldest published age for Cullen Supersuite granites is an ID-TIMS age of 1860 ± 45 Ma for the Margaret Granite (not plotted). The oldest SHRIMP dates for granites within the Cullen Supersuite include the 1835 ± 6 Ma McMinns Bluff Granite and the 1831 ± 6 Ma Mount Bundey Granite (Page, OZCHRON). Rasmussen et al. (2006) report a similar result for the Mount Bundey Granite at 1821 ± 5 Ma, and from the Mount Goyder Syenite immediately east of Mount Bundey, they analysed monazite which yielded an emplacement age of 1829 ± 31 Ma (not plotted). Rasmussen et al. (2001) obtained ages of 1840 ± 14 Ma, 1824 ± 10 Ma, and 1824 ± 7 Ma for monazite and xenotime crystallised in the hornfelsed Wildman Siltstone around the Mount Bundey Granite. The Umbrawarra Granite was emplaced at 1825 ± 7 Ma, while the Fingerpost Granite yielded an intrusion age of 1823 ± 6 Ma. Two emplacement ages (1822 ± 6 Ma and 1818 ± 5 Ma) have been obtained for the Allamber Springs Granite. The sole published data (ID-TIMS) for the Prices Springs Granite reveal a crystallisation age of 1804 ± 50 Ma (not plotted). The Burnside Granite was emplaced at 1800 ± 5 Ma, and ID-TIMS data for the Shoobridge Granite suggest crystallisation occurred at 1775 ± 16 Ma. Data for the last two granites are derived from analysis of high U zircon, affected by high common Pb and discordance, and should be cautiously interpreted as intrusion ages, as noted by Rasmussen et al. (2006).

Also within the Central Domain are granites which have been grouped into the David Suite, as defined by Ferenczi and Sweet (2005). This group of granitic rocks was formerly recognised as comprising part of the Jim Jim Suite (e.g. Budd et al., 2001). In the Central Domain, David Suite granitic rocks occur south of the Jim Jim Fault Zone. The oldest dated granite is the Grace Creek Granite, which revealed a crystallisation age of 1863 ± 5 Ma (Page, OZCHRON). This result is considered to contain a significant component of inherited zircon, and as such has not been included within the interpreted Davis Suite magmatic event on the plot (Budd et al., 2001). Similarly, the Nilyanjurrung Syenite has an apparent crystallisation age of 1859 ± 17 Ma (Page, OZCHRON), and is also likely to include analysis of inherited zircon. It has not expressly been included within the Davis Suite, although it is proximal to many of the David Suite granites. With an intrusion age of 1838 ± 7 Ma, the Jim Jim Granite records the oldest intrusion age within Central Domain David Suite granites (Page, OZCHRON). The Malone Creek Granite was intruded at 1820 ± 8 Ma (Page, OZCHRON). Volcanic activity along strike from this granite in the South Alligator Valley has been grouped in the Davis Suite (e.g. Gimbat Formation: Budd et al., 2001). This geochronology has been plotted with the El Sherana and Edith River Groups, and is discussed below.

Renewed extension contemporaneous with emplacement of post-tectonic granites was focused in the South Alligator Valley region, and resulted in deposition of the El Sherana and Edith River Groups. A number of age determinations exist for volcanics within these unconformity-bound sequences, although many are dominated by ca 1860 Ma inheritance (Jagodzinski, 1998). Age determinations which are both imprecise and affected by inheritance are not plotted. The El Sherana Group is constrained by a 1829 ± 5 Ma crystallisation age for the Pul Pul Rhyolite (Jagodzinski, 1998), and two crystallisation ages for the Gimbat Ignimbrite Member (1828 ± 4, 1827 ± 4 Ma: Jagodzinski, E., unpublished data). An unnamed porphyry within the El Sherana Group intrudes the Gimbat Ignimbrite Member, and has a crystallisation age of 1831 ± 11 Ma (Jagodzinski, E., unpublished data). Two other plotted age determinations for this unit are beyond error from these results, and are not included within the interpreted magmatic event.

The El Sherana Group is unconformably overlain by the Edith River Group, which is capped by the Plum Tree Creek Volcanics. These volcanics have a crystallisation age of 1825 ± 4 Ma (Page, OZCHRON).

Several pegmatites which intrude the South Alligator Valley region have K-Ar dates obtained from analyses of muscovite (Page et al., 1980). However, their ~1823-1796 Ma ages have not been plotted, given their relative imprecision.

Soon after deposition of the El Sherana and Edith River Groups, the basal stratigraphy of the McArthur Basin was deposited. This extended from the eastern part of the Central Domain, including the South Alligator Valley region, across the Nimbuwah Domain, and southeast to the Mount Isa region. Discussion of the overlying Palaeo-Mesoproterozoic basin stratigraphy occurs in the following sections.

Several Cullen Supersuite granites have wholerock and pooled Rb-Sr ages of ca 1784-1763 Ma, which coincide with intrusion of the Shoobridge Granite (Stuart-Smith et al., 1993). These include the McMinns Bluff Granite, the Umbrawarra Granite, the Fingerpost Granite, the Allamber Springs Granite, and the Saunders Creek Granite. This resetting of the Rb-Sr system has been assigned to the Shoobridge Event, and is interpreted as a widespread period of retrogression across the Pine Creek Orogen. David Suite granites also reflect variable resetting of the Rb-Sr system, evidenced by a 1711 ± 24 Ma age for the Grace Creek Granite (Page, OZCHRON), and a 1732 ± 11 Ma age for the Jim Jim Granite (Page et al., 1980).

This time interval represents a period of gold mineralisation in the Central Pine Creek Orogen. Hydrothermal minerals from Au-bearing veins have been dated from several deposits, revealing crystallisation ages of ca 1810-1717 Ma. For Toms Gully, Rasmussen et al. (2006) determined an age of 1780 ± 10 Ma for hydrothermal monazite. A number of mineralisation ages exist for the Goodall deposits: Compston and Matthai (1994) determined a mineralisation age of 1810 ± 10 Ma, while Sener et al. (2005) determined an age of 1727 ± 13 Ma. Re-evaluation of the latter data for the Goodall deposit by Rasmussen et al. (2006) determined two generations of hydrothermal monazite growth at 1776 ± 13 Ma and 1717 ± 16 Ma. Sener et al. (2002) have also reported a preliminary age constraints for mineralisation at the Gold Ridge deposit of 1610 ± 80 Ma. Direct dating of various uraniferous minerals reveal uranium mineralisation at Rum Jungle at 1627 ± 45 Ma (Von Pechmann, 1986).

<1400 Ma

Proterozoic rocks of the Central Domain are variably covered by Palaeozoic rocks of the Jindare Formation, and the Cambrian Antrim Plateau Volcanics and Daly River Group. Mesozoic stratigraphy includes the Cretaceous-Jurassic Petrel Formation and the Cretaceous Bathurst Island Formation.

Nimbuwah Domain/Arnhem Shelf

>1900 Ma

The 2470 +47/-40 Ma Nanambu Complex (Page et al., 1980) comprises the oldest rocks in the Nimbuwah Domain, and crops out north of the Jim Jim Fault Zone. The earliest recognised basins were filled by locally derived fluviatile to shallow marine sedimentary rocks which formed on the flanks of exposed Nanambu Complex, and now constitute the meta-arkose, quartzite, and quartzo-feldspathic gneiss of the Kakadu Group (Ferenczi and Sweet, 2005).

Conformably overlying the Kakadu Group are the carbonate rocks, and carbonaceous pelitic and quartzo-feldspathic psammitic metasedimentary rocks of the Cahill Formation. The Cahill Formation could be correlated with the Manton and Namoona Groups in the Central Domain and the Litchfield

Province. It is unconformably overlain by the Nourlangie Schist, and has been correlated with the Wildman Siltstone of the Mount Partridge Group (Needham, 1988). This is supported by maximum deposition ages for the Nourlangie Schist of 2024 ± 7 Ma and 1955 ± 10 Ma (Worden et al., 2006b; Worden et al, in review). Another series of metasedimentary rocks grouped as the Myra Falls Metamorphics are not correlated, and are only constrained by their deposition prior to ca 1860 Ma regional metamorphism.

1900-1400 Ma

Given the lack of constraints on the Myra Falls Metamorphics, stratigraphy equivalent to the South Alligator and Finniss River Groups has not been correlated in the Nimbuwah Domain. The Zamu Dolerite, described in the Central Domain, is present in the Nimbuwah Domain, and intrudes the Cahill Formation, Nourlangie Schist and Nanambu Complex north of the Jim Jim Fault Zone. Following intrusion of the Zamu Dolerite, the first recorded event in the Nimbuwah Domain is the Nimbuwah Event itself, which involved complex folding of stratigraphy, Barrovian metamorphism to granulite facies, and intrusion of granitic rocks. Early ID-TIMS dating of Nimbuwah Complex granites indicate this event occurred between 1886-1866 Ma (Page et al., 1980) and recent SHRIMP dating of Nimbuwah Complex granite *sensu stricto* produced ages of 1860 ± 5 Ma and 1864 ± 4 Ma (Worden et al., in review). The ca 1886 Ma age has not been included in the magmatic event. Deformation associated with this event is constrained by the 1847 ± 1 Ma age of a post-tectonic pegmatite at Ranger uranium mine (Annesley et al., 2002).

A number of post-tectonic granites also intruded the Nimbuwah Domain, and comprise part of the David Suite described in the Central Domain (Ferenczi and Sweet, 2005). These include the Nabarlek Granite, which crystallised at 1818 ± 7 Ma (Worden et al., 2006b) and the 1846 ± 13 Ma Tin Camp Granite (Worden et al., in review). Granites of this suite are contemporaneous with granites of the Cullen Supersuite in the Central Domain.

Leichhardt/Calvert Superbasin

The Katherine River Group comprises the lowermost stratigraphy of the platform cover which overlies the eastern/south-eastern Central Domain and the Nimbuwah Domain. It is correlated with the Donydji Group in the Walker Fault Zone, the Spencer Creek Group in the northern Caledon Shelf, and the Groote Eyelandt Group in the southern Caledon Shelf. The Katherine River Group is also correlated with the Tawallah Group in the southern McArthur Basin (Rawlings, 1999).

Maximum deposition ages for the basal Kombolgie Subgroup based on zircon analyses from sedimentary rocks range between ca 1860-1810 Ma (Page, OZCHRON), although they generally do not have uncertainties attributed to them, save for the 1830 ± 30 Ma rhyolitic McAddens Creek Volcanic member (equivalent to the Nungbalgarri Volcanics), which contains inherited zircon (Page, OZCHRON). An Ar-Ar age determination on diagenetic illite within the Kombolgie Subgroup at the Jabiluka uranium deposit yields a minimum depositional age of 1798 ± 18 Ma (Polito et al., 2005), which refines the previous 1650 ± 80 Ma age (Kyser et al., 2000; not plotted). The top of the Katherine River Group is constrained by depositional ages for the West Branch Volcanics of 1712-1705 Ma (Kruse et al., 1994). The upper Katherine River Group is further constrained by the Jimbu Microgranite at 1720 ± 7 Ma, the intrusion of which is interpreted to be synchronous with deposition of the Gundi Sandstone (Rawlings and Page, 1999). Parts of the Katherine River Group are also intruded by the 1723 ± 6 Ma Oenpelli Dolerite (Page, OZCHRON).

The Kombolgie Subgroup is significant in that it comprises the cover sequence under which the unconformity-related uranium deposits of the Alligator Rivers uranium field formed. Numerous efforts have been made to date these deposits, and the results indicate complex remobilisation and resetting histories. The oldest dated deposit is Ranger, where uranium-bearing minerals are considered to have initially precipitated at 1737 ± 20 Ma (Ludwig et al., 1987). Ludwig et al. (1987) also report a U-Pb wholerock age of 1437 ± 20 Ma for the Jabiluka deposit. Recent dating of uraninite from the Jabiluka deposit by Polito et al. (2005) revealed a series of ages, with the oldest having a $^{207}Pb/^{206}Pb$ age of 1680 ± 17 Ma. Younger populations have U-Pb discordia ages at 1302 ± 37 Ma, 1191 ± 27 Ma, and 802 ± 57 Ma. These are attributed as responses to regional tectonic events, and one of these ages coincides with intrusion of the Derim Derim Dolerite, described below. An imprecise Sm-Nd age determination of 1614 ± 132 Ma (Mass, 1989) for primary mineralisation at Jabiluka is not plotted. At the Nabarlek deposit, Polito et al. (2004) determined that uraninite commenced precipitating at 1642 ± 33 Ma (single grain $^{207}Pb/^{206}Pb$ age), and was remobilised and partially reset, as defined by U-Pb discordia ages, at 1393 ± 76 Ma, 1178 ± 56 Ma, and 948 ± 47 Ma. The older age is in agreement with a Sm-Nd wholerock age determination of 1616 ± 50 Ma by Mass (1989).

Isa Superbasin

The Katherine River Group is unconformably overlain by dolostones and sandstones of the Mount Rigg Group (Rawlings, 1999). It is correlated with the Nathan Group, which occurs to the southeast in the southern Walker Fault Zone, on the northern and central Caledon Shelf, and in the Urapunga Fault Zone. These groups have not been directly dated, and are only constrained in the Arnhem Shelf by the unconformably underlying ca 1710 Ma West Branch Volcanics, and volcanics from the unconformably overlying Roper Group, discussed below.

Roper Superbasin

The Mount Rigg Group is unconformably overlain by the Roper Group, a cyclic sequence of fine- and coarse-grained siliciclastic rocks that blankets much of the McArthur Basin, although it is absent from the Walker Fault Zone and the central and southern regions of the Caledon Shelf (Rawlings, 1999). The Roper Group is constrained by a 1492 ± 4 Ma depositional age for a tuffite within the Mainoru Formation of the Lower Roper Group (Jackson et al., 1999). This has been correlated with a tuff from the same formation within the southern McArthur Basin, which yielded an indistinguishable depositional age of 1493 ± 4 Ma (Jackson et al., 1999). A minimum constraint of 1429 ± 31 Ma for deposition of the Roper Group is provided by Rb-Sr measurements of diagenetic illite within the McMinn Formation near the top of the Roper Group in the southern McArthur Basin (Kralik, 1982). Neither of the southern McArthur Basin samples is plotted.

<1400 Ma

A period of extension followed deposition of the Roper Group, resulting in widespread mafic magmatism, and emplacement of the 1324 ± 4 Ma Derim Derim Dolerite (Claoué-Long, J.C., unpublished data). The Arnhem Shelf is overlain by the Neoproterozoic-Cambrian sedimentary rocks of the Arafura Basin (Wessel and Goulburn Groups), and undifferentiated Cretaceous sedimentary rocks.

Walker Fault Zone/Urapunga Fault Zone

>1900 Ma

Pre-1900 Ma rocks have not been detected in the Walker Fault Zone.

1900-1400 Ma

The earliest rocks observed within the Walker Fault Zone occur in the south, where basal stratigraphy overlies the Mirrarrmina Complex. Budd et al. (2001) report a crystallisation age of

1875 ± 6 Ma for these metamorphic and anatectic granitic 'basement' rocks (Rawlings et al., 1997), although this age determination could not be located in Geoscience Australia's OZCHRON database. In the south, where the E-W-trending Urapunga Fault Zone truncates the Walker Fault Zone, the 1858 ± 7 Ma Urapunga Granite constitutes basement, and is associated with the Mount Reid Rhyolite which was extruded at 1847 ± 16 Ma (Page et al., 2000).

Leichhardt/Calvert Superbasin

Coarse-grained siliciclastic rocks and bimodal volcanic rocks of the Donyjdi Group comprise the basal stratigraphy of the Walker Fault Zone, and are inferred to unconformably overlie the Mirrarrmina Complex (Rawlings et al., 1997). The Donyjdi Group comprises the Dhonganda Formation, the Ritarango Formation, and the Fagan Volcanics (Rawlings, 1994, Rawlings et al., 1999).

Initial deposition commenced in the southern Walker Fault Zone, with deposition of the Dhunganda Formation (basal Donydji Group), equivalent to the lower Katherine River Group on the Arnhem Shelf and the Woodah Sandstone on the southern Caledon Shelf. This is thought to be unconformably overlain by the remainder of the Donydji Group, which contains the Fagan Volcanics. These have ages of 1707 ± 12 Ma and 1706 ± 10 Ma (Page, OZCHRON) and are equivalent in age to the West Branch Volcanics at the top of the Katherine River Group on the Arnhem Shelf, the Cato Volcanics from the northern Caledon Shelf, and possibly the Gadabara Volcanics from the southern Caledon Shelf.

The Donyjdi Group is conformably overlain in the southern Walker Fault Zone by siliciclastic sedimentary rocks of the Parsons Range Group. This group has not been directly dated, and is constrained by the ca 1707 Ma ages of the underlying Fagan Volcanics, and by ages of volcanics within the overlying Balma Group (discussed below). In the northern Walker Fault Zone, only correlatives of the upper sandstone unit within the Parsons Range Group are observed. This is considered potentially time equivalent to the Rorruwuy Sandstone and the Coast Range Sandstone from the northern and central Caledon Shelves respectively (Rawlings, 1999).

Isa Superbasin

The Parsons Range Group is conformably overlain by the Habgood Group in the north, and the Balma Group in the south. These packages are predominantly comprised of evaporitic and stromatolitic dolostone and fine-grained siliciclastic rocks (Rawlings, 1999). Deposition of these groups is constrained by volcanics within the Balma Group, namely the 1620 ± 21 Ma Yarrawirrie Formation and the 1599 ± 11 Ma Bath Range Formation (Pietsch et al., 1994). Correlated with parts of the Balma and Habgood Groups is the Vizard Group, which occurs on the southern flank of the Urapunga Fault Zone. It comprises two units: the lower St Vidgeon Group, and the upper Nagi Formation. These have crystallisation ages of 1640 ± 4 Ma and 1634 ± 4 Ma respectively (Page et al., 2000). The Vizard Group is correlated with the McArthur Group in the southern McArthur Basin.

In the south, the Bath Range Formation is thought to be unconformably overlain by the Nathan Group, which is correlated with the Mount Rigg Group (Jackson et al., 1987). Neither group has been described from the northern Walker Fault Zone.

Roper Superbasin

Sedimentary rocks of the Roper Basin are not described in the Walker Fault Zone.

<1400 Ma

Analysis of baddeleyite separated from a drillcore sample of Derim Derim Dolerite yielded an emplacement age of 1324 ± 4 Ma (Claoué-Long, J.C., unpublished data). This coincides with a period of extension and widespread mafic magmatism following deposition of the Roper Group, which crops out to the west on the Arnhem Shelf, and to the southeast.

The Palaeo- to Mesoproterozoic rocks of the Walker Fault Zone are covered in the north by Neoproterozoic-Cambrian sedimentary rocks of the Arafura Basin (Wessel and Goulburn Groups), the Antrim Plateau Volcanics (lowermost Daly Basin stratigraphy), and the Mesozoic-Cretaceous Carpentaria Basin, including the Walker River and Yirrkala Formations (Krassay, 1994).

Caledon Shelf/Arnhem Inlier

>1900 Ma

Archaean rocks have not been identified in the Arnhem Inlier. The oldest known rocks are the turbiditic metasedimentary rocks of the Grindall Formation, which are the partial precursors to the previously described ca 1875 Ma Mirrarrmina Complex and the ca 1867-1845 Bradshaw Complex described below.

1900-1400 Ma

In the Arnhem Inlier (northern Caledon Shelf), granitic rocks of the Bradshaw Complex intruded turbiditic sedimentary rocks of the Grindall Formation at 1867 ± 12 Ma (Page, OZCHRON), and late stage metamorphic felsic melt sweats formed at 1854 ± 6 Ma (Page, OZCHRON) and 1845 ± 10 Ma (Page, OZCHRON). Subsequently, post-orogenic A-type granites of the Giddy Suite were intruded into the Arnhem Inlier, including the Giddy Granite (1836 ± 4 Ma), the Bukudal Granite (1836 ± 5 Ma; 1835 ± 4 Ma), and the Garrthalala Granite (1833 ± 3 Ma), as determined by Page (OZCHRON).

Leichhardt/Calvert Superbasin

The earliest depositional sequence is the Groote Eyelandt Group in the southern Caledon Shelf. The lower Bustard Subgroup is constrained by a crystallisation age for the Bickerton Rhyolite of 1814 ± 8 Ma (Pietsch et al., 1994; Pietsch et al., 1997).

In the central Caledon Shelf, basement is inferred to be covered by the Woodah Sandstone, equivalent to Alyinga Sandstone (Alyangula Subgroup, Groote Eyelandt Group). This is overlain by the Gadabara Volcanics. No age determination is reported for the Gadabara Volcanics; however, they are considered correlatives with the Cato Volcanics in the northern Caledon Shelf, which are described below.

In the northern Caledon Shelf the lower Spencer Creek Group comprises the basal stratigraphy. This group unconformably overlies granites of the ca 1835 Ma Giddy Suite, and is capped by the Cato Volcanics which have a crystallisation age of 1717 ± 10 Ma (Page, OZCHRON). The Latram Granite intrudes the Spencer Creek Group at 1712 ± 10 Ma (Page, OZCHRON). It appears transitional into the Yanungbi Volcanics, which are interpreted to lie at the base of the Spencer Creek Group, suggesting that the Yanungbi Volcanics may also intrude the Spencer Creek Group, rather than comprising concordant stratigraphy (Rawlings, 1999).

The Spencer Creek Group correlates broadly with the upper Tawallah in the southern McArthur Basin, the upper Katherine River Group of the Arnhem Shelf, and the Donydji Group of the Walker Fault Zone (Rawlings, 1994).

The Cato Volcanics are unconformably overlain by the Rorruwuy Sandstone, and may be correlated with the upper Parsons Range Group in the Walker Fault Zone, and also with the Coast Range Formation in the central Caledon Shelf, which unconformably overlies the Gadabara Volcanics (Rawlings, 1999). These units have a maximum depositional constraint provided by the unconformably underlying ~1717 Ma Cato Volcanics.

Isa Superbasin

In the northern Caledon Shelf, the unconstrained Durabudboi beds unconformably overlie the Rorruwuy Sandstone. This unit is correlated with the Mt Bonner Sandstone, which unconformably overlies the Cato Volcanics, although it is not considered equivalent to the Rorruwuy and Coast Range Sandstones (Rawlings, 1999). In the central Caledon Shelf, the Jalma Formation unconformably overlies the Coast Range Sandstone. None of these units has been geochronologically constrained, although they are all correlated with Middle Habgood Group and Middle Balma Group sedimentary rocks which outcrop in the Walker Fault Zone (Rawlings, 1999). The geochronological constraints for these groups have been previously discussed.

The Mount Bonner Sandstone and the Jalma Formation are unconformably overlain by the Nathan Group, which is correlated across the McArthur Basin. The Nathan Group is not observed above the Durabudboi beds. These are instead unconformably overlain by the Roper Group, discussed below.

Roper Superbasin

Rocks of the Lower Roper Group crop out in the northern Caledon Shelf. No geochronological constraints have been obtained for this group within the Caledon Shelf, although a tuffite sampled from the Mainoru Formation on the Arnhem Shelf yielded a ca 1492 Ma depositional age, which is comparable to ca 1493 Ma Mainoru Formation tuff collected from the southern McArthur Basin. The Roper Group is further constrained by intrusion of the 1324 ± 4 Ma Derim Derim Dolerite (Claoué-Long, J.C., unpublished data).

<1400 Ma

Early to Middle Cretaceous sedimentary rocks of the Carpentaria Basin were deposited over the Groote Eyelandt Group in the Groote Eyelandt region into two separate sub-basins (Pietsch et al., 1997).

OUTSTANDING QUESTIONS AND SCOPE FOR FUTURE PROJECTS

The following geochronological investigations are recommended to resolve gaps in the current understanding of the time-space evolution of the Pine Creek Orogen and northern McArthur Basin:

Litchfield Province

- Detailed detrital provenance studies of the Fitzmaurice and Auvergne Groups to better constrain their stratigraphic position.
- Determine intrusion ages of the Murrenja Dolerite and Ti-Tree Granophyre. This will further constrain the Fitzmaurice Group and the Auvergne Group.
- Investigate whether zircon or monazite are present in contact aureoles of post-tectonic granites to better constrain their emplacement ages.

Central Domain

- Re-analysis of members of the Cullen Supersuite which have dispersed emplacement ages; in particular, the Shoobridge Granite and the Burnside Granite. Analysis of monazite within contact aureoles may be a preferred method of dating these intrusions, given the high U contents of their constituent zircons.
- Further investigations of the Woolner Granite and Dirty Water Metamorphics for comparison with the Rum Jungle and Waterhouse Complexes, and also the Stanley Metamorphics.

Nimbuwah Domain/Arnhem Shelf

- Further analysis of components of the Nanambu Complex, to confirm its Archaean age, and decipher its complex history.
- Re-sampling of Nungbalgarri Volcanics equivalents, such as the McAddens Creek Volcanic member, to better constrain deposition and evolution of the Kombolgie Subgroup.
- Establish/refine age constraints for the Myra Falls Metamorphics, the Cahill Formation, and the Nourlangie Schist.
- Establish/refine age constraints for Mesoproterozoic intrusives including the Maningkorrirr Phonolite and the Mudginberri Phonolite.

Walker Fault Zone/Urapunga Fault Zone

- Characterise the provenance of the Dhunganda Formation, and date felsic volcanics within the formation.
- Geochemistry of the mafic Yalwarra Volcanics in the Nathan Group, Urapunga Fault Zone.

Caledon Shelf/Arnhem Inlier

- Characterise the provenance of the Grindall Formation for comparison with sedimentary units in the Pine Creek Orogen.
- Establish inheritance patterns of the Mirrarrmina and Bradshaw Complexes.
- Compare geochemistry of the Bartalumba Basalt with other basaltic units within the basal sequences in the McArthur Basin.
- Establish depositional constraints and provenance data for the Durabudboi beds, Mount Bonner Sandstone, and the Jalma Formation.
- Determine the crystallisation age of the Gadabra Volcanics to assess the correlation with the Cato Volcanics, the Fagan Volcanics, and the West Branch Volcanics.

Regional

- Conduct provenance comparisons between sedimentary rocks of the Tolmer Group, the McArthur Basin, and the Victoria River Basin to determine whether they are equivalent.

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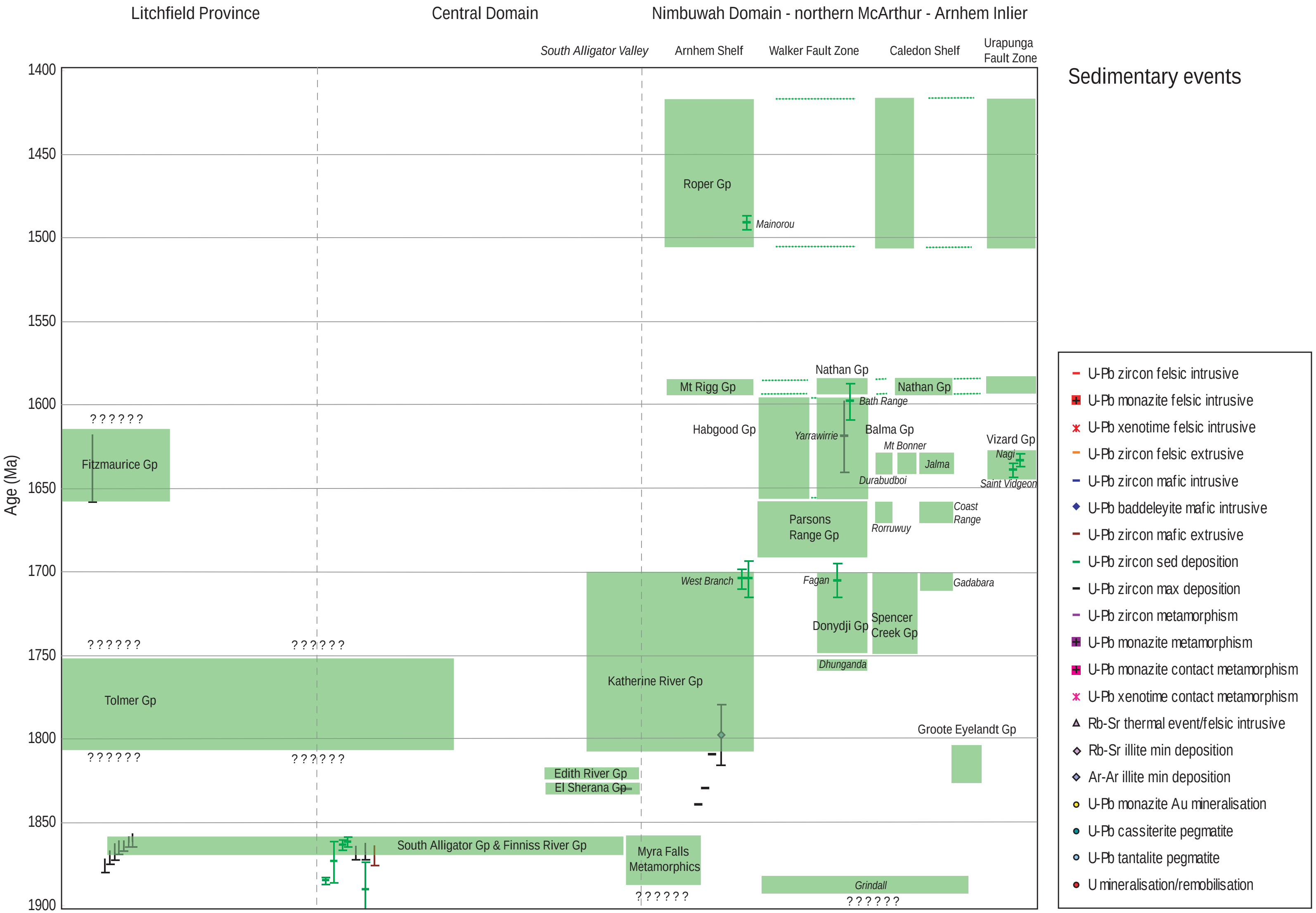
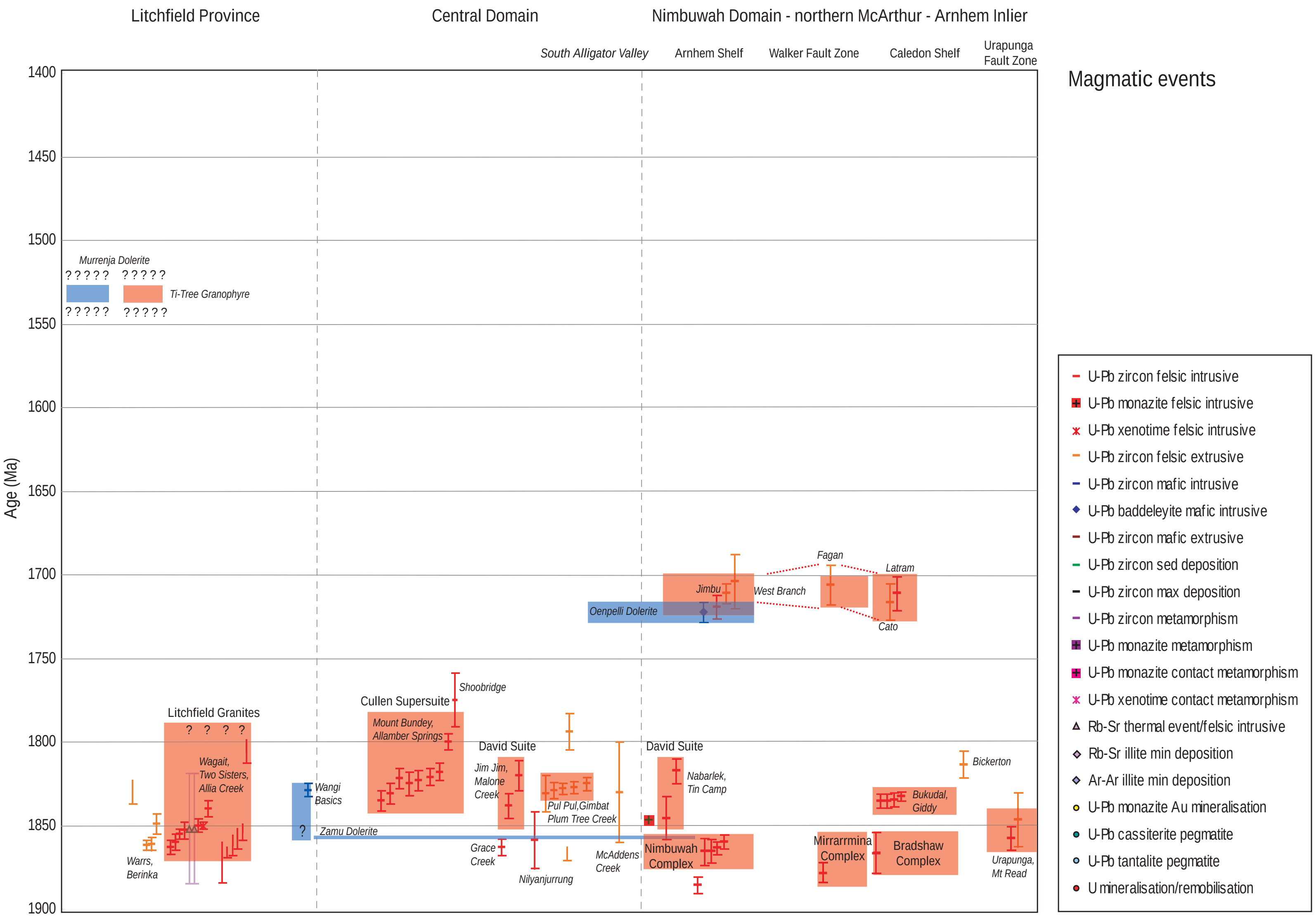
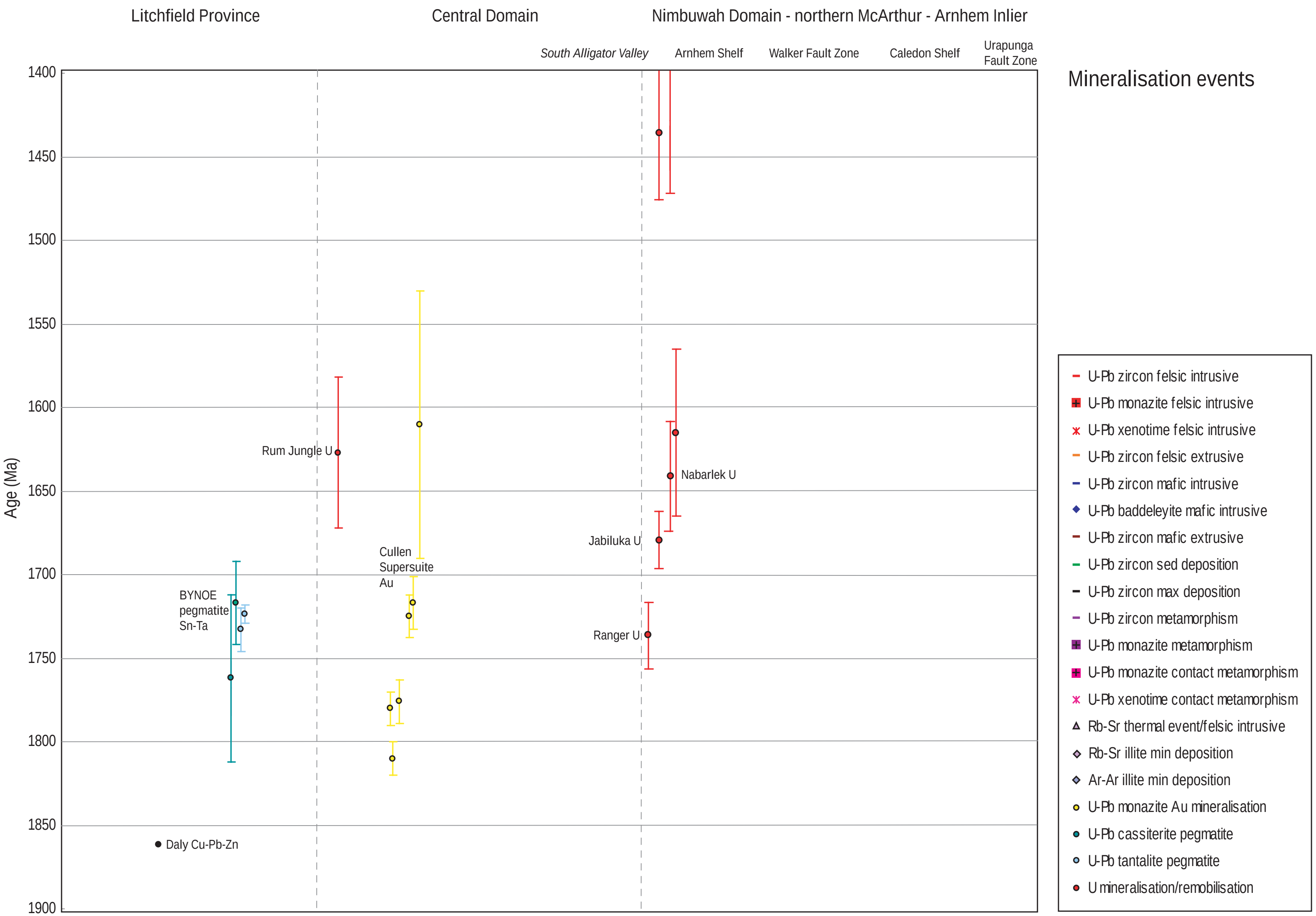

Litchfield Province
Central Domain
Nimbuwah Domain - northern McArthur - Arnhem Inlier
South Alligator Valley
Arnhem Shelf
Walker Fault Zone
Caledon Shelf
Urapunga Fault Zone
Sedimentary events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Roper Gp
Mainorou
Mt Rigg Gp
Nathan Gp
Nathan Gp
Bath Range
Habgood Gp
Yarrawirrie
Balma Gp
Mt Bonner
Jalma
Vizard Gp
Nagi
Saint Vidgeon
Durabudboi
Fitzmaurice Gp
Parsons Range Gp
Rorruwuy
Coast Range
West Branch
Fagan
Gadabara
Donydji Gp
Spencer Creek Gp
Dhunganda
Tolmer Gp
Katherine River Gp
Groote Eyelandt Gp
Edith River Gp
El Sherana Gp
South Alligator Gp & Finniss River Gp
Myra Falls Metamorphics
Grindall
??????
U-Pb zircon felsic intrusive
U-Pb monazite felsic intrusive
U-Pb xenotime felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb baddeleyite mafic intrusive
U-Pb zircon mafic extrusive
U-Pb zircon sed deposition
U-Pb zircon max deposition
U-Pb zircon metamorphism
U-Pb monazite metamorphism
U-Pb monazite contact metamorphism
U-Pb xenotime contact metamorphism
Rb-Sr thermal event/felsic intrusive
Rb-Sr illite min deposition
Ar-Ar illite min deposition
U-Pb monazite Au mineralisation
U-Pb cassiterite pegmatite
U-Pb tantalite pegmatite
U mineralisation/remobilisation



Litchfield Province
Central Domain
Nimbuwah Domain - northern McArthur - Arnhem Inlier
South Alligator Valley
Arnhem Shelf
Walker Fault Zone
Caledon Shelf
Urapunga Fault Zone
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Murrenja Dolerite
Ti-Tree Granophyre
Oenpelli Dolerite
Jimbu
West Branch
Fagan
Latram
Cato
Shoobridge
Cullen Supersuite
Mount Bundey, Allamber Springs
Litchfield Granites
David Suite
Jim Jim, Malone Creek
Pul Pul, Gimbat Plum Tree Creek
Nabarlek, Tin Camp
Bickerton
Bukudal, Giddy
Wagait, Two Sisters, Allia Creek
Wangi Basics
Zamu Dolerite
Warrs, Berinka
Grace Creek
Nilyanjurrung
McAddens Creek
Nimbuwah Complex
Mirrarmina Complex
Bradshaw Complex
Urapunga, Mt Read
Magmatic events
U-Pb zircon felsic intrusive
U-Pb monazite felsic intrusive
U-Pb xenotime felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb baddeleyite mafic intrusive
U-Pb zircon mafic extrusive
U-Pb zircon sed deposition
U-Pb zircon max deposition
U-Pb zircon metamorphism
U-Pb monazite metamorphism
U-Pb monazite contact metamorphism
U-Pb xenotime contact metamorphism
Rb-Sr thermal event/felsic intrusive
Rb-Sr illite min deposition
Ar-Ar illite min deposition
U-Pb monazite Au mineralisation
U-Pb cassiterite pegmatite
U-Pb tantalite pegmatite
U mineralisation/remobilisation

Litchfield Province
Central Domain
Nimbuwah Domain - northern McArthur - Arnhem Inlier
South Alligator Valley
Arnhem Shelf
Walker Fault Zone
Caledon Shelf
Urapunga Fault Zone
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Shoobridge Event
Retrogression
Retrogression
Retrogression
Welltree
Contact metm
Upper amphibolite-granulite facies
Sub-greenschist-greenschist facies
Nimbuwah Event
Fog Bay, Hermit Creek
Upper amphibolite-granulite facies
Bradshaw
U-Pb zircon felsic intrusive
U-Pb monazite felsic intrusive
U-Pb xenotime felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb baddeleyite mafic intrusive
U-Pb zircon mafic extrusive
U-Pb zircon sed deposition
U-Pb zircon max deposition
U-Pb zircon metamorphism
U-Pb monazite metamorphism
U-Pb monazite contact metamorphism
U-Pb xenotime contact metamorphism
Rb-Sr thermal event/felsic intrusive
Rb-Sr illite min deposition
Ar-Ar illite min deposition
U-Pb monazite Au mineralisation
U-Pb cassiterite pegmatite
U-Pb tantalite pegmatite
U mineralisation/remobilisation


Litchfield Province
Central Domain
Nimbuwah Domain - northern McArthur - Arnhem Inlier
South Alligator Valley
Arnhem Shelf
Walker Fault Zone
Caledon Shelf
Urapunga Fault Zone
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Rum Jungle U
Cullen Supersuite Au
BYNOE pegmatite Sn-Ta
Daly Cu-Pb-Zn
Nabarlek U
Jabiluka U
Ranger U
Mineralisation events
U-Pb zircon felsic intrusive
U-Pb monazite felsic intrusive
U-Pb xenotime felsic intrusive
U-Pb zircon felsic extrusive
U-Pb zircon mafic intrusive
U-Pb baddeleyite mafic intrusive
U-Pb zircon mafic extrusive
U-Pb zircon sed deposition
U-Pb zircon max deposition
U-Pb zircon metamorphism
U-Pb monazite metamorphism
U-Pb monazite contact metamorphism
U-Pb xenotime contact metamorphism
Rb-Sr thermal event/felsic intrusive
Rb-Sr illite min deposition
Ar-Ar illite min deposition
U-Pb monazite Au mineralisation
U-Pb cassiterite pegmatite
U-Pb tantalite pegmatite
U mineralisation/remobilisation

Time-Space evolution of the Halls Creek Orogen

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OVERVIEW

Located in the Kimberley region of northern Western Australia, adjacent to the Northern Territory border (Figure 15), the Halls Creek Orogen is a north-east trending corridor of well-exposed highly deformed and metamorphosed sedimentary rocks, volcanogenic sedimentary rocks, volcanics, felsic and mafic intrusive and extrusive rocks (e.g. Griffin and Grey, 1990; Plumb, 1990; Blake et al., 2000). The Halls Creek Orogen, together with the adjacent northwest trending King Leopold Orogen, forms the eastern and southern margin of the concealed Kimberley Craton. The Halls Creek Orogen is considered to broadly represent the lateral equivalent of the Litchfield Province of the Pine Creek Orogen in the Northern Territory, a logical and compelling geological relationship, but one which remains, in detail, not well understood.

This chapter principally describes the time-space evolution of the Halls Creek Orogen, with brief reference to overlying Speewah Group and the Kimberley Group sedimentary rocks, during the interval 1900-1500 Ma. This geological summary is extracted principally from the work of Blake et al. (2000), which summarises the geological observations and relationships, available geochronological data and presents current tectonic models of this region. For a more comprehensive account of the Halls Creek region, the interested reader is directed to Blake et al. (2000) and the references therein.

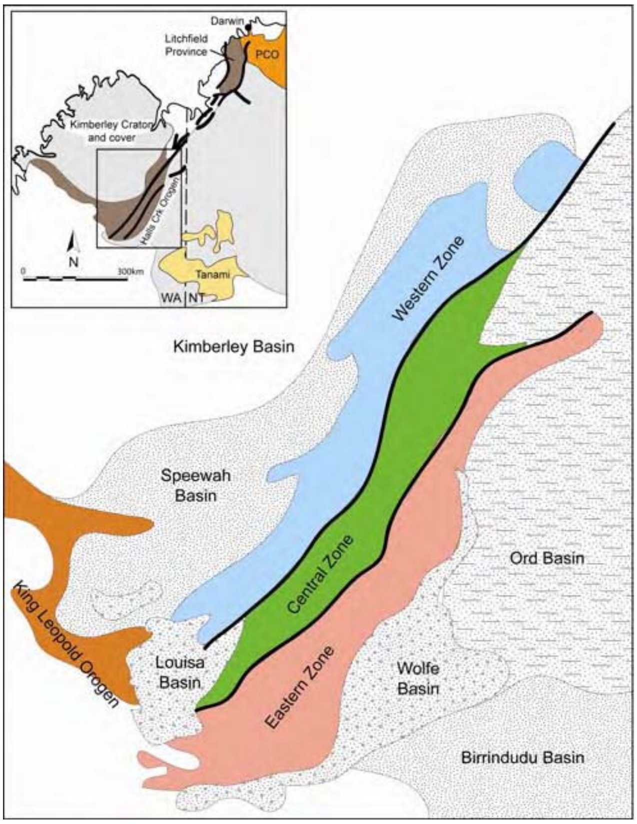


Figure 15: *Location and domain divisions within the Halls Creek Orogen.*

Domain Subdomains

The Halls Creek Orogen has been divided into three north-east trending tectonic domains, each separated by major strike-slip faults. In the following, geological domains of the Halls Creek Orogen are discussed with an emphasis on geochronological constraints, as plotted in the accompanying Time-Space plot (Figure 16).

Mapping by the Geological Survey of Western Australia (GSWA) and the Australian Geological Survey Organisation (AGSO; now Geoscience Australia) in the 1990's resulted in the subdivision of the Halls Creek Orogen into three geologically distinct fault bounded northeast-trending linear belts, namely the Western, Central and Eastern zones (e.g. Tyler et al., 1995; Sheppard et al., 1999; Blake et al., 2000). The western extent of the Western Zone is obscured by the overlying sedimentary rocks of the Palaeoproterozoic Speewah and Kimberley Basins. The boundary between the eastern extent of the Western Zone and the Central Zone is defined by the Ramsay Range Fault and part of the Springvale Fault. The boundary between the Central and Eastern Zone is defined by the Angelo and Halls Creek Fault system. In many places the bounding fault systems have been obscured by 'stitching' 1830-1805 Ma granite plutons of the Sally Downs Supersuite. The eastern extent of the Eastern Zone is obscured by the overlying sedimentary rocks of the Neoproterozoic Wolfe and Palaeozoic Ord Basins.

Each of these zones preserves, in detail, a different geological history and they are interpreted to represent separate tectono–stratigraphic terranes (Tyler et al., 1995). These differences include the timing of sedimentation, deformation and metamorphism (e.g. Sheppard et al., 1999; Tyler et al., 1995, 1999). The present juxtaposition and configuration of these three north-east trending terranes are currently thought to have been accomplished by the closure of an oceanic basin during convergent Phanerozoic-style plate tectonics during the interval ~1860-1835 Ma, a model supported by igneous geochemical signatures indicative of convergent plate tectonic magmatic processes (e.g. Myers 1996; Sheppard et al., 1999, 2001; Griffin et al., 2000; Tyler et al., 1995, 1999, 2001). In contrast, a previously popular model for the tectonic evolution of the Halls Creek orogen (and other northern Australian Proterozoic orogens) favoured incomplete ensialic intracratonic rifting and basin formation driven by localised mantle convection cells with basin inversion following cessation of mantle activity (e.g. Hancock and Rutland, 1984; Etheridge et al., 1987).

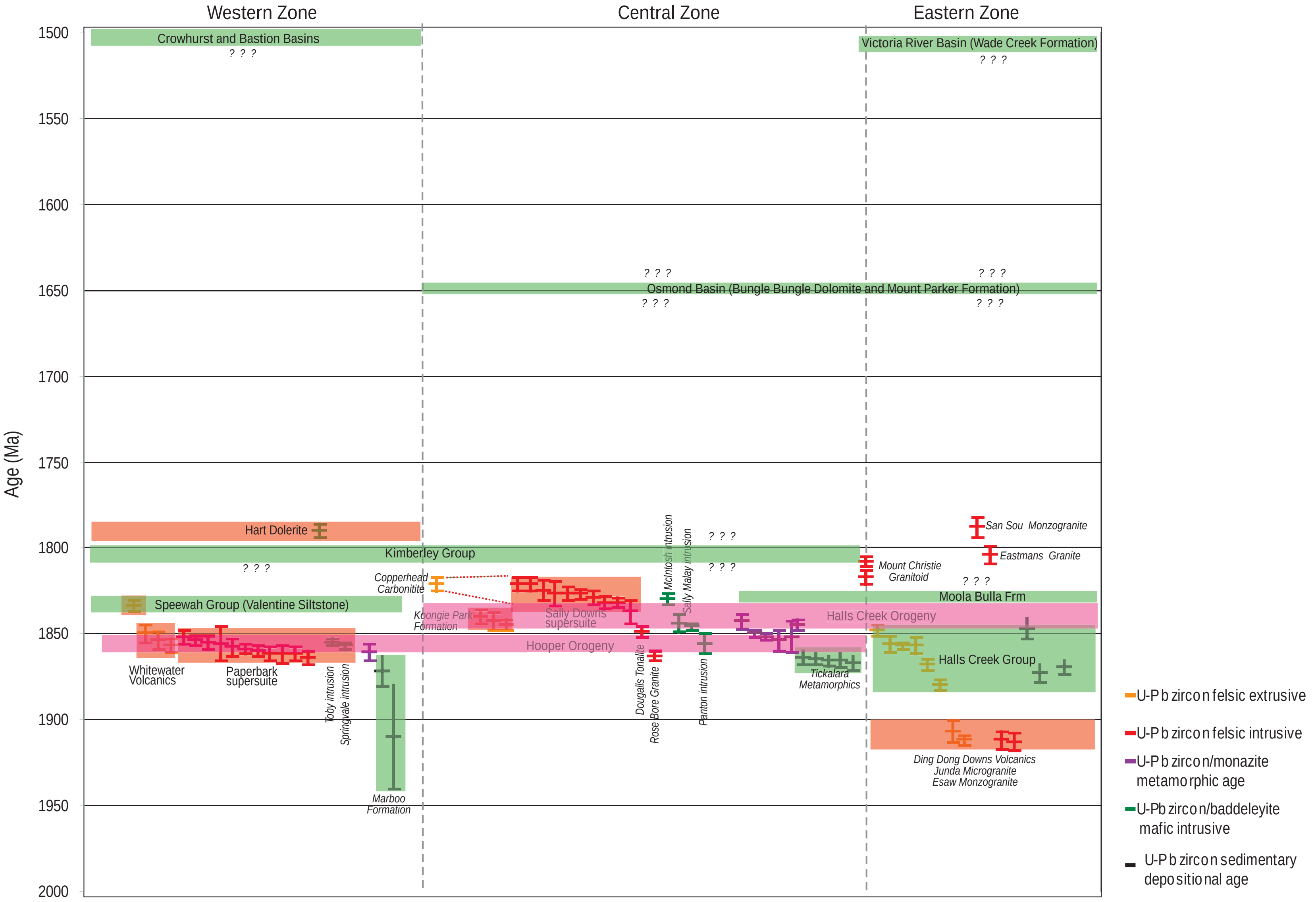
REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Eastern Zone

> 1900 Ma

Unlike the Pine Creek Orogen, no Archaean basement has been detected anywhere in the Halls Creek region. The oldest package of rocks recognised to date in the Halls Creek Orogen include the bimodal Ding Dong Downs Volcanics, the Junda Microgranite and the Sophie Downs Granophyre Member (previously the Sophie Downs Granite), all dated at ~1912-1907 Ma and which may also include the Esaw Monzogranite. These units are exposed in a series of northeast trending anticlinal crests and domes in the southeast extent of the Eastern Zone.

Figure 16 (overleaf): *Geochronological data and summary Time-Space plot for the Halls Creek Orogen.*



Western Zone
Central Zone
Eastern Zone
Age (Ma)
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Crowhurst and Bastion Basins
Victoria River Basin (Wade Creek Formation)
Osmond Basin (Bungle Bungle Dolomite and Mount Parker Formation)
? ? ?
Hart Dolerite
Kimberley Group
Speewah Group (Valentine Siltstone)
Copperhead Carbonitite
Koongie Park Formation
Sally Downs supersuite
McIntosh intrusion
Sally Malay intrusion
Moola Bulla Frm
Halls Creek Orogeny
Hooper Orogeny
San Sou Monzogranite
Eastmans Granite
Mount Christie Granitoid
Halls Creek Group
Tickalara Metamorphics
Whitewater Volcanics
Paperbark supersuite
Toby intrusion
Springvale intrusion
Marboo Formation
Dougalls Tonalite
Rose Bore Granite
Panton intrusion
Ding Dong Downs Volcanics
Junda Microgranite
Esaw Monzogranite
U-Pb zircon felsic extrusive
U-Pb zircon felsic intrusive
U-Pb zircon/monazite metamorphic age
U-Pb zircon/baddeleyite mafic intrusive
U-Pb zircon sedimentary depositional age

1900-1750 Ma

The ~1910 Ma package of bimodal volcanics and intrusives are unconformably overlain by the Halls Creek Group, which is represented by three formations; the Saunders Creek Formation, the Biscay Formation and the Olympio Formation.

The Saunders Creek Formation is characterised by fluvial to shallow marine quartz sandstones and conglomerate that is dominated by Palaeo- to Neoarchaean zircon detritus (Page and Sun, 1994). The Biscay Formation, which conformably overlies the Saunders Creek Formation, consists of low-grade mafic and subordinate felsic volcanics, and clastic sedimentary units and minor carbonate and chert. A felsic ignimbrite and a tuff within the Biscay Formation have been dated by R. Page at ~1880 Ma and 1868 Ma respectively. The Biscay Formation is interpreted by Sheppard et al. (1999) to have been deposited in a shallow marine setting with subaerial to subaqueous volcanism, either on a passive continental margin or intracratonic setting.

The Olympio Formation consists of a package of low- to medium grade turbiditic greywacke, quartz wacke, siltstone, and arkosic sandstone and also contains two alkaline volcanic units, the Maude Headley Member and the Butchers Gully Member. The Maude Headley Member consists of andesitic to trachytic volcanic and volcaniclastic units that have been dated at ~1857 Ma. The Butchers Gully Member contains pillow lavas, chert and trachyte volcanics, that have been dated at ~1857 Ma and ~1848 Ma. Both of these members are underlain and overlain by turbidites. These ages and maximum deposition ages based on detrital zircon from greywacke from the Olympio Formation (~1873 Ma and ~1847 Ma) suggest deposition of the upper Halls Creek Group continued until at least ~1847 Ma.

Following the deposition of the Olympio Formation, both the Halls Creek Group and the underlying ~1910 Ma Ding Dong Downs Volcanics and associated rocks the Eastern Zone was intruded by the undated Woodward Dolerite, and tightly folded and metamorphosed to greenschist to amphibolite facies during the Halls Creek Orogeny at ~1845-1835 Ma. The Halls Creek Orogeny is considered to represent the final stages of collision between the Kimberley Craton and the western margin of the proto-North Australian Craton.

Following the cessation of tectonic activity associated with the ~1835 Ma Halls Creek Orogeny, the emplacement of the post-tectonic Eastman Granite (~1804 Ma), San Sou Monzogranite (~1788 Ma) and the Mount Christine Granitoid (~1817-1808 Ma; considered part of the 1835-1805 Ma Sally Downs Supersuite) occurred (Page et al., 2001). The Mount Christine Granitoid is a ‘stitching granite’ that intrudes across and into both the Eastern and Central Zones and thus represents a minimum limit on the amalgamation of these two terranes. The Moola Bulla Formation, a fluvial or shallow marine deltaic sandstone and mudstone sequence, was deposited into a localised basin (the Moola Bulla basin) in the vicinity of Halls Creek township. The Moola Bulla Formation is thought to have been deposited shortly after the Halls Creek Orogeny, synchronously with the ~1835 Ma Speewah Group in the Western Zone and is unconformably overlain by the Kimberley Group.

<1750 Ma

In the northern part of the Eastern Zone, along the Osmand Range area, Kimberley Group sedimentary rocks are unconformably overlain by the Mount Parker Formation (sandstone, pebbly sandstone, conglomerate and siltstone) and the Bungle Bunge Dolomite (includes stromatolitic chert, sandstone and siltstone) of the Osmond Basin. The Osmond Basin is overlain by the Wade Creek Formation, Ahern Formation and Helicopter Siltstone, all of the Victoria River Basin. Age constraints on the deposition of the Osmond and Victoria River Basin sedimentary rocks are poorly known, but are considered early to middle Mesoproterozoic in age respectively.

Central Zone

1900-1750 Ma

Possibly the oldest rocks in the Central Zone, based on inferred time constraints, are the tightly-folded low-grade mudstones, siltstones, sandstones, carbonates and basaltic volcanics of the Milba Formation. There are no known isotopic dates from this unit. The Milba Formation is fault bounded with all adjacent Proterozoic units and, as such, age constraints are difficult to determine.

Presumably overlying the Milba Formation, the Tickalara Metamorphics represent a diverse and complex package of amphibolite to low-P granulite facies metasedimentary rocks and meta-igneous rocks that are confined to the Central Zone. The sedimentary protoliths of the Tickalara Metamorphics include turbiditic mudstone, siltstone, quartz sandstone, greywacke, chert, carbonate and BIF, whereas igneous precursors include mafic volcanics and bimodal sheet-like felsic intrusives. Pillow basalts have also been recognised. Detrital zircon studies on the sedimentary protoliths indicate a maximum depositional age of ~1865 Ma (Page, OZCHRON; Bodorkos et al., 1999, 2000a). The Tickalara Metamorphics are intruded by the Rose Bore Granite (~1863 Ma, Page and Hoatson 2000) which provides a local minimum constraint of deposition.

The Central zone experienced high–grade metamorphism at ~1855 Ma which correlates with the high–grade metamorphic event observed in the Western Zone (the Hooper Orogeny). Page and Hancock (1988) reported an ID–TIMS U–Pb zircon age of 1854 ± 6 Ma from an anatectic ‘sweat’ pegmatite within the migmatitic Tickalara Metamorphics in the northeast Central Zone and Page and Sun (1994) present a SHRIMP age of 1852 ± 2 Ma from the same ‘sweat’ pegmatite. The Panton layered mafic–ultramafic intrusion was emplaced into the Tickalara Metamorphics at 1856 ± 2 Ma (Page and Hoatson, 2000) crosscutting tight to isoclinal D2 structures and regional metamorphic isograds (Tyler and Page, 1996).

The Tickalara Metamorphics were intruded by the Fletcher Creek Monzogranite, Dougall Tonalite (~1849 Ma), and other tonalite, quartz diorite and gabbro of the Dougalls suite. This suite of intrusions, which includes trondhjemite and tonalite, is notable in that they have geochemistry (low Y, high Sr) that is reminiscent of high-Al tonalite-trondhjemite suites in island-arc in Phanerozoic convergent continental margin settings (Sheppard et al., 1997).

The Koongie Park Formation is exposed in the southern part of the Central Zone, and consists of turbidites sequences, volcaniclastics, shale, chert, basalt and rhyolite and which also contains a sub-economic Zn-Cu-Pb VMS deposit. Three samples of rhyolite have been dated (Page and Sun, 1994) yielding ages of ~1845-1840 Ma which are interpreted to represent extrusion ages.

The Central Zone was tightly folded and regionally metamorphosed during the Halls Creeks Orogeny at ~1845 Ma, before being intruded by the voluminous Sally Downs Supersuite and several layered mafic-ultramafic intrusions (groups VI and VII of Hoatson 2000). The timing of the Halls Creek Orogen is largely defined by Bodorkos et al. (1999, 2000a) and Oliver et al. (1999) using monazite and metamorphic rims on detrital zircon grains from migmatised Tickalara Metamorphics from the northeast Central Zone. These studies conclude that high-grade metamorphism occurred at ~1845 Ma and is attributed to the peak Halls Creek orogenesis.

The Sally Malay intrusion was emplaced at ca1845 Ma based on zircon and baddeleyite U-Pb ages (Page and Hoatson, 2000). Migmatisation in the contact aureole around the McIntosh intrusion has been dated at ~1830 Ma (Page and Hoatson, 2000) which has been interpreted as closely approximating the emplacement age of the McIntosh mafic intrusion. Other ultramafic-mafic intrusions in the Central Zone, such as the Spring Creek and Armanda intrusions, were probably emplaced ~1845-1830 Ma.

The emplacement of the Sally Downs Supersuite largely post-dated the Halls Creek Orogeny. Currently available emplacement ages on the various components of the Sally Downs supersuite are six samples of the Mabel Downs Tonalite (~1837-1827 Ma), McHale Granodiorite and Loadstone monzogranite (~1827 Ma), Sally Downs Tonalite (~1821 Ma), and the Mount Christine Granitoid (~1817-1808 Ma). The emplacement of the Mabel Downs Tonalite has been determined by Bodorkos et al. (2000) to have been emplaced synchronous with the development of the northeast trending Ord River Shear Zone. The Copperhead Carbonatite (including albitite, albite-carbonate fenite and carbonitite breccia), was emplaced at ~1821 Ma. The Eastman Granite (which also intrudes the Eastern Zone) was emplaced at ~1804 Ma.

<1750 Ma

Following tectono-metamorphism associated with the Halls Creek Orogeny, the Central Zone was unconformably overlain by a number of sedimentary sequences of uncertain age. In the southern part of the Central Zone, the Koongie Park Formation is unconformably overlain by the Moola Bulla Formation (see previous description) and the Kimberley Group. In the northeast extent of the Central Zone, the Kimberley Group and possible equivalents (the Red Rock Formation and Texas Downs Formation) lie unconformably on the McHale Granodiorite which is in turn overlain unconformably by the Mount Parker Formation and the Bungle Bunge Dolomite of the ?Mesoproterozoic Osmond Basin.

Western Zone

1900-1750 Ma

The oldest identified rocks in the Western zone are the variably metamorphosed turbiditic sandstones, greywackes and mudstones of the Marboo Formation. The Marboo Formation is interpreted to represent a submarine fan system with palaeo-current data indicating sediment transport from the north and northeast. Based on detrital zircon ages Tyler et al. (1999) concluded that the Marboo Formation was deposited after ~1872 Ma. The Amherst Metamorphics, a package of migmatised paragneisses and orthogneiss, located in the southern regions of the Western Zone, is thought to represent the metamorphosed equivalents of the Marboo Formation. The Amherst Metamorphics was metamorphosed at LPHT conditions sometime 'between 1860 and 1805 Ma' (Griffin et al. 1998; Blake et al. 2000). Similarly, the Mount Joseph migmatite, located in the King Leopold Orogen, is thought to represent metamorphosed Marboo Formation which underwent granulite–grade anatexis at 1861 ± 5 Ma (Tyler et al., 1999) during an early high-temperature phase of the Hooper Orogeny.

Upright folding attributed to later stages of the Hooper Orogeny (ca 1865-1850 Ma) affected the Marboo Formation. Unconformably overlying the folded Marboo Formation, the felsic Whitewater Volcanics consist of quartz-phyric rhyolite, rhyodacite, welded ignimbrite and tuff that were erupted during an episode of subaerial volcanism at ~1860-1850 Ma. The Whitewater Volcanics are co-magmatic with the high-level Castlereagh Hill Porphyry (~1855 Ma) and the Greenvale Porphyry.

Granite plutons of the Paperback Supersuite are confined to the Western Zone (and the King Leopold Orogen) and have high K_2O, Rb, Y and low Sr, typical of many Australian Palaeoproterozoic granite suites. The Paperbark supersuite was emplaced in the interval ~1865-1850 Ma. Individual members of the Paperback Supersuite that have been dated (e.g. Page et al., 2001) include the Lennard Granite (2 samples; ~1863 Ma), Mondooma Granite (~1862 Ma), McSherrys Granodiorite (~1862 Ma), Neville Granodiorite (~1860 Ma), Nyalassy Granite (~1859 Ma), Richenda Microgranodiorite (~1858 Ma), Bow River Granite (~1856 Ma), Paperbark Granite (~1854 Ma) and the Kongorow Granite (~1852 Ma). Recent SHRIMP dating of granitic xenoliths (~1851

Ma) entrained in micaceous kimberlite pipes intruding the Kimberley Basin strongly suggest that the Paperbark supersuite may, in part, underlie the central Kimberley Basin (Downes et al. 2007). Springvale and Toby layered mafic intrusions (Groups II and III of Hoatson et al., 2000), located in the central Western Zone, are coeval with the Paperback supersuite and the Whitewater Volcanics of the Western Zone and the Panton layered mafic-ultramafic intrusion (~1856 Ma) in the Central zone. These mafic intrusions intrude the Marboo Formation and locally the Paperback supersuite. The Springvale intrusion (Group II of Hoatson et al., 2000) is comprised of olivine gabbro, gabbronorite, troctolite, leucogabbro and anorthosite. The leucogabbro component returned a zircon age of ~1857 Ma which is interpreted as an emplacement age (Page and Hoatson, 2000). The Toby intrusion (Group III of Hoatson, 2000) is comprised of biotite-quartz gabbro, biotite gabbro, olivine gabbro and minor troctolite. An inferred emplacement age of ~1855 Ma has been obtained from the biotite-quartz gabbro component. Other, similar, mafic intrusions in the Western Zone such as the Wilagee and Foal Creek intrusions are considered to be of a similar age to the Springvale and Toby intrusions.

In contrast to the Central and Eastern Zones, the Western Zone does not appear to have experienced the effects of the ~1845-1835 Ma Halls Creek Orogeny. Following cessation of tectonothermal activity associated with the ~1865-1850 Ma Hooper Orogeny, the Speewah Group, a sequence of fluvial to shallow marine pebbly conglomerate, sandstone and siltstone, was unconformably deposited onto deformed Whitewater Volcanics. The Valentine Siltstone, a unit within the Speewah Group, contains ~1835 Ma felsic volcanics (Page and Sun, 1994) suggesting the Speewah Group could be up to ca 20 Ma younger that the underlying Whitewater Volcanics. The Speewah Group is in turn disconformably (or very low angle unconformably) overlain by the Kimberley Group. The Kimberley Group (~1800 Ma) is dominated by clastic sedimentation (sandstone, siltstone and mudstone) and a mafic volcanic unit, the Carson Volcanics, which is comprised of basalt, basaltic volcaniclastics, amygdaloidal basalt and minor sandstone and siltstone. A possible correlative of the Kimberley Group, the Revolver Creek Formation (arkose, siltstone, conglomerate and basaltic rocks) is exposed in northern regions of the Western Zone. The Kimberley Group extends eastward (but not the Speewah Group) over the Central and Eastern Zones, and westward to conceal much of the inferred Kimberley Craton. Intruding both the Speewah and Kimberley Group is the Hart Dolerite (~1790 Ma).

OUTSTANDING QUESTIONS AND SCOPE FOR FUTURE PROJECTS

The three tectonic domains of the Halls Creek Orogen exhibit differences in timing of sedimentation, deformation events and metamorphism (e.g. Sheppard et al., 1999; Tyler et al., 1995, 1999).Together with igneous geochemical signatures, these differing characteristics have been used in support of convergent plate tectonic processes (e.g. Sheppard et al., 1999, 2001). In this model, the closure of a wide oceanic basin between the Kimberley Craton and the proto–North Australian Craton resulted in unification of the three Halls Creek domains, once widely separated geological entities. Better discrimination of the relationships and differences between the three tectonic domains is central to the understanding of the three tectonic domains and of refinement of any proposed tectonic model and how such a model may relate to the Pine Creek Orogen and the North Australian Craton.

Possible avenues of future research might include:

- Improved discrimination of the depositional age of turbidite sequences from the three domains, via intercalated tuffs or detrital zircon analysis. The difference in depositional ages of turbidite sequences in the three domains is an important component of the currently accepted plate tectonic model, but the available dataset can be refined considerably.
- Provenance studies of the sedimentary sequences from the three domains in order to assess the similarity or otherwise of the source regions. This will facilitate assessment of proximity (or otherwise) of the NAC and the Kimberley regions during the evolution of the Halls Creek Orogen. Nd isotopes studies on these sedimentary rocks and Hf isotope work on detrital zircons may also provide critical information on source regions.
- Better understand the links, or otherwise, between the pre- and post-tectonic sedimentary packages in the Halls Creek Orogen with similar units in the Litchfield Province and central Pine Creek regions, via detrital zircon analysis to better constrain the lithostratigraphic relationships between the Halls Creek and Pine Creek regions.
- Available chronology of metamorphic events across the Halls Creek Orogen is somewhat limited. Resolution of the areal distribution of Halls Creek (currently recognised in the Central and Eastern Zones) and Hooper aged metamorphism (currently recognised in Western and Central Zones) will enable better correlation of tectonic events within the Halls Creek region, better constrains of tectonic models and further understanding of the relations with the Pine Creek Orogen.

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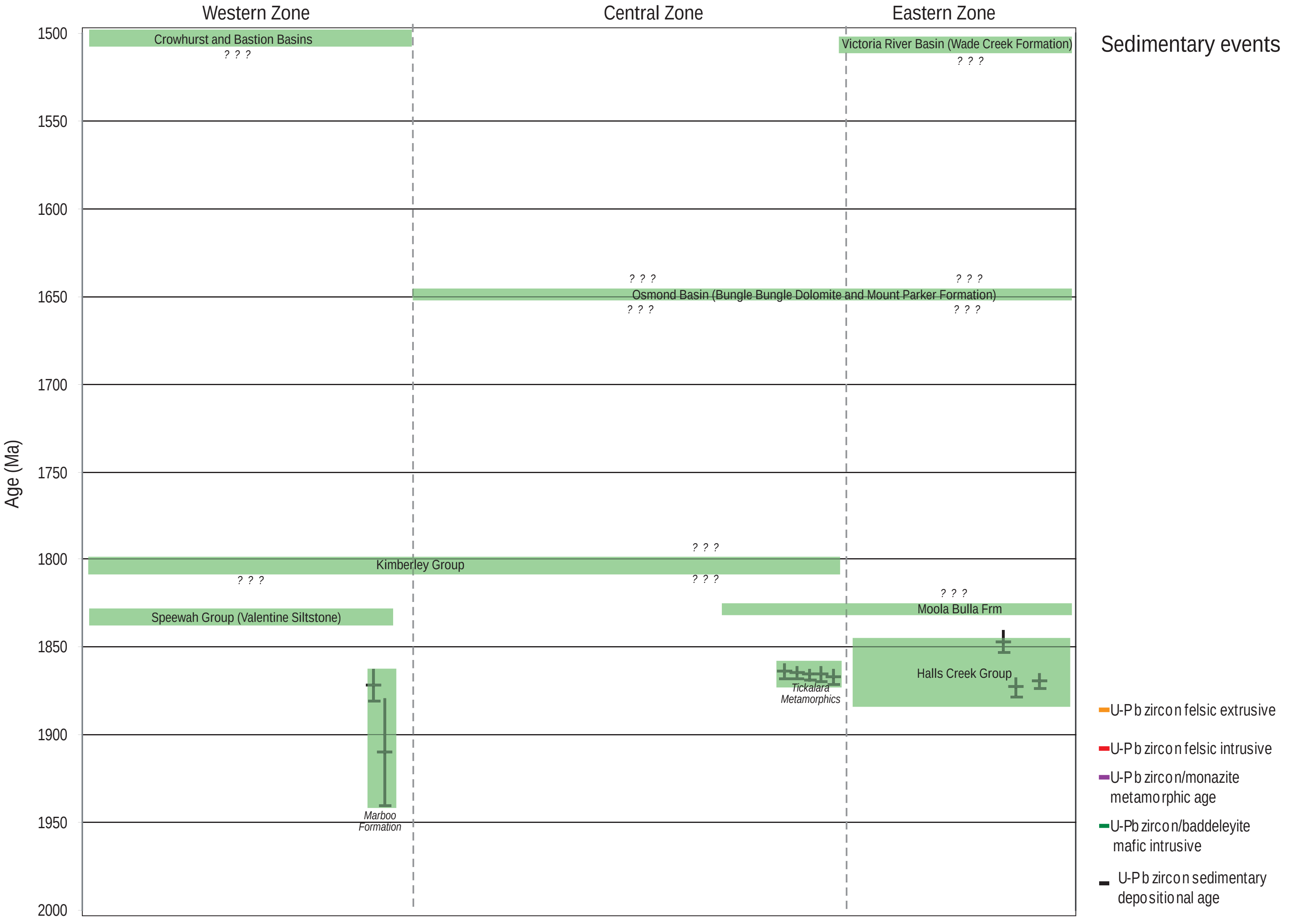
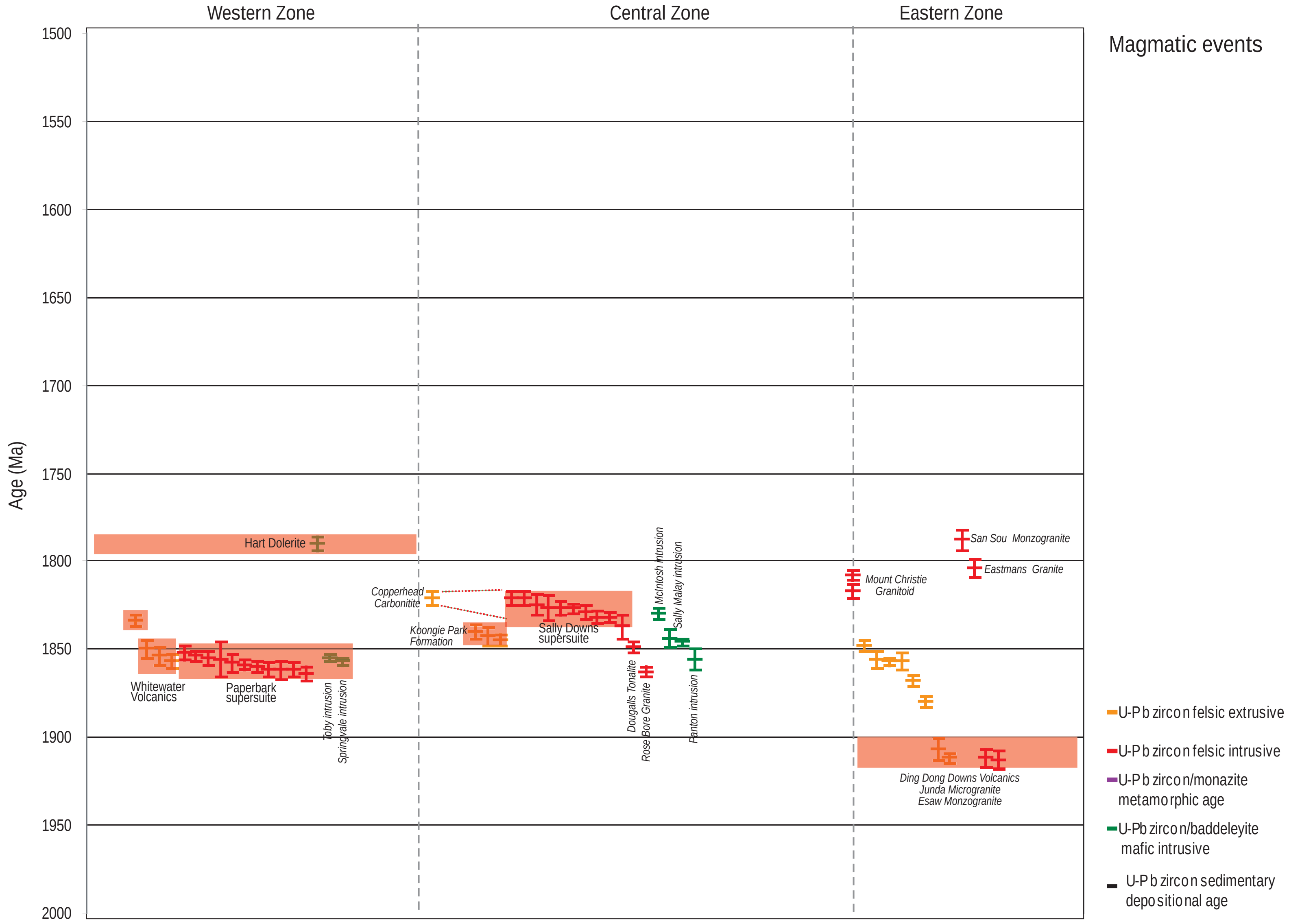
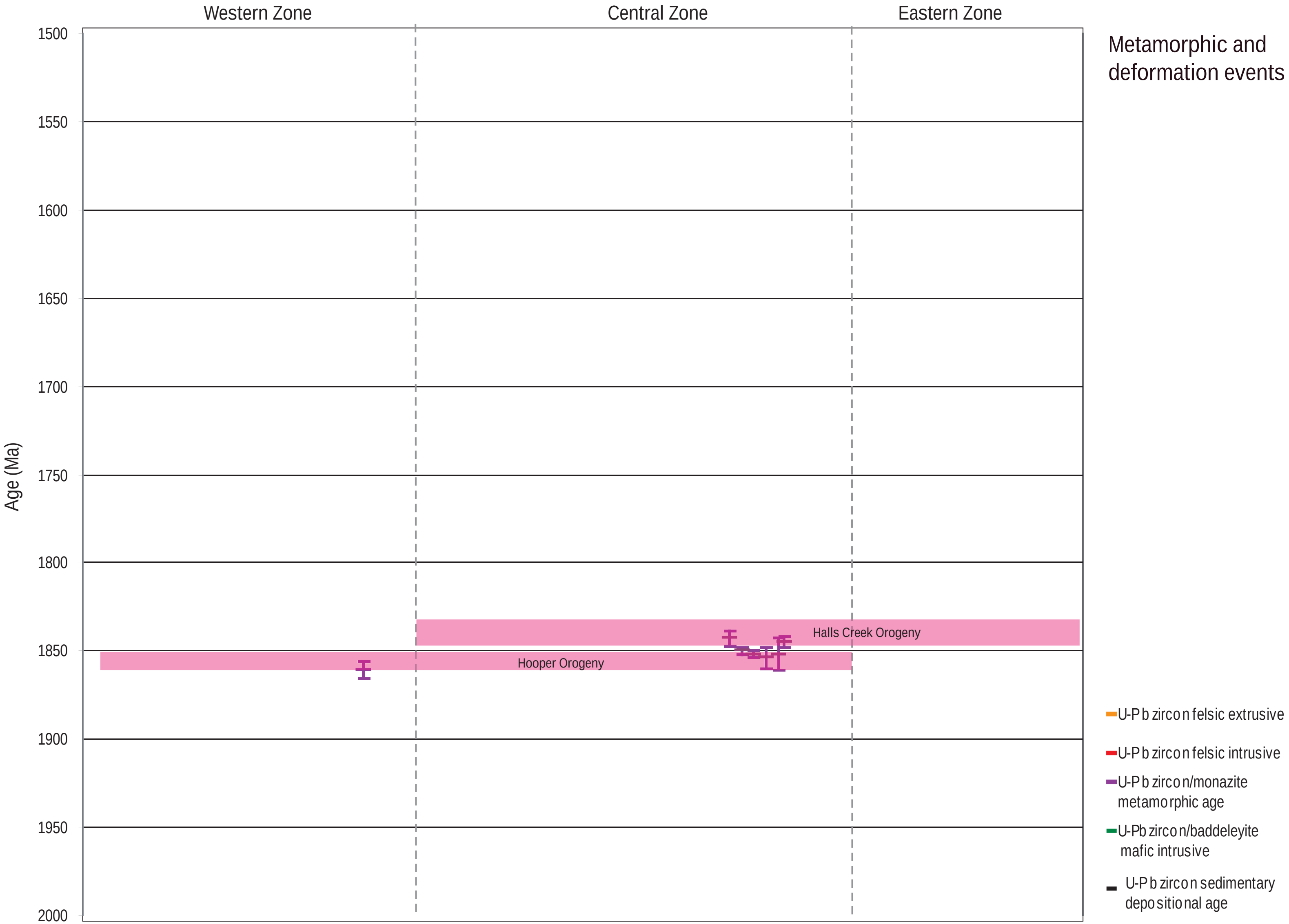

Western Zone
Central Zone
Eastern Zone
Sedimentary events
Age (Ma)
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Crowhurst and Bastion Basins
? ? ?
Victoria River Basin (Wade Creek Formation)
? ? ?
Osmond Basin (Bungle Bungle Dolomite and Mount Parker Formation)
Kimberley Group
Speewah Group (Valentine Siltstone)
Moola Bulla Frm
Halls Creek Group
Tickalara Metamorphics
Marboo Formation
U-Pb zircon felsic extrusive
U-Pb zircon felsic intrusive
U-Pb zircon/monazite metamorphic age
U-Pb zircon/baddeleyite mafic intrusive
U-Pb zircon sedimentary depositional age


Western Zone
Central Zone
Eastern Zone
Magmatic events
Age (Ma)
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Hart Dolerite
Whitewater Volcanics
Paperbark supersuite
Toby intrusion
Springvale intrusion
Copperhead Carbonitite
Koongie Park Formation
Sally Downs supersuite
McIntosh intrusion
Sally Malay intrusion
Dougalls Tonalite
Rose Bore Granite
Panton intrusion
Mount Christie Granitoid
San Sou Monzogranite
Eastmans Granite
Ding Dong Downs Volcanics
Junda Microgranite
Esaw Monzogranite
U-Pb zircon felsic extrusive
U-Pb zircon felsic intrusive
U-Pb zircon/monazite metamorphic age
U-Pb zircon/baddeleyite mafic intrusive
U-Pb zircon sedimentary depositional age


Metamorphic and deformation events
Western Zone
Central Zone
Eastern Zone
Age (Ma)
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Halls Creek Orogeny
Hooper Orogeny
U-Pb zircon felsic extrusive
U-Pb zircon felsic intrusive
U-Pb zircon/monazite metamorphic age
U-Pb zircon/baddeleyite mafic intrusive
U-Pb zircon sedimentary depositional age

Time-Space evolution of the Rudall Complex and eastern Pilbara Craton

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OVERVIEW

The Rudall Complex is an inlier of multiply deformed and metamorphosed Palaeo- to Mesoproterozoic rocks comprising part of the Paterson Province of Western Australia (Figure 17). The Rudall Complex is situated ~150 km east of the Archaean Pilbara Craton and is overlain by Neoproterozoic and Phanerozoic sedimentary successions of the Yeneena, northwest Officer and Canning basins.

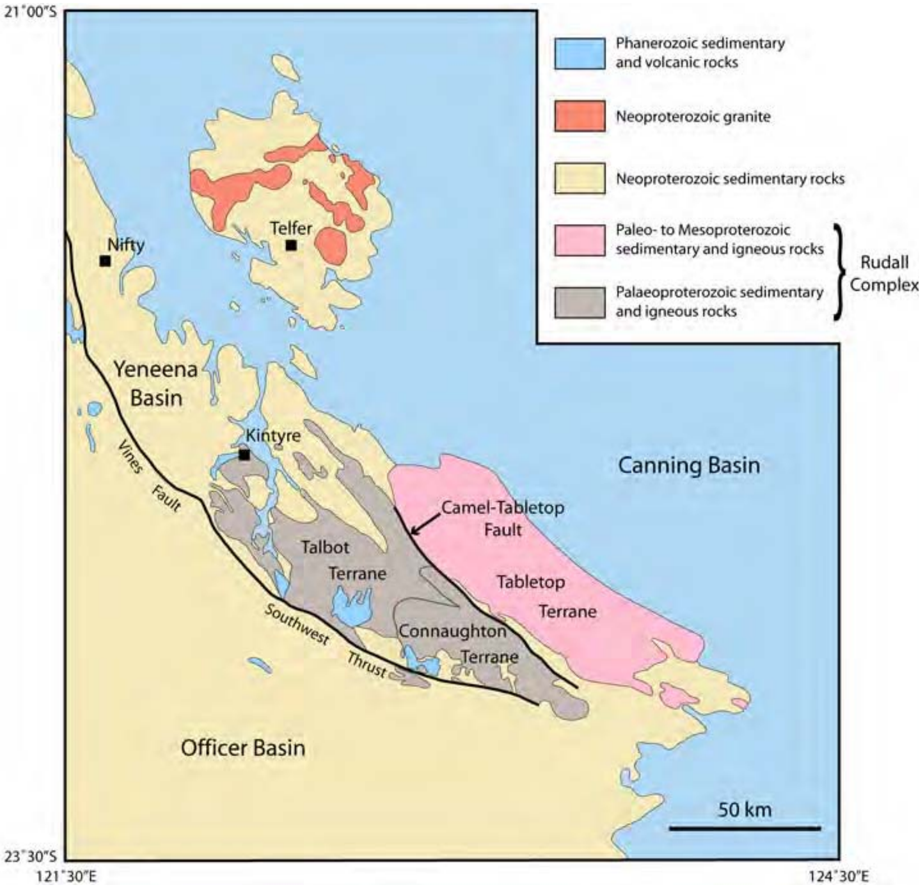


Figure 17: *Geological subdivision of the Paterson Province (after Ferguson and Bagas 2005).*

The Rudall Complex has been subdivided into three major lithological and structural components: the Talbot, Connaughton and Tabletop Terranes (e.g. Bagas, 2004). Although there are relatively few geochronological data constraining the ages the supracrustal successions in these terranes, the available data suggests that the Talbot and Connaughton terranes share some common aspects of their evolution. In contrast, the poorly exposed Tabletop Terrane, which is separated from the Talbot and Connaughton terranes by the Camel-Tabletop Fault, appears to have significant differences from the two western terranes. For this reason, the Talbot and Connaughton terranes have been presented separately from the Tabletop Terrane in this summary.

The geological domains of the Paterson Orogen are discussed below with an emphasis on geochronological constraints, as plotted in the accompanying Time-Space plot (Figure 18). The geochronological data are plotted in one 500 million year interval, 1900 Ma to 1400 Ma, although an overview of geochronological data not encompassed in these time intervals is provided where applicable. Also included on the time-space-event plot are geochronological data from the only Proterozoic granitic suite within the Pilbara Craton (Bridget Suite), which forms a NNW-trending belt ~200 km to the west of the Rudall Complex. The Archaean geological record in the Pilbara Craton is not considered in this compilation.

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

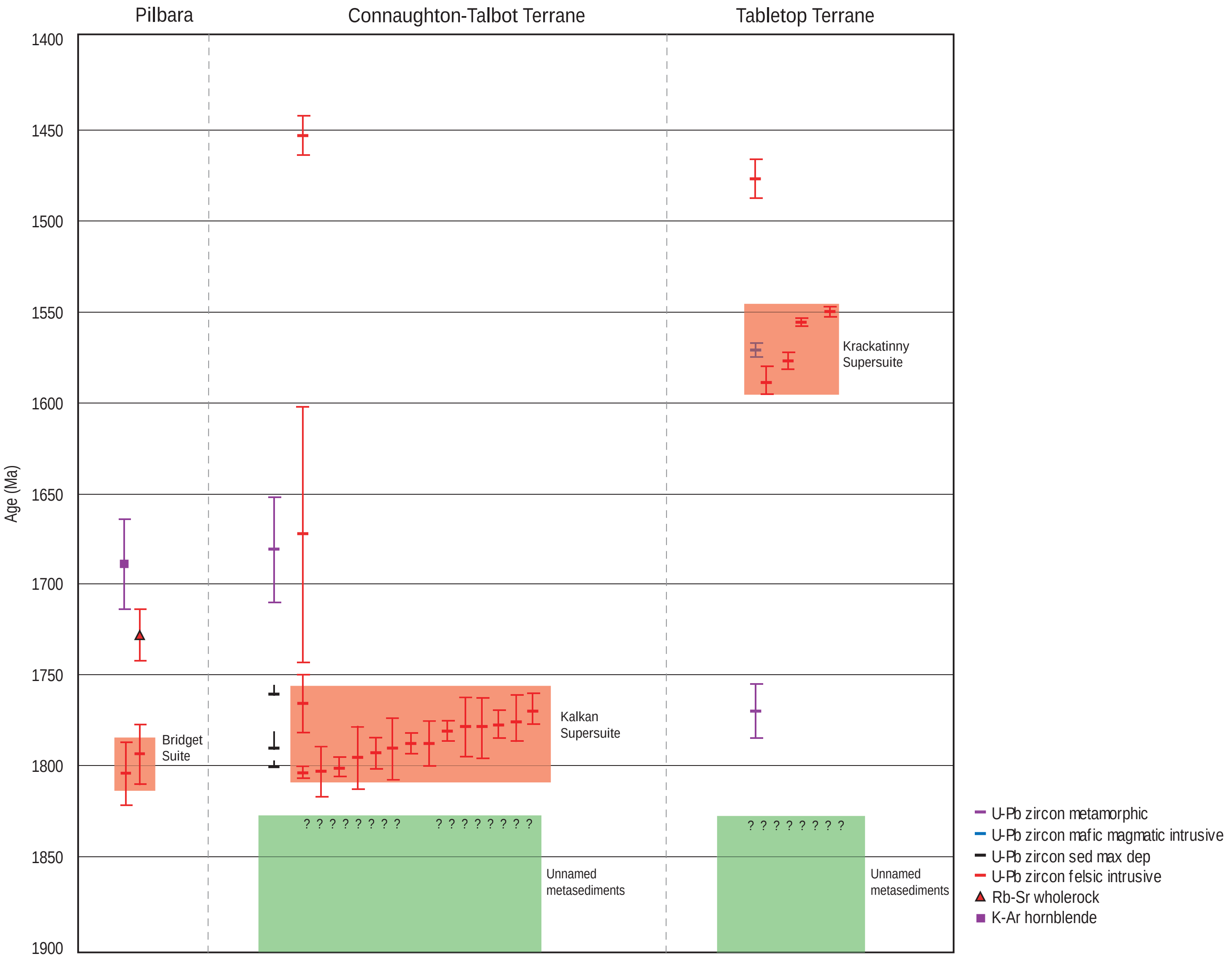
Talbot-Connaughton Terranes

Talbot Terrane

The Talbot Terrane consists of supracrustal rocks and felsic intrusives that have been multiply deformed and metamorphosed up to amphibolite-facies (Smithies and Bagas, 1997). The supracrustal rocks consist of quartzite, metapelite, amphibolite, ultramafic rock and iron formation. These rocks have been intruded by voluminous felsic intrusives termed the Kalkan Supersuite by Budd et al. (2001), and constitute ~50% of the terrane by area (Hickman and Bagas, 1998). The felsic intrusives, which intrude all levels of the supracrustal succession, range in age between ~1800 Ma and ~1760 Ma (Nelson, 1995, 1996; Maidment et al., in prep.). This provides a minimum age constraint on the depositional age of the protoliths to the metasedimentary succession, which have few detrital zircon dates to provide a maximum age constraint. The only unit for which detrital zircon data are available, the Fingoon Quartzite, has an essentially unimodal population of zircon at 1800-1790 Ma (Nelson, 1995; Maidment et al., unpubl. data), consistent with derivation from the oldest felsic intrusives in the region. Two samples of layered orthogneiss from the terrane yielded populations of 2015 ± 26 and 1972 ± 4 Ma (not plotted), interpreted as intrusive ages (Nelson, 1995), which would indicate that some metasedimentary units in the succession are significantly older than the ~1800-1760 Ma depositional age of the Fingoon Quartzite. However, it is not clear to what extent these age populations might reflect inheritance and it remains an open question whether the Talbot Terrane contains an older metasedimentary succession.

The precise timing of metamorphic and deformational events within the Talbot Terrane remains to be established. The terrane experienced two high-grade events in the Palaeoproterozoic (D1/D2), comprising phases of the Yapungku Orogeny (Bagas, 2004). The timing of the Yapungku Orogeny is interpreted to be coincident with the emplacement of the widespread felsic intrusives in the region, i.e. 1800-1760 Ma (Bagas, 2004; Hickman and Bagas, 1999), though there is little in the way of metamorphic zircon age data to confirm this. A SHRIMP U-Pb zircon age of 1778 ± 16 Ma obtained for an aplite dyke (Nelson, 1995) has been used to constrain the minimum age of the D2 event, based on an interpretation that it post-dates the S2 foliation (e.g. Bagas, 2004; Hickman and Bagas, 1999). However, more recent examination of aplite dykes in the area suggests that these intrusives were variably foliated during the D2 event and thus do not provide a minimum age constraint (Maidment et al., unpubl. data). Three analyses of low-U metamorphic rims from a ~1800 Ma felsic orthogneiss yielded an imprecise age of 1680 ± 29 Ma (Maidment et al., in prep.), but until further metamorphic ages are obtained, it remains uncertain whether this age reflects metamorphism of the Yapungku Orogeny or a separate thermal event.

Figure 18 **(overleaf):** *Geochronological data and summary Time-Space plot for the Rudall Complex and eastern Pilbara Craton.*



Pilbara
Connaughton-Talbot Terrane
Tabletop Terrane
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Krackatinny Supersuite
Kalkan Supersuite
Bridget Suite
? ? ? ? ? ? ? ?
? ? ? ? ? ? ? ?
? ? ? ? ? ? ? ?
Unnamed metasediments
Unnamed metasediments
U-Pb zircon metamorphic
U-Pb zircon mafic magmatic intrusive
U-Pb zircon sed max dep
U-Pb zircon felsic intrusive
Rb-Sr wholerock
K-Ar hornblende

Connnaughton Terrane

The Connaughton Terrane has a significantly higher proportion of amphibolite than the Talbot Terrane, derived from metamorphism of tholeiitic basaltic precursors (Bagas and Smithies, 1998). The amphibolite is interlayered with banded iron formation, quartzite, metapelite, chert and ultramafic rock. Only one sample of the supracrustal succession has been dated using detrital zircon, a quartzite which yielded a maximum depositional age of ~2300 Ma (Maidment et al., in prep.). The provenance signature of this metasedimentary rock is significantly different from those obtained from the Fingoon Quartzite in the Talbot Terrane, but there are insufficient data available to determine whether the metasedimentary successions in the two terranes are of different ages.

Felsic intrusives with similar ages to those dated in the Talbot Terrane occur within the Connaughton Terrane. Felsic orthogneisses have yielded ages of 1781 ± 5 Ma, 1777 ± 7 Ma, 1769 ± 7 Ma (Nelson, 1995; Bagas and Smithies, 1998, Maidment et al., in prep.), indicating that protoliths to the metasedimentary rocks in the terrane were deposited between ~2300 Ma and ~1780 Ma. A pegmatite with an age of 1291 ± 10 Ma close to the Camel-Tabletop Fault (Nelson, 1995) reflects a later thermal event.

The rocks of the Connaughton Terrane have been metamorphosed at upper amphibolite- to granulite-facies conditions (peak 800ºC, 12 kbar), interpreted to reflect collision between the Western Australian Craton and a continent to the northeast (Smithies and Bagas, 1997). The timing of this metamorphism remains unclear, but has been interpreted to be coeval with the lower-pressure metamorphism of the Yapungku Orogeny (D2) in the Talbot Terrane (Smithies and Bagas, 1997; Hickman and Bagas, 1999; Bagas, 2004). The only sample with dated metamorphic zircon overgrowths from the Connaughton Terrane yielded an age of ~1334 Ma (Maidment et al., in prep.), but it is unclear whether this records the timing of the high-pressure event or later tectonism. SHRIMP U-Pb dating of a sheared garnet microgneiss in the Harbutt Range yielded three populations at ~1800 Ma, 1672 ± 70 Ma and 1222 ± 63 Ma (Nelson, 1995), with the youngest group interpreted to date crystallisation of the felsic intrusive precursor. However, other interpretations are possible, and the two younger events might record the effects of overprinting tectonism.

Tabletop Terrane

Exposures of the poorly exposed Tabletop Terrane are dominated by weakly deformed and metamorphosed felsic and mafic igneous rocks, with minor quartzite, banded iron formation, ultramafic rock and calc-silicate (Bagas, 1999). The first felsic intrusive samples to be dated from the terrane yielded ages of 1476 ± 10 Ma (PNC unpubl. data, referred to in Bagas, 2004) and 1310 ± 4 Ma (Nelson, 1996). Recent geochronology in the terrane has revealed that many, if not most, of the felsic and mafic intrusives away from the Camel-Tabletop Fault (termed the Krackatinny Supersuite) were emplaced between ~1590 Ma and ~1550 Ma (Maidment et al., in prep.). The Tabletop Terrane has a generally high Bouguer gravity signature, indicating that mafic rocks are more widespread than outcrop exposures would suggest.

A sample of quartzite analysed for detrital zircon gave a maximum depositional age of ~2840 Ma, with a significantly different provenance spectrum to sedimentary rocks in the Talbot or Connaughton terranes. There are not enough detrital zircon data for the Rudall Complex as a whole to evaluate whether this difference indicates that there is a significant difference between the supracrustal successions in the Talbot-Connaughton and Tabletop terranes. However, the apparent absence of 1800-1760 Ma magmatism in the Tabletop Terrane and the lack of 1590-1550 Ma magmatism in the Talbot-Connaughton terranes implies that the Camel-Tabletop is a major crustal boundary.

Eastern Pilbara Craton

Bridget Suite

The Bridget Suite, named by Budd et al. (2001) after the 'Bridget Adamellite' (Hickman, 1978), forms a north-northwest trending belt in the Bamboo Creek area of the Archaean Pilbara Block of Western Australia, which is sub-parallel to, and about 100 km to the west of, the Paterson Orogen (Bagas, 2004). The Pilbara Craton comprises Palaeo- to Mesoarchaean (3655-2830 Ma) granite–greenstone successions of the northern Pilbara Craton, and the unconformably overlying Neoarchaean to Palaeoproterozoic (2770-2400 Ma) volcanic and sedimentary formations of the Hamersley Basin (Fortescue and Hamersley Groups of the Mount Bruce Supergroup; Hickman, 1983; Trendall, 1990; Blake, 1993). The Bridget Suite intrudes the Mosquito Creek Formation, Mount Bruce Supergroup, Warrawoona and Gorge Creek Groups. It is the only known Proterozoic granite suite in the Pilbara Block, and hence, a brief overview of the available geochronology is warranted. Limited age data for this suite is included on the time-space-event plot for the Paterson Orogen, and is thus discussed in this section.

The Bridget Suite includes the Parnell Quartz Monzonite (after Collins et al., 1988) and several other unnamed plutons, and is dominantly comprised of fine- to medium-grained, massive hornblende-bearing granodiorite to monzogranite. Rock and Barley (1988) classified the suite as calc-alkaline lamprophyres using texture and chemistry (e.g. high F, Ba, and K). The suite is Sr-undepleted, Y-depleted, fractionated, and shows minor alteration (Budd et al., 2001). Bagas (2005) raises the possibility that the Bridget Suite may represent a far-field effect of major continent–continent collision during the Yapungku Orogeny.

The Parnell Quartz Monzonite at Granite Hills Well (sample 169030), was sampled for dating by Nelson (2002). The preferred interpretation is that an age of 1803 ± 19 Ma, indicated by the weighted mean $^{207}Pb/^{206}Pb$ ratio of four slightly discordant analyses, provides an estimate of the age of igneous crystallization of the monzodiorite. Dating of zircons from a trondhjemitic pegmatite vein (GSWA sample 178232) yielded a weighted mean U-Pb age of 1793 ± 17 Ma, interpreted as the crystallization age of the sample (GSWA, 2006).

Collins et al. (1988) provides an imprecise Rb-Sr whole-rock age of 1731 ± 14 Ma (initial ratio: 0.7055 ± 2) for samples of quartz monzonite of the Parnell Quartz Monzonite, which the authors concluded as the best estimate of the age of the pluton.

K-Ar analyses were obtained from two samples by Nelson (2002). Both samples yielded K-Ar analyses not within error of a single value, indicating that the K and/or Ar within either or both hornblende fractions analysed for each sample have been disturbed since crystallization. The oldest K-Ar date of 1674 ± 33 Ma for micromonzonite intruding the Mount Edgar Granitoid Complex, East Pilbara Granite–Greenstone Terrane (sample 169032) is interpreted as a minimum age for igneous crystallization. The oldest K–Ar date of 1310 ± 27 Ma for monzonite intruding basalts of the Kylena Formation, Fortescue Group, Hamersley Basin (sample 144683) is interpreted as a minimum age for igneous crystallization of the monzonite (not plotted). Ion-microprobe U–Pb zircon data for the same sample yield a weighted mean U-Pb age of 2764 ± 6 Ma, interpreted by Nelson (2002) to provide a maximum age for igneous crystallization of the monzonite. It is most likely that this age records that of xenocrysts within the sample and is not plotted.

OUTSTANDING QUESTIONS AND SCOPE FOR FUTURE PROJECTS

The general paucity of geochronological data in the Rudall Complex, despite recent advances, means that many of the major tectonothermal events in the region are still poorly understood:

Timing of high-grade (high-P) metamorphism.

There is a need to directly date the high-grade metamorphism within the Rudall Complex, particularly the 12 kbar event which could reflect a continental collision, possibly the docking of the North and West Australian cratons. Metamorphic zircon overgrowths are rare within the complex, and there are few rocks which preserve high-P assemblages due to the greenschist-facies overprint of the ~650 Ma Miles Orogeny, but a focussed study might yield suitable samples for dating.

Ages of the supracrustal successions in the Talbot, Connaughton and Tabletop terranes.

There are currently insufficient data to resolve whether there are significant differences between the successions in the three identified terranes, or whether there might be basement and cover relationships within them. Further dating of metasedimentary rocks and bracketing igneous events would help to resolve to what degree these three blocks represent distinct terranes, and when they were juxtaposed.

Effects and geodynamic setting of the ~1330-1290 Ma event.

There is currently a relatively small dataset indicating that there was both magmatism and high-grade metamorphism at this time, but the nature of any associated deformation and the geodynamic setting of this event are largely unknown, though it coincides with the onset of tectonism in both the Albany-Fraser and Musgrave provinces.

The geodynamic setting and mineral potential of 1590-1550 Ma magmatism.

The geodynamic setting of the recently dated Krackatinny Supersuite remains to be established. Further geochemical and isotopic studies, particularly of mafic lithologies from drillcore beneath the weathering profile could provide important information about the setting of this magmatism and its potential role in mineral systems.

Age of the Bridget Suite

While a tentative intrusive age of ~1800 Ma for the Bridget Suite is indicated, it is clear that additional geochronology is required to ascertain the Proterozoic status of this suite.

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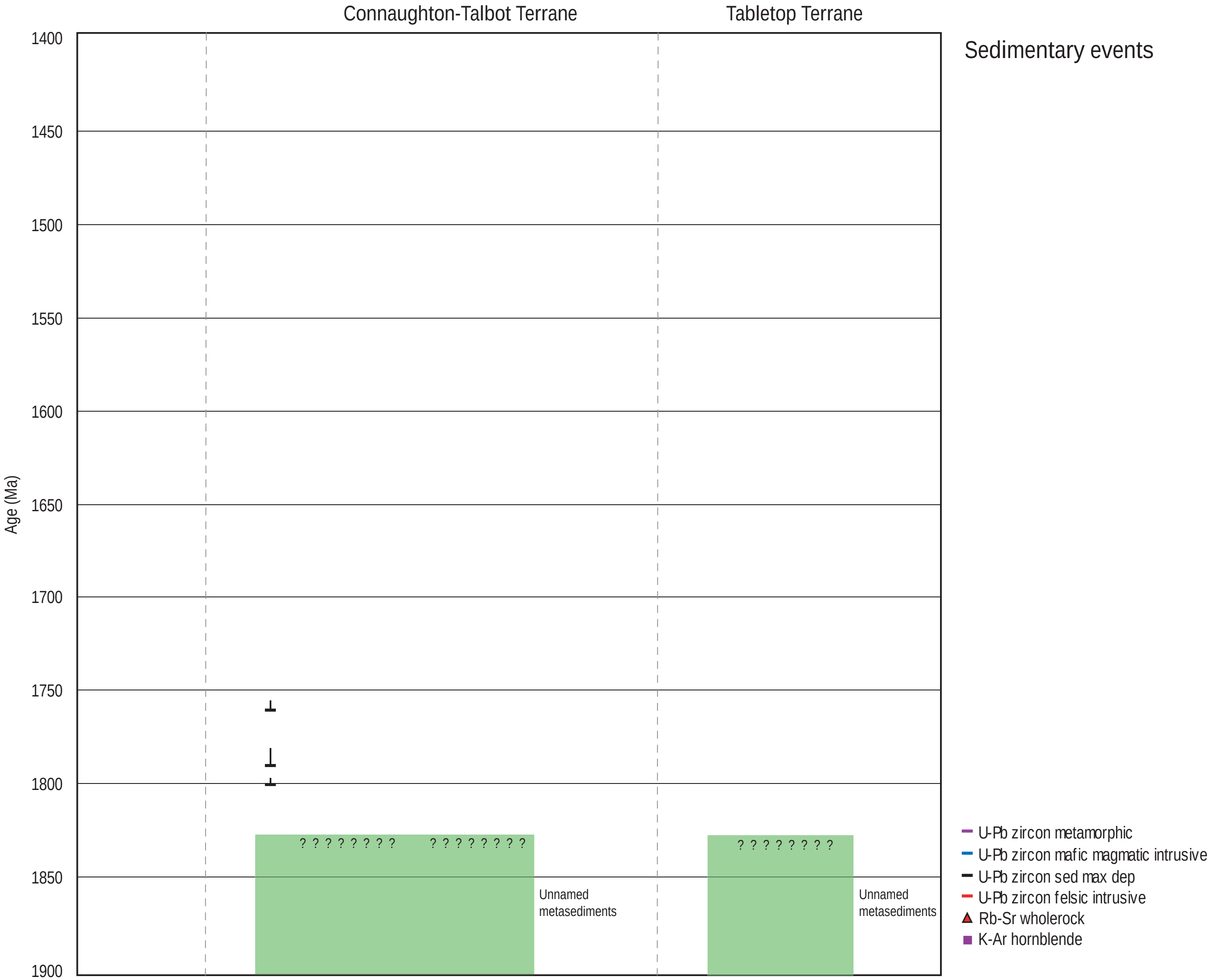
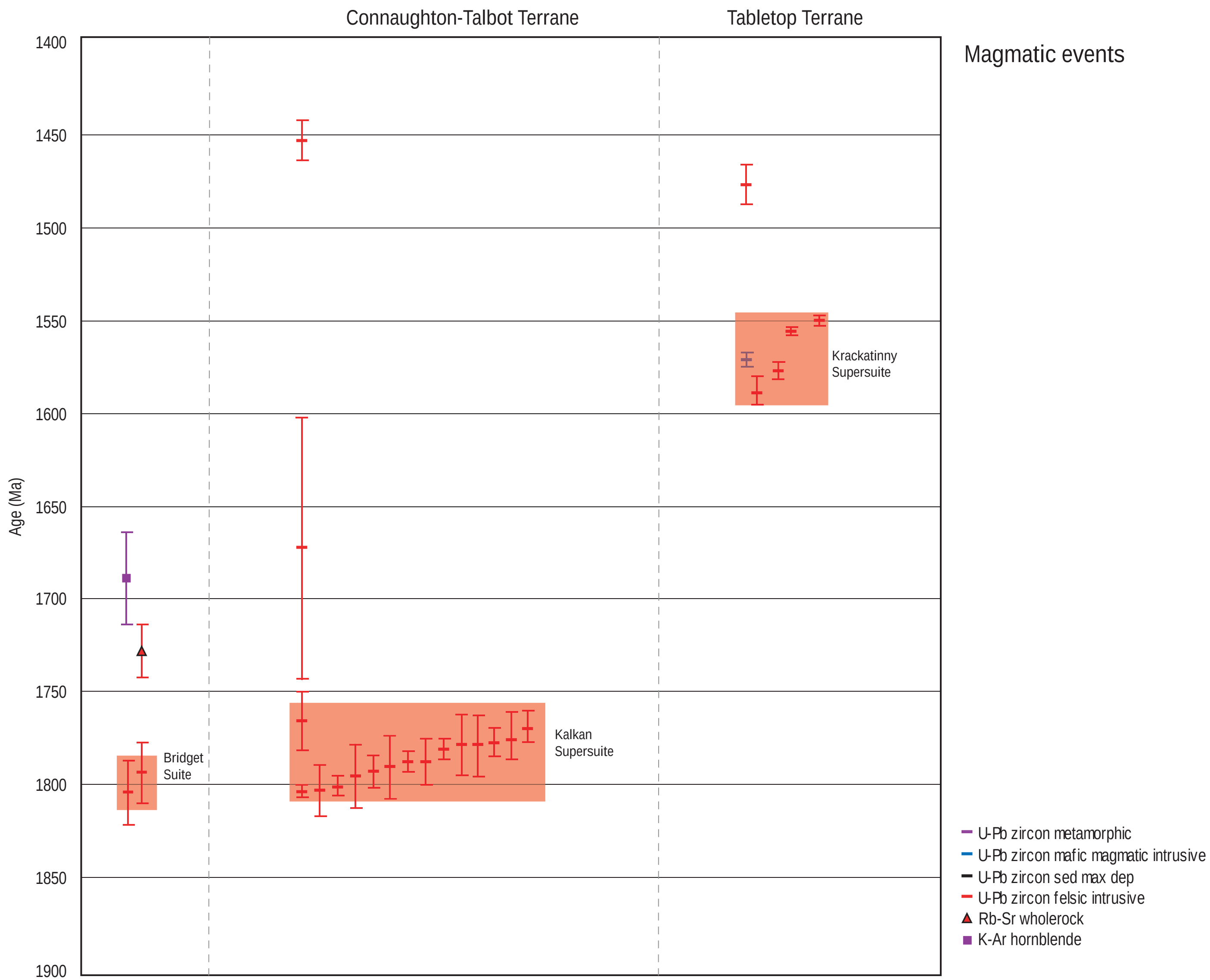
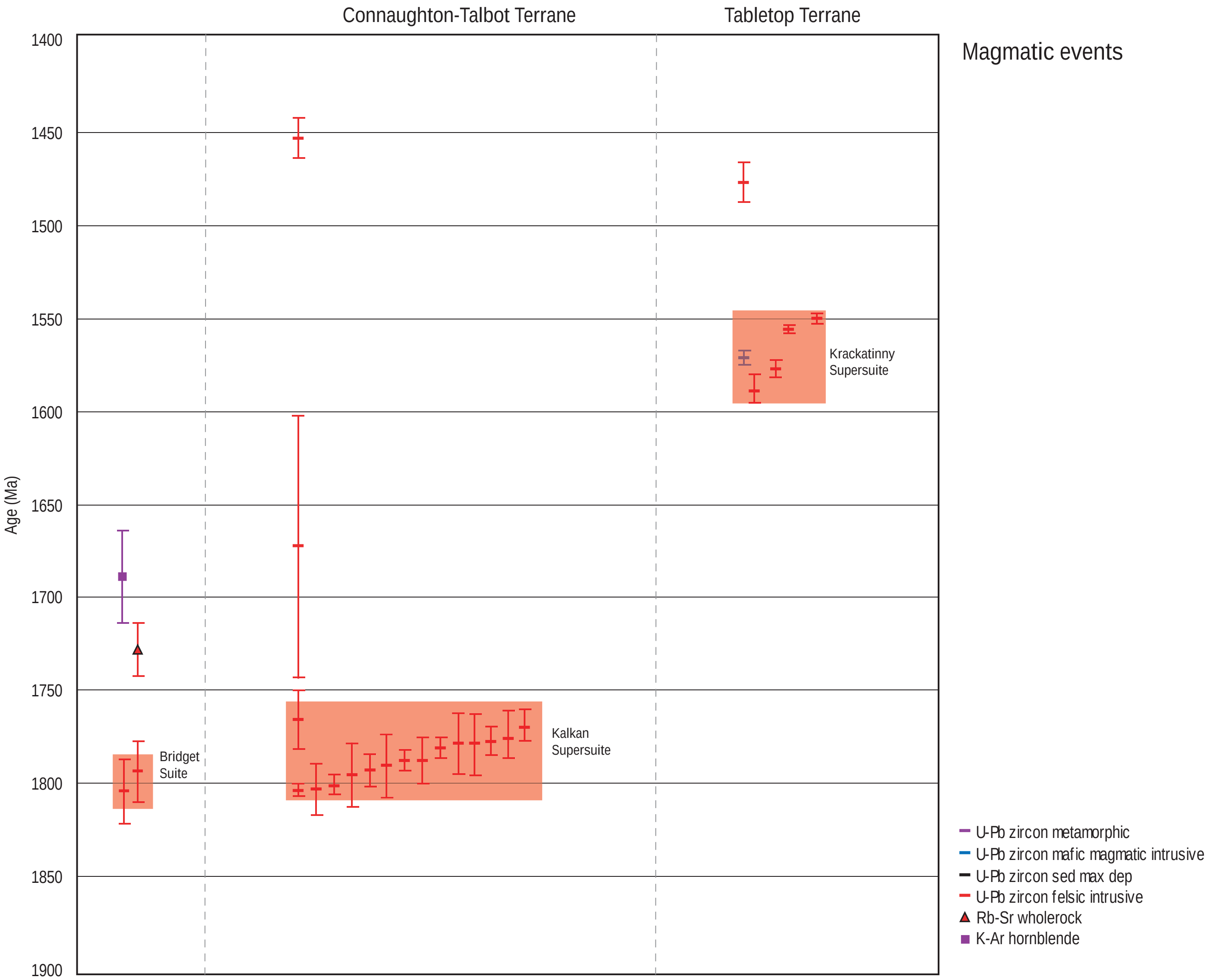
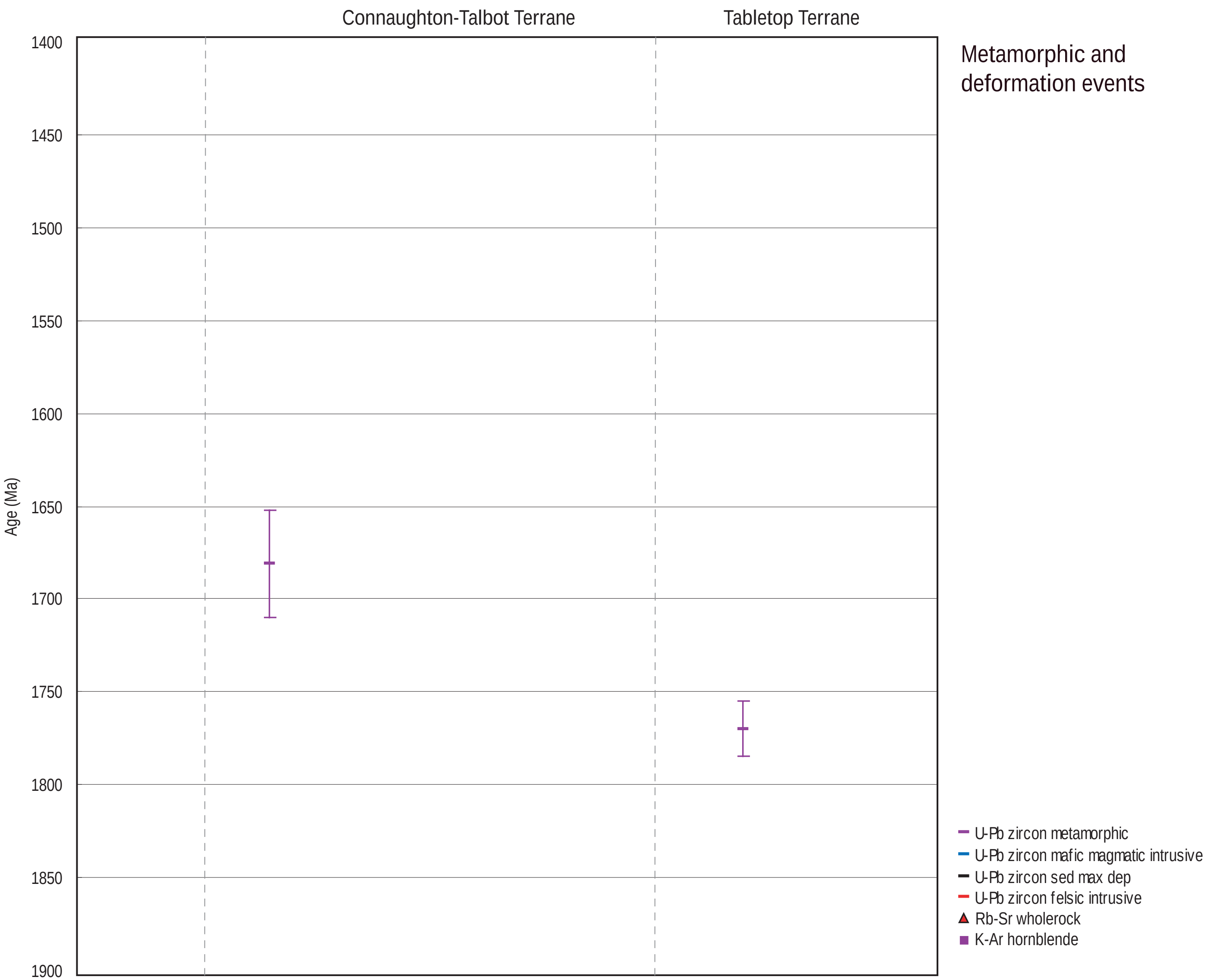
Sedimentary events





Connaughton-Talbot Terrane
Tabletop Terrane
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Krackatinny Supersuite
Kalkan Supersuite
Bridget Suite
U-Pb zircon metamorphic
U-Pb zircon mafic magmatic intrusive
U-Pb zircon sed max dep
U-Pb zircon felsic intrusive
Rb-Sr wholerock
K-Ar hornblende


Connaughton-Talbot Terrane
Tabletop Terrane
Magmatic events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Krackatinny Supersuite
Kalkan Supersuite
Bridget Suite
U-Pb zircon metamorphic
U-Pb zircon mafic magmatic intrusive
U-Pb zircon sed max dep
U-Pb zircon felsic intrusive
Rb-Sr wholerock
K-Ar hornblende


Connaughton-Talbot Terrane
Tabletop Terrane
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
U-Pb zircon metamorphic
U-Pb zircon mafic magmatic intrusive
U-Pb zircon sed max dep
U-Pb zircon felsic intrusive
Rb-Sr wholerock
K-Ar hornblende

Time-Space evolution of the Capricorn Orogen

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OVERVIEW

The Capricorn Orogen is a zone of deformed, low-grade volcano-sedimentary belts, high-grade metamorphic belts and granitoid intrusions, formed during Palaeoproterozoic tectonic activity that involved collision and suturing of the Archaean Pilbara and Yilgarn Cratons to form the West Australian Craton (Tyler and Thorne, 1990; Myers, 1990, 1993; Myers et al., 1996; Tyler et al., 1998; Cawood and Tyler, 2004; Figure 19). The orogen includes the Palaeoproterozoic plutonic igneous rocks and medium- to high-grade metamorphic rocks of the 2550-1620 Ma Gascoyne Complex, a series of Palaeoproterozoic volcano-sedimentary and sedimentary basins, including the 2200-1805 Ma Ashburton Basin, the ~1805 Ma Blair Basin, the 2150-1840 Ma Yerrida Basin, the 2020-1900 Ma Bryah and Padbury basins, and the 1840–1800 Ma Earaheedy Basin, together with the deformed margins of the Pilbara and Yilgarn cratons. It is exposed for a distance of 1000 km in an east-southeasterly trending belt between opposing cratonic margins (Cawood and Tyler, 2004).

The Capricorn Orogen underwent a series of orogenic events as lithotectonic elements were accreted to the orogenic margins and stabilized which include the ~2200 Ma Ophthalmian Orogeny developed along the northern margin of the orogen (Tyler and Thorne, 1990; Martin et al., 1998, 2000; Cawood and Tyler, 2004), the 2000-1960 Ma Glenburgh Orogeny which affected the southern margin (Occhipinti et al., 2001, 2004), both of which were followed by the widespread 1830-1780 Ma Capricorn Orogeny (Tyler and Thorne, 1990; Myers, 1993; Occhipinti et al., 2001). Later orogenic events resulted in reactivation of earlier structures and include the Mangaroon Orogeny at 1680-1620 Ma in the Gascoyne Complex (Sheppard et al., 2005; Pearson et al., 1996; Sheppard and Swager, 1999; Martin et al., 2002), and the Edmundian Orogeny between 1070 and 750 Ma, which also deformed the Edmund and Collier Basin successions (Martin and Thorne, 2001).

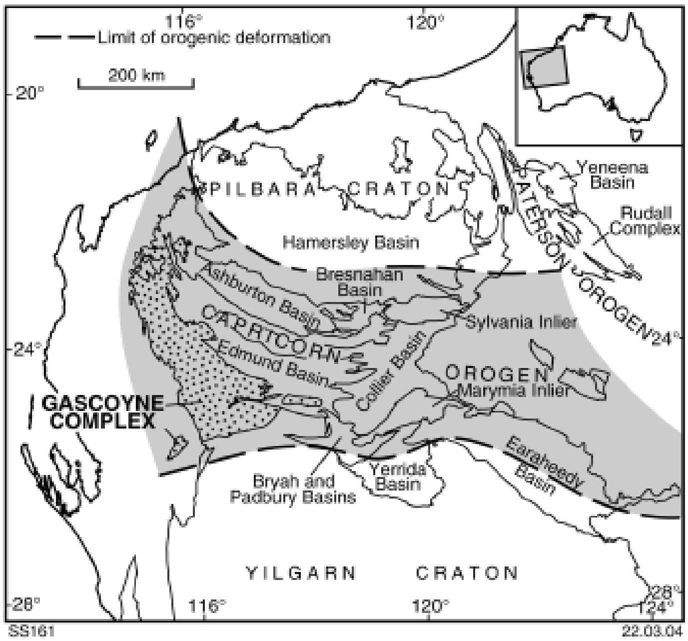


Figure 19: Location of the Capricorn Orogen and its constituent tectonic units, including the Gascoyne Complex (from Sheppard et al., 2005).

Mineral resources within the lithotectonic elements of the Capricorn Orogen include a wide variety of deposit types containing precious and base metals, uranium, manganese and iron (Tyler et al., 1998; Pirajno, 2004). The metallogeny of the Capricorn Orogen is considered to reflect syn- to post-Capricorn orogenic events, linked to either protracted convergence tectonics between the Pilbara and Yilgarn cratons, or to a two-stage convergence history, one during the Capricorn Orogeny (~1830 Ma; Pilbara–Yilgarn convergence), the other during the Yapungku Orogeny (~1790 Ma; North Australian–West Australian convergence) (Pirajno et al., 2004a; Cawood and Tyler, 2004).

Domain Subdivisions

In the following, geological domains of the Capricorn Orogen are discussed with an emphasis on geochronological constraints, as plotted in the accompanying Time-Space plots. The geochronological data are plotted in two 500 million year intervals (2100-1600 Ma and 1500-1000 Ma; Figure 20), although an overview of geochronological data not encompassed in these time intervals is provided where applicable.

The Capricorn Orogen is divided here into nine domains, each of which reflects different deformational, metamorphic, and stratigraphic attributes (Occhipinti et al., 2003, 2004). These are, plotted from left to right: the Ashburton Basin, the Glenburgh Terrane (southern Gascoyne), the Errabiddy Shear Zone, the Gascoyne Complex (northern Gascoyne), the Yarlarweelor Gneiss Complex, and the Edmund-Collier, Bryah-Padbury, Yerrida and Earaheedy Basins.

Geochronological data compilation involved merging data extracted from Geoscience Australia's OZCHRON database with pre-existing data compilations (e.g., GSWA, 2005; GSWA, 2006), data available from the literature and unpublished reports where available. Data interpretations have focussed on U-Pb SHRIMP data, with less emphasis placed on whole rock Rb-Sr and K-Ar data.

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

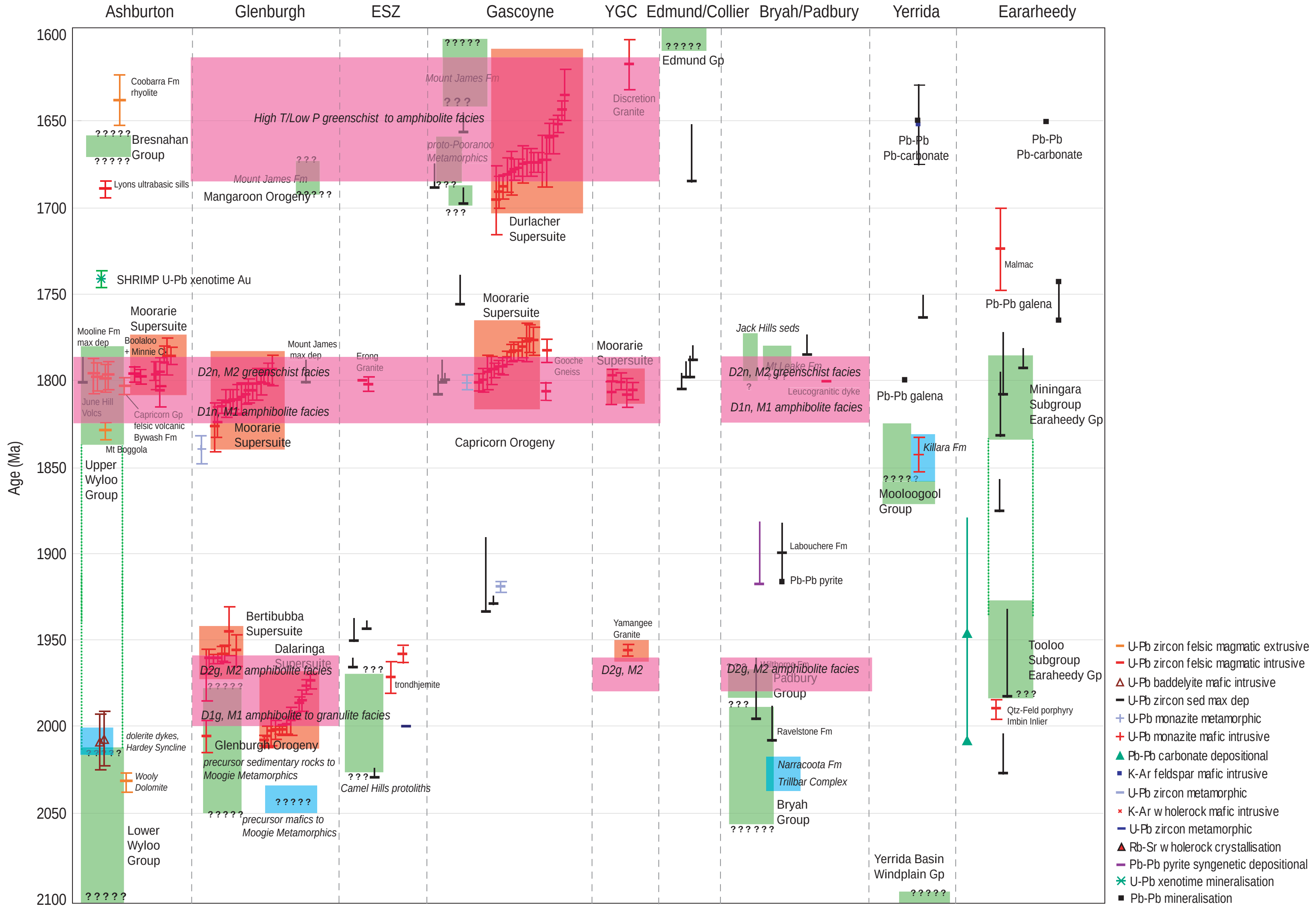
Ashburton Basin

The Proterozoic Ashburton Basin lies along the northern margin of the Capricorn Orogen and comprises variably deformed, low-grade sedimentary and volcanic rocks of the Wyloo Group with a thickness of about 12 km (Thorne, 1990; Thorne and Seymour, 1991). Strata within the basin unconformably overlie the Hamersley Basin of the Pilbara Craton and are in turn unconformably overlain by younger basin sequences (Blair and Mount Minnie Basins) formed during the closing stages of the Capricorn Orogeny or by the overlying Bresnahan, Edmund and Collier basins. The term 'Ashburton Province' is used here for the purpose of broad geographical description of all stratigraphy between the Hamersley and Edmund/Collier Basins, including the lower and upper Wyloo Groups, Capricorn Group, Mount Minnie Group, and Bresnahan Group.

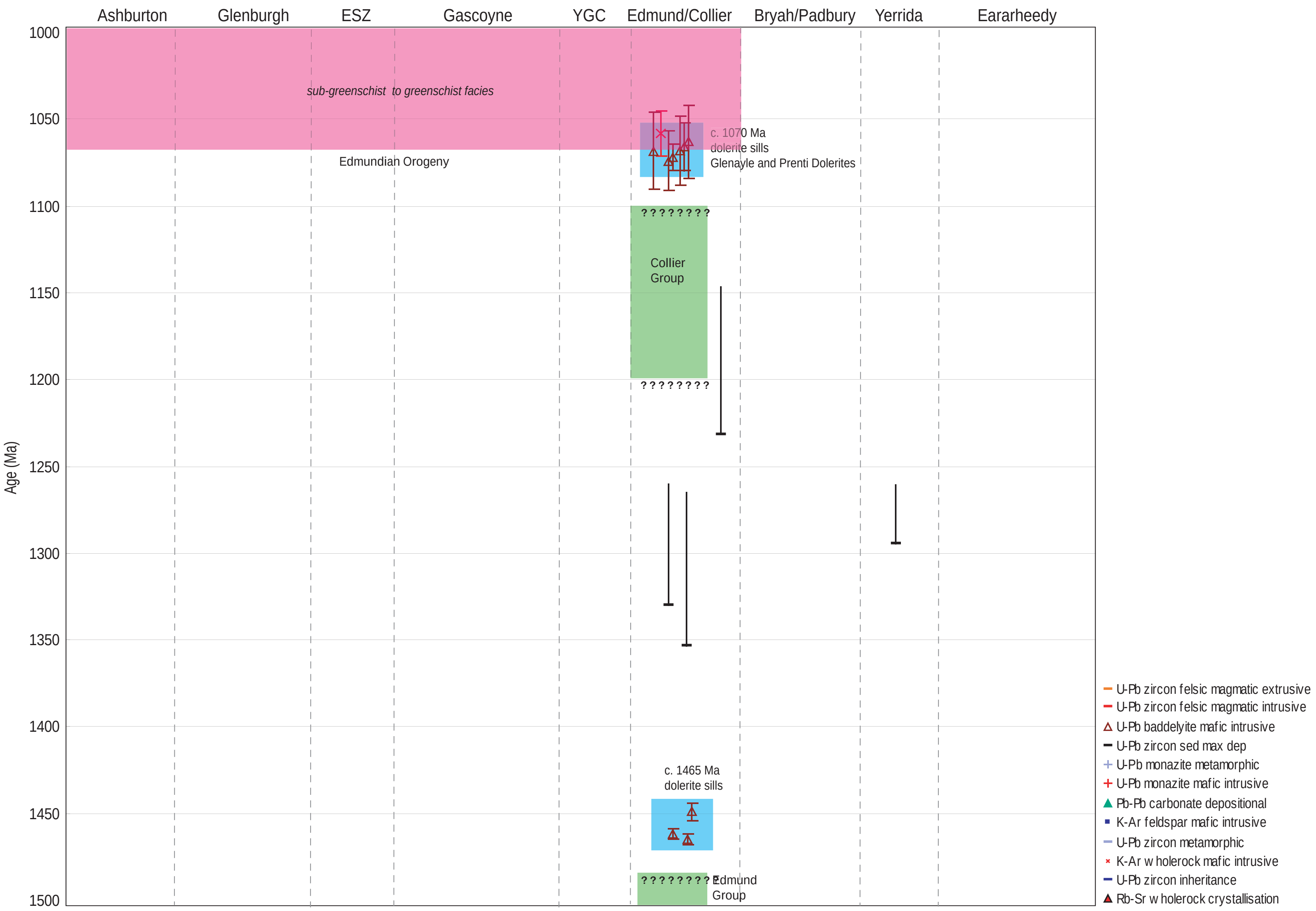
>2100 Ma

The oldest rocks in the region are Archaean granite and greenstone units in the Pilbara Craton with several inliers along the southern margin of the craton (e.g., Wyloo and Rocklea Domes, and Sylvania Inlier to the east). The Hamersley Basin unconformably overlies the Archaean rocks and consists of the Mount Bruce Supergroup subdivided as the Fortescue, Hamersley, and Turee Creek Groups (Trendall, 1990). Volcanic units within the Hamersley Group range in age from 2597 to 2449 Ma (Trendall et al., 1998; Barley et al., 1997).

Figure 20 (overleaf): *Geochronological data and summary Time-Space plot for the Capricorn Orogen, subdivided into the (a) 2100-1600 and (b)1500-1000 Ma timeslices.*



Geochronological synthesis and time-space plots for Proterozoic Australia



Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
sub-greenschist to greenschist facies
Edmundian Orogeny
c. 1070 Ma
dolerite sills
Glenayle and Prenti Dolerites
????????
Collier
Group
????????
c. 1465 Ma
dolerite sills
????????
Edmund
Group
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon inheritance
Rb-Sr w holerock crystallisation

The Hamersley Group is gradationally overlain by turbidites, shallow marine carbonate rocks, and fluvial and marine siliciclastic rocks of the Turee Creek Group (Martin et al., 2000). Unconformable on the Turee Creek Group, the Wyloo Group overlies the Mount Bruce Supergroup and is itself divided into subgroups (Lower and Upper Wyloo Groups; Occhipinti et al., 2003).

<2100 Ma

The base of the Wyloo Group is defined by an unconformity below the shallow-marine Beasley River Quartzite of the Mount Bruce Supergroup (Thorne and Seymour, 1991). The youngest population of detrital zircons in sandstone from the Beasley River Quartzite gives a maximum SHRIMP U–Pb age of 2446 ± 8 Ma (GSWA, 2005, sample 169084; not plotted).

The Beasley River Quartzite is overlain by continental tholeiites of the Cheela Springs Basalt. For the latter, Martin et al. (1998) provide a maximum SHRIMP U–Pb zircon age of 2209 ± 15 Ma for a volcaniclastic breccia (not plotted). The Cheela Springs Basalt is partially overlain by dolomitic siltstone and mudstone of the Wooly Dolomite (Occhipinti et al., 2003). Pumice-bearing tuffaceous siltstone at the base of Wooly Dolomite has an interpreted SHRIMP U-Pb zircon age of syn-eruptive volcaniclastic sedimentation at 2031 ± 6 Ma (Müller et al., 2005). Northeast-trending dolerite dykes intruding the Lower Wyloo Group have SHRIMP U-Pb baddeleyite ages of 2009 ± 16 Ma and 2007 ± 16 Ma (Müller et al., 2005). The Lower Wyloo Group has been interpreted to have been deposited in a foreland basin during development of the Ophthalmian thrust and fold belt (Cawood and Tyler, 2004 and references therein).

The age of the upper part of the Wyloo Group is constrained by data from volcaniclastic units within the June Hill Volcanics and overlying Ashburton Formation. Evans et al. (2003) obtained SHRIMP U–Pb zircon ages of 1799 ± 8 Ma and 1786 ± 11 Ma from a pumice-breccia sandstone within the locally developed June Hill Volcanics, whereas zircon from a thick felsic volcaniclastic sandstone and siltstone unit within the Ashburton Formation has yielded a SHRIMP U–Pb age of 1806 ± 9 Ma (GSWA, 2005; GSWA 148922). In addition, Evans et al. (2003) provide age data for an unnamed dacitic porphyry at 1790 ± 10 Ma. These dates are slightly younger than the SHRIMP U–Pb zircon age of 1829 ± 5 Ma obtained from a felsic volcaniclastic rock within the Ashburton Formation (Mt Boggola Formation; Sircombe, 2003). The younger age limit for the Upper Wyloo Group is also constrained by the SHRIMP U–Pb zircon age of 1786 ± 5 Ma for the Boolaloo Granodiorite that intrudes the Ashburton Formation (Krapez and McNaughton, 1999), and the SHRIMP U-Pb zircon age of the Minnie Creek Granodiorite (1795 ± 8 Ma; Evans et al., 2003).

The only recognised stratigraphic unit in the overlying Blair Basin is the Capricorn Formation (Thorne and Seymour, 1991). The age of the Capricorn Group is constrained by SHRIMP U–Pb zircon data from the lower and upper parts of the succession. Hall et al. (2001) reported a SHRIMP U-Pb zircon age of 1804 ± 7 Ma for a felsic volcanic unit (Koonong Member) in the Bywash Formation (age recalculated to 1806 ± 7 Ma by Evans et al., 2003), whereas the youngest population of detrital zircons in a coarse-grained lithic sandstone from the overlying Mooline Formation (Blair Basin) provides a SHRIMP U-Pb maximum age of 1801 ± 14 Ma (GSWA, 2005; GSWA 148925). These ages are within error of the 1799 ± 8 Ma and 1806 ± 9 Ma ages obtained respectively from the June Hill Volcanics and Ashburton Formation in the underlying Wyloo Group. The discrepancy in age data is considered likely to reflect the diachronous nature of facies during foreland basin sedimentation during the Capricorn Orogeny (1830-1780 Ma; Sheppard and Occhipinti, 2000; Occhipinti and Sheppard, 2001; Occhipinti et al., 2001; Evans et al., 2003; Martin et al., 2005).

The youngest possible age of the Capricorn Formation is constrained by the unconformably overlying Edmund Group. Zircons extracted from a rhyolite that intrudes the Coobarra Formation of the Edmund Group provide a SHRIMP U-Pb maximum depositional age of 1638 ± 14 Ma (Nelson, 1995). A swarm of ultrabasic bodies (Lyons River ultrabasic sills and intrusions) were emplaced into the Gascoyne Complex prior to the deposition of the Edmund Group and are possibly related to the initial rifting of the Edmund Basin. Pearson (1996) obtained a SHRIMP U–Pb zircon date of 1679 ± 6 Ma for a sample of fenitized Pimbyana Granite adjacent to an ultrabasic sill. The igneous crystallization age of the Pimbyana Granite (U-Pb SHRIMP zircon age 1673 ± 15 Ma; Nelson, 2002) is indistinguishable from the date from the fenite, indicating that they may be of similar age. Based on these data, the minimum age of the Capricorn Formation is regarded as ca 1680 Ma (Hall et al., 2001).

The Bresnahan Basin contains conglomerate and sandstone of the Bresnahan Group unconformably overlying folded rocks of the Hamersley and Ashburton basins (Hunter, 1990). The precise age of the Bresnahan Group is not known, but it must be younger than the underlying Wyloo and Capricorn Groups and older than the overlying Edmund Group, suggesting a late Palaeoproterozoic to early Mesoproterozoic age for the unit. Palaeo-current data and composition of the siliciclastic units suggest derivation from the Gascoyne Complex (Hunter, 1990).

A U-Pb SHRIMP xenotime age of 1738 ± 5 Ma for gold mineralisation at the Mount Olympus gold deposit hosted in the Mount McGrath Formation of the Upper Wyloo Group was recorded by Sener et al. (2005).

Glenburgh Terrane

The southern part of the Gascoyne Complex comprises late Archaean to Palaeoproterozoic foliated and gneissic granitic and metasedimentary rock, collectively referred to as the Glenburgh Terrane. The relationship of the Glenburgh Terrane to the remainder of the Gascoyne Complex is unclear; the Glenburgh Terrane may either extend underneath the northern part of the complex, or have been accreted to it (Occhipinti et al., 2004). The Glenburgh Terrane consists of latest Archaean to earliest Proterozoic basement gneisses, granitic rocks of the Dalgaringa Supersuite, and calc-silicate gneiss, amphibolite, and pelitic metasedimentary rocks of the Moogie Metamorphics (Occhipinti et al., 2004), and intruded by the I-type granites of the Bertibubba Supersuite. Granite and pegmatite of the Moorarie Supersuite also intruded across the Yilgarn Craton-Glenburgh Terrane boundary during the Capricorn Orogeny (Occhipinti et al., 1998). Both the Glenburgh Terrane and the northern edge of the Yilgarn Craton are unconformably overlain by scattered outcrops of the Palaeoproterozoic Coor-de-wandy Formation, the ~1800 Ma Mount James Formation, and outliers of the Mesoproterozoic Edmund Group (Williams et al., 1983; Martin et al., 1999; Occhipinti and Sheppard, 2001).

>2100 Ma

Basement to the Glenburgh Terrane consists of a suite of ~2550 Ma deformed and metamorphosed granodiorites, tonalites and monzogranites (Sheppard et al., 1999; 2004) collectively known as the Halfway Gneiss (Occhipinti and Sheppard, 2001; Occhipinti et al., 2001).

Zircons derived from a sample of augen gneiss define a U-Pb SHRIMP zircon igneous crystallization age of 2544 ± 5 Ma for the granodiorite precursor to the gneiss (Nelson, 2000). Nelson (2000) also dated the tonalitic component of a mesocratic, banded granitic gneiss. The youngest population consists of five analyses of five zircons with a pooled age of 2550 ± 7 Ma. Six analyses of six zircons define a date of 2663 ± 7 Ma, four analyses of a further four zircons define a date of 2709 ± 10 Ma, whereas the remaining zircons are ca 3300 Ma or older. The youngest population at 2550 ± 7 Ma probably represents the igneous crystallization age of the tonalite precursor.

In another sample, zircons derived from a sample of leucocratic granitic gneiss define a U-Pb SHRIMP zircon igneous crystallization age of 2006 ± 6 Ma for the granite precursor to the gneiss (Nelson, 2001). The ~2006 Ma age suggests that some granite of the Dalgaringa Supersuite (see below) has been included in the Halfway Gneiss. The original relationship of the ~2006 Ma component to the ~2550 Ma components of the Halfway Gneiss is unknown, although it is considered likely that they are tectonically interleaved (Occhipinti et al., 2003).

Rocks of the Halfway Gneiss are younger than any dated rocks from the northwestern part of the Yilgarn Craton, which are all older than ~2600 Ma (Myers, 1995) and those from the Pilbara Craton (no granite younger than ~2750 Ma, Nelson et al., 1999). Rocks of the southern Gascoyne Complex may be part of a terrane separate from the Archaean Yilgarn and Pilbara Cratons (Occhipinti et al., 2003).

A U-Pb SHRIMP zircon age of 1919 ± 3 Ma (GSWA, 2006; 168950) for a pegmatite-banded biotite tonalite gneiss of the Halfway Gneiss, has been interpreted as a metamorphic age.

<2100 Ma

Supracrustal rocks including mafic schist and gneiss, pelitic schist, calc-silicate gneiss and dolomitic marble, form distinct bands within the Halfway Gneiss and are called the Moogie Metamorphics (Occhipinti and Sheppard, 2001). These metasedimentary and metamorphosed mafic and ultramafic igneous rocks were previously included within the ‘Morrissey Metamorphic Suite’ (Williams et al., 1983; Williams, 1986).

The age of the Moogie Metamorphics is poorly constrained. It is intruded by granites of the Dalgaringa Supersuite and therefore must be older than ~2005 Ma. Rocks of the Moogie Metamorphics are faulted against the Halfway Gneiss, so the relative age of the two units is uncertain (Occhipinti and Sheppard 2001). Early, originally sub-horizontal folds that deform bedding within the Moogie Metamorphics also deform a well-developed gneissic layering in the Halfway Gneiss. If the two units initially developed in the same terrane, then the Moogie Metamorphics must be younger than the Halfway Gneiss. However, if the two units initially developed in separate terranes and were juxtaposed by layer-parallel deformation (D2g of the Glenburgh Orogeny), then it is not possible to establish their relative ages (Occhipinti and Sheppard, 2001).

The Dalgaringa Supersuite comprises sheets, dykes and veins of foliated and gneissic I-type tonalite, granodiorite, quartz diorite and monzogranite, dated between 2005-1985 Ma (U-Pb SHRIMP zircon ages of 2003 ± 8 Ma to 1987 ± 4 Ma; Nelson, 1999; Kinny et al., 2004; Sheppard et al., 2004). The Dalgaringa Supersuite intrudes the Halfway Gneiss and Moogie Metamorphics (Sheppard et al., 1999; 2004), and is itself intruded by a large pluton of ~1975 Ma mesocratic and leucocratic I-type tonalite (U-Pb SHRIMP zircon ages of 1977 ± 4 Ma and 1974 ± 4 Ma for the Nardoo Granite; Nelson, 1999). Xenocrystic zircons within rocks of the Dalgaringa Supersuite all have Palaeoproterozoic ages (Sheppard et al., 2004). A mafic granulite intruded by the Nardoo Granite gave a U-Pb SHRIMP zircon age of 1989 ± 3 Ma (Nelson, 1999).

The older parts of the Dalgaringa Supersuite were metamorphosed and deformed by ~1989 Ma, during the Glenburgh Orogeny (Occhipinti and Sheppard, 2001). Two main phases of deformation are associated with the Glenburgh Orogeny (Occhipinti et al., 2004). The first event, restricted to the

Glenburgh Terrane, produced an early foliation and isoclinal folds, and was associated with amphibolite to granulite facies metamorphism. It was synchronous with the emplacement of the 2005-1970 Ma Dalgaringa Supersuite. The second deformational event in the Glenburgh Terrane (also found in the Errabiddy Shear Zone and Yarlarweelor Gneiss Complex and possibly the Bryah and Padbury basins; Occhipinti et al., 2004) produced metamorphism up to amphibolite facies. This event produced a penetrative foliation in the ~1975 Ma Nardoo Granite, and this fabric is cut by ~1950 Ma granitic dykes (see below; Occhipinti et al., 2004), providing an age limit for this deformation (Occhipinti et al., 2004; Sheppard et al., 2004).

At 1965-1945 Ma, intrusion of silicic I-type granites of the Bertibubba Supersuite in the northwestern edge of the Yilgarn Craton and the southern margin of the Glenburgh Terrane coincided with the end of the Glenburgh Orogeny (Sheppard et al., 1999; 2004). The Bertibubba Supersuite (ages ranging from 1970 ± 15 Ma to 1956 ± 9 Ma; Nelson, 1998, 1999; Kinny et al., 2004) is the first element common to both terranes (Sheppard et al., 1999). Granite dykes (U-Pb SHRIMP zircon age of 1945 ± 14 Ma; Nelson, 1999) that cut the Nardoo Granite in the southernmost Glenburgh Terrane may also be related to the Bertibubba Supersuite (Occhipinti and Sheppard, 2001).

The Moorarie Supersuite in the Glenburgh Terrane comprises dykes, sheets, plugs, and plutons of granite and pegmatite dated at between 1830 and 1780 Ma (e.g., Dumbie Granodiorite U-Pb SHRIMP zircon ages of 1811 ± 6 Ma and 1810 ± 9 Ma; Scrubber Granite U-Pb SHRIMP zircon age of 1796 ± 6 Ma; Occhipinti and Sheppard, 2001). These granites and pegmatites extensively intrude the Glenburgh Terrane and were emplaced during and after deformation and regional metamorphism associated with the Capricorn Orogeny (Occhipinti et al., 1998).

SHRIMP U–Pb ages on detrital zircons from a sample of quartzite from the Mount James Formation contain a youngest population at 1801 ± 13 Ma (Nelson, 2001), providing a maximum age for deposition. An older population, 1968 ± 7 Ma, and the presence of Archaean grains, indicate derivation from Gascoyne Complex and main Yilgarn. The Mount James Formation is unconformably overlain by the Edmund Group. The maximum age of the lower part of the Edmund Group (1640 Ma, Nelson, 1995; see below) provides a minimum age for the Mount James Formation. The Mount James Formation is not cut by granites of the Moorarie Supersuite, and as the youngest granites mapped so far in contact with the Mount James Formation are ~1796 Ma old, the Mount James Formation was deposited and deformed between 1796 and 1640 Ma (Occhipinti and Sheppard, 2001).

Errabiddy Shear Zone

The crustal-scale Errabiddy Shear Zone defines the boundary between the northwestern part of the Yilgarn Craton (early to late Archaean Narryer Terrane), the 3300-1800 Ma Yarlarweelor Gneiss Complex (reworked Narryer Terrane), and the southern part of the Gascoyne Complex (2540-1970 Ma Glenburgh Terrane). The shear zone contains components of the: Narryer Terrane, Warrigal Gneiss, Yarlarweelor Gneiss Complex, Camel Hill Metamorphics, Bertibubba Supersuite, Coor-de-wandy and Mount James Formations. All components have fault-bounded contacts with each other except for some of the granites of the Bertibubba Supersuite, which intrude granitic gneiss of the Narryer Terrane (Occhipinti et al., 2003).

>2100 Ma

The Warrigal Gneiss consists of well-foliated to banded, interleaved mesocratic and leucocratic granite phases. These granites have been dated giving SHRIMP U–Pb zircon ages of 2700-2600 Ma

(Nelson, 2000; Occhipinti et al., 2001), similar to ages of late Archaean granites of the Narryer Terrane of the Yilgarn Craton. An unpublished (GSWA, 2006; 139463) U-Pb SHRIMP zircon age of 2000 Ma has been obtained for a pegmatite-banded gneiss, part of the Warrigal Gneiss, which is possibly a metamorphic age.

<2100 Ma

The Camel Hills Metamorphics are dominantly Palaeoproterozoic metasedimentary rocks, and include the Petter Calc-silicate and the Quartpot Pelite. These calc-silicate gneisses and pelitic schists and gneisses crop out exclusively in the Errabiddy Shear Zone. The Camel Hills Metamorphics represent the remnants of a sedimentary basin, or basins, that developed either along the passive margin of the Yilgarn Craton, or between the craton and the Glenburgh Terrane (Sheppard et al., 2003).

U–Pb SHRIMP dating of zircon from two samples of the Quartpot Pelite yielded pitted zircon grains with ages of 2550-2025 Ma interpreted to be of detrital origin. The youngest zircon population (from zircon rims) consisted of only two zircons dated at 1951 ± 13 and 1966 ± 5 Ma (Nelson, 1998, 1999, 2001). Nelson (1998, 1999) suggested that the rims were incorporated into the zircon prior to detrital sedimentary transport, therefore providing a maximum depositional age for the sedimentary protolith. However, this interpretation implies that no new zircon growth took place during migmatisation, and is contradicted by the 1970 ± 15 Ma age (Nelson, 1998) of a trondhjemite dyke that cuts the migmatised Quartpot Pelite. Occhipinti et al. (2001, 2003) suggest the zircon rims are related to zircon growth during partial melting of metasedimentary rocks, and thus that the pelitic schists were locally migmatised at 1966 ± 5 Ma and 1951 ± 13 Ma (Occhipinti et al., 2001), and intruded by 1970 ± 15 Ma (Nelson, 1999) trondhjemite indicating that metamorphism of the pelitic schists and intrusion of the trondhjemite occurred over only a few million years (Occhipinti et al., 2001). Detrital zircons from within the pelitic schists are dominated by ~2250-2025 Ma ages, the youngest maximum depositional U-Pb SHRIMP zircon age being 2028 ± 5 Ma (Nelson, 2001).

The age of high-grade metamorphism and its associated migmatisation was c. 1960 Ma, and the maximum age of deposition of the protolith to the Quartpot Pelite was ~2025 Ma (2028 ± 5 Ma; Nelson, 2001). Most of the detrital zircons dated from the Quartpot Pelite were probably sourced from the Glenburgh Terrane of the southern Gascoyne Complex. Only a minority of zircons were sourced from the Yilgarn Craton, and a few ~2250 Ma zircons are from an unknown source.

In a sample of the Petter Calc-silicate, most analysed zircons have U-Pb ages between 2700 and 2600 Ma (Nelson, 1999). Three of the zircons have ages older than 3000 Ma, and one was dated at 1944 ± 5 Ma. Nelson (1999) described the youngest zircon as rounded and pitted and interpreted the date on this grain as providing the maximum age of deposition of the precursor to the calc-silicate gneiss. However, this age is younger than the 1970 ± 15 Ma trondhjemite sheet that cuts S2 gneissic layering within the Quartpot Pelite (Nelson, 1999). The provenance of the Petter Calc-silicate indicates the zircons were probably largely sourced from the Yilgarn Craton and thus was different to that of the Quartpot Pelite. Overall, sedimentary protoliths in the Camel Hills Metamorphics were deposited between ~2025-1970 Ma (Occhipinti et al., 2001).

A SHRIMP U–Pb zircon age of 1958 ± 5 Ma has been interpreted as the age of igneous crystallization for a porphyritic biotite monzogranite of the Bertibubba Supersuite, with an older group of zircons dated at 2619 ± 8 Ma interpreted as xenocrysts (Nelson, 2000).

Low-grade siliciclastic sedimentary rocks of the Coor-de-wandy and unconformably overlying Mount James Formations were deposited in a series of small fault-bounded basins on top of the

Glenburgh Terrane, Camel Hills Metamorphics, and northwestern edge of the Yilgarn Craton. There are no direct age constraints on the Coor-de-wandy Formation in the Errabiddy Shear Zone, other than being older than ~1800 Ma. The Mount James Formation must be younger than ~1800 Ma. These sedimentary rocks were probably deposited during the latter stages of the Capricorn Orogeny (Occhipinti et al., 1999).

The Camel Hills Metamorphics is intruded by muscovite–biotite–garnet monzogranite to pegmatite of the Erong Granite. The Erong Granite both cuts and is deformed by ~1800 Ma D1 structures of Occhipinti et al. (2003) and is thought to be c. 1800 Ma in age (Nelson, 2000), based on correlations with similar granites in the region. These include a plug of similar biotite–muscovite granite from within the Errabiddy Shear Zone to the northeast that gave a SHRIMP U–Pb age of 1802 ± 9 Ma (Nelson, 1998). Unfortunately, zircons dated from the Erong Granite are mainly Archaean xenocrysts. The low Zr content of the Erong Granite may have precluded the growth of new zircon (Occhipinti et al., 2003).

Gascoyne Complex

The Gascoyne Complex forms the western side of the Capricorn Orogen. The southern part of the complex includes the Glenburgh Terrane, with the northern part including extensive medium- to high-grade metamorphic rocks. The Errabiddy Shear Zone marks the southern boundary of the complex, whereas to the north it has been interpreted to pass with decreasing metamorphic grade into the units of the Ashburton Basin (Thorne, 1990; Williams, 1986). The Phanerozoic Carnarvon Basin overlies the western margin, whereas the Mesoproterozoic Edmund Basin overlies the eastern margin (Cawood and Tyler, 2004).

The Gascoyne Complex is composed of Palaeoproterozoic metasedimentary and meta-igneous rocks, which are extensively intruded by large volumes of granite. The Palaeoproterozoic geology of the northern Gascoyne Complex can be described in terms of three zones: the Boora Boora, Mangaroon, and Limejuice Zones (Occhipinti et al., 1999). The Boora Boora and Limejuice Zones, which flank the Mangaroon Zone, contain metasedimentary rock successions that were intruded by granitic rocks during the Capricorn Orogeny (Occhipinti and Myers, 1999; Sheppard and Swager, 1999). Deformation and metamorphism related to the Capricorn Orogeny affected the entire Gascoyne Complex (Occhipinti et al., 1998; Krapez and McNaughton, 1999; Occhipinti and Sheppard, 2001; Sheppard et al., 2003).

<2100 Ma

Deposition of quartzite at Koolyin Hills is interpreted by Kinny et al. (2004) to have occurred after ~2270 Ma, the youngest recorded detrital zircon age. A lower age limit to deposition is given by the age of in situ zircon overgrowths dated at 1934 ±43 Ma. The rather large uncertainty associated with the latter age means that the timing of rim growth brackets both the latter stages of the Glenburgh Orogeny and a period of intrusion of massive to weakly foliated granitic dykes which followed (the ~1950 Ma dykes of Nelson 1999, 2000 which cut the Dalaringa Supersuite). These ~1950 Ma dykes are virtually undeformed and have only undergone low grade metamorphism. Occhipinti et al. (2004) suggest that their intrusion marks the end of the Glenburgh Orogeny. Therefore, given that low-grade conditions prevailed by ~1950 Ma, it is likely that the growth of zircon rims in the quartzite occurred before this time, under conditions of higher metamorphic grade associated with the Glenburgh Orogeny (Kinny et al., 2004).

Leucocratic gneiss from Mount Remarkable Bore yielded zircons ranging in age from ~1920 to 3170 Ma, although the youngest concordant $^{207}Pb/^{206}Pb$ date of 1929 ± 4 Ma was obtained on an irregular shaped grain fragment with an intensively pitted surface (consistent with detrital transport) and therefore provides a maximum age for deposition of the sedimentary component to the gneiss (Nelson, 2002).

Foliated granite and augen gneiss of the Gooche Gneiss forms basement to the Mangaroon Zone and is part of the Moorarie Supersuite (Martin et al., 2005). The Gooche Gneiss, which ranges from a foliated, porphyritic biotite granodiorite or monzogranite, to a pegmatite-banded augen gneiss, gave a SHRIMP U–Pb zircon age of 1776 ± 8 Ma, which is interpreted as the age of igneous crystallization of the precursor granite (Nelson, 2002). The precursor granite is at least 30-40 m.y. older than sedimentary protoliths to the Pooranoo Metamorphics (see below), to which it probably comprises basement. A mafic gneiss interleaved with the Gooche Gneiss gave a SHRIMP U-Pb zircon age of 1806 ± 5 (Nelson, 2002) for the igneous crystallisation of the tonalite precursor to the gneiss.

The Pooranoo Metamorphics comprise pelitic gneiss and metamorphosed feldspathic sandstone, with minor amounts of metamorphosed conglomerate, quartz sandstone, amphibolite, and calc-silicate rock. These metasedimentary and meta-igneous rocks were previously included within the ‘Morrissey Metamorphic Suite’ (Williams et al., 1983; Williams, 1986). Two samples of metamorphosed feldspathic sandstone in the Mangaroon Zone (dated by Sheppard et al., 2005) provide U-Pb SHRIMP zircon maximum depositional ages of 1808 ± 11 Ma and 1800 ± 4 Ma for the protoliths. The youngest population of detrital zircons from a sample of unmelted pelitic gneiss of the Pooranoo Metamorphics gives a U-Pb SHRIMP maximum depositional age of 1680 ± 13 Ma (Sheppard et al., 2005). As the pelitic rocks are interbedded with the metamorphosed feldspathic sandstone, a maximum depositional age of c. 1680 Ma is inferred for protoliths to the Pooranoo Metamorphics (Martin et al., 2005). These data indicate that the protoliths to rocks of the Pooranoo Metamorphics are younger than sedimentary rocks of the Ashburton Formation (Evans et al., 2003; Sircombe, 2003), although metasedimentary rocks of the Boora Boora Zone (and the Limejuice Zone) appear to have been deposited at the same time as the Ashburton Formation (Occhipinti and Myers, 1999; Sheppard and Occhipinti, 2000; Occhipinti and Sheppard, 2001). In addition, the sedimentary protoliths in the Pooranoo Metamorphics are much younger than those in the Camel Hills Metamorphics (2025-1970 Ma; Occhipinti et al., 2001) and Moogie Metamorphics (>2005 Ma; Occhipinti and Sheppard, 2001). These data indicate that the metasedimentary rock packages throughout the Gascoyne Complex are not correlatives.

The Durlacher Supersuite comprises granitic and minor gabbroic intrusions emplaced at 1680-1620 Ma, during the Mangaroon Orogeny (e.g. Dingo Creek Granite 1674 ± 8 Ma; Pimbyana Granite 1673 ± 15 Ma; Yangibana Granite 1659 ± 10 and 1660 ± 9 Ma; Nelson, 2002). The bulk of the granites intruded the Pooranoo Metamorphics in the Mangaroon Zone at 1680–1660 Ma, but large plutons also intruded the adjacent Boora Boora and Limejuice Zones, as well as the Glenburgh Terrane in the southern Gascoyne Complex, and the adjacent Yarlarweelor Gneiss Complex (Sheppard and Swager, 1999) until as late as ~1620 Ma (Sheppard et al., 2005).

The Mangaroon Orogeny (High-T/low-P regional greenschist to amphibolite facies metamorphism) involved pervasive reworking of crust in the northern Gascoyne Complex at 1680-1660 Ma and coeval voluminous granitic magmatism, followed by reactivation of faults and shear zones and intrusion of granite plutons over a wide area of the Gascoyne Complex until 1620 Ma. The age of D1m/M1m is constrained by the youngest detrital zircon population of 1680 ± 13 Ma in pelitic gneisses of the Pooranoo metamorphics (Sheppard et al., 2005) and by granites of the Durlacher Supersuite that intrude S1m (<~1675 Ma).

Yarlarweelor Gneiss Complex

Immediately to the south of the Capricorn Orogen, the Narryer Gneiss Complex of the Yilgarn Craton is characterised by voluminous granite plutonism during the period 2750-2620 Ma (Nutman et al., 1993). These granites mostly intrude gneisses of Mesoarchaean age (3000-2920 Ma). The Yarlarweelor Gneiss Complex is defined as that part of the Narryer Gneiss Complex which was deformed, metamorphosed and intruded by voluminous felsic magmas during the Capricorn Orogeny (Occhipinti et al., 1998). It occurs within and to the south of the Errabiddy Shear Zone, together with other parts of the Narryer Gneiss Complex which escaped significant reworking in the Palaeoproterozoic (Kinny et al., 2004).

The northwestern edge of the Archaean Yilgarn Craton in Western Australia was intensely deformed and metamorphosed during the Palaeoproterozoic Capricorn Orogeny (D1n and D2n; 1830-1780 Ma) to form the Yarlarweelor Gneiss Complex. The Yarlarweelor Gneiss Complex is mainly composed of Archaean and Palaeoproterozoic banded leucocratic and mesocratic granitic gneisses, consisting of several interlayered rock types (Occhipinti et al., 1998; Occhipinti and Myers, 1999; Sheppard and Swager, 1999). The Yarlarweelor Gneiss Complex is in faulted contact with the low- to locally medium-grade sedimentary and mafic igneous rocks of the Bryah and Padbury Basins in the south and east. To the west, the Errabiddy Shear Zone cuts the Yarlarweelor Gneiss Complex and separates it from rocks of the Glenburgh Terrane.

<2100 Ma

The Yarlarweelor Gneiss Complex was locally intruded by biotite monzogranite of the Bertibubba Supersuite. A sample of the Yamangee Granite which intruded early to late Archaean granitic gneiss as well as amphibolite and metasedimentary gneisses (Sheppard and Swager, 1999) has a SHRIMP U–Pb zircon crystallisation age of 1958 ± 4 Ma (Nelson, 1999).

High-grade metamorphism and crustal thickening in the complex during the Capricorn Orogeny was accompanied by voluminous veins and sheets of I-type granite and pegmatite of the Moorarie Supersuite, which may comprise up to a quarter of the whole gneiss complex. U-Pb zircon SHRIMP dating of granites indicates that two deformation ‘events’ took place (D1n and D2n of the Capricorn Orogeny). A sheet of granite was dated at 1813 ± 8 Ma and a granite dyke folded by F1n was dated at 1811 ± 9 Ma (Nelson, 1998; Occhipinti et al., 1998). Thus D1n and intrusion of granite and pegmatite is constrained to ~1812 Ma, which also constrains the maximum age of deformation and metamorphism. The second deformation event occurred at ~1800 Ma with the intrusion of syn-D2 granites which intrude D1n structures (1801 ± 7 Ma; 1808 ± 6 Ma, 1797 ± 4 Ma; Nelson 1998; Occhipinti et al., 1998), although deformation and metamorphism were probably continuous between ~1820 and ~1795 Ma (Sheppard et al., 2003). The intrusion of the syn-D2 granites is interpreted to be related to decompression of the Yarlarweelor Gneiss Complex between ~1812 and ~1800 Ma.

A sample of porphyritic, medium-grained monzogranite from the Discretion Granite was dated by SHRIMP U–Pb in zircon at 1619 ± 15 Ma (Nelson, 1998). The Discretion Granite is the youngest granite in the Gascoyne Complex (Sheppard and Swager, 1999).

Edmund and Collier Basins

The Edmund and Collier Basins correspond to the present day outcrop of the Edmund and Collier Groups that together make up the former Bangemall Supergroup, which forms a broad regional syncline between the Yilgarn and Pilbara Cratons (Martin and Thorne, 2002, 2004). These rocks unconformably overlie the Palaeoproterozoic Ashburton and Blair Basins to the northeast and rocks of the Palaeoproterozoic Gascoyne Complex to the southwest. The Collier Group unconformably overlies Archaean to early Palaeoproterozoic rocks of the Pilbara Craton (including the Fortescue and Hamersley Groups) to the north, whereas to the south it is unconformable on Archaean rocks of the Marymia Inlier and the Palaeoproterozoic Bryah/Padbury and Earaheedy Groups (Martin et al., 2005). The Late Palaeoproterozoic to Mesoproterozoic Edmund Group is at least 4 km thick and consists of mostly fine-grained siliciclastic and carbonate sedimentary rocks. The 2–2.5 km thick Collier Group disconformably overlies the Edmund Group and consists largely of siliciclastic sedimentary rock. The age of sediment accumulation is poorly constrained by the ages of pre- and post-depositional igneous bodies. In the western part of the Bangemall Basin, the Edmund and Collier Groups are overlain by the Phanerozoic Carnarvon Basin (Williams et al., 1983), whereas to the east it is overlain by the Neoproterozoic–Palaeozoic Officer Basin (Williams, 1990).

<2100 Ma

The Edmund Group consists, from bottom to top, of the Yilgatherra, Irregully, Gooragoora, Blue Billy, Cheyne Springs, Kiangi Creek, Muntharra, Discovery, Devil Creek, Ullawarra, and Coodardoo Formations. The maximum age of the Edmund Group can be broadly constrained by SHRIMP U–Pb zircon ages of units truncated by the basal unconformity, and by the ages of detrital zircons in sandstones. The underlying Capricorn Group has been dated at 1804 ± 7 Ma (Hall et al., 2001). Granodiorite from the Coobarra Dome (basement to Coobarra Formation) has been dated at 1797 ± 8 Ma (Nelson, 1995), and the Boolaloo Granodiorite at 1786 ± 5 Ma (Krapez and McNaughton, 1999). The Dingo Granite (1674 ± 6 Ma; Pearson et al., 1996), Lyons River ultrabasic sills (1679 ± 6 Ma; Pearson, 1996), and Durlacher Supersuite granites also predate the Edmund Group (Pearson et al., 1996; Sheppard and Swager, 1999, 2002).

The youngest population of detrital zircons in two samples from the Yilgatherra Formation have been dated at 1805 ± 9 Ma (Nelson, 2000) and 1685 ± 33 Ma (GSWA, 2006, 169093), although the maximum age of the Yilgatherra Formation is constrained by its unconformable relationship to the 1674 ± 8 Ma Dingo Creek Granite (Nelson, 2002; Pearson et al., 1996), the 1673 ± 15 Ma Pimbyana Granite and the c. 1660 Ma Yangibana Granite (Nelson, 2002). A granophyric plug that intrudes the Yilgatherra Formation contains a ~1778 Ma (1778 ± 11 Ma) population of zircons (GSWA, 2006, 169089) that are interpreted as xenocrysts. This plug provides a slightly younger maximum age. The Discretion Granite (1619 ± 15 Ma; Nelson, 1998) is the youngest granite in the Gascoyne Complex (Sheppard and Swager, 1999). Since no granites are known to intrude the Edmund Group, these data suggest a probable maximum age for the Yilgatherra Formation of about 1620 Ma (Martin and Thorne, 2004).

SHRIMP U–Pb detrital zircon ages from two sandstone samples in the Kiangi Creek Formation suggest a maximum depositional age between 1798 ± 12 Ma (Nelson, 2002) and 1782 ± 13 Ma (Cawood, P., and Nemchin, A., 2002, GSWA 156734, cited in Martin et al., 2005). However, regional stratigraphic and intrusive relationships indicate that the Kiangi Creek Formation is similar in age to older units in the Edmund Group, ranging from about 1620 to 1465 Ma (Martin et al., 2005). While the youngest detrital zircons in sandstones at the base of the Edmund Group are about 1805 Ma, a poorly defined SHRIMP U–Pb zircon age of 1638 ± 14 Ma has been reported for the Tangadee rhyolite (Coobarra Formation; Nelson, 1995) in the lower Edmund Group based on 2 zircons. This age suggest that the maximum age of the former Bangemall Supergroup is about 1620 Ma.

The Collier Group is subdivided, in ascending order, into the Backdoor, Calyie, and Ilgarari Formations (Martin and Thorne, 2002). Detrital zircons from the Backdoor Formation, constrain a maximum age of about 1400 Ma (1352 ± 89 Ma) for the group (Cawood, P., and Nemchin, A., 2002 GSWA 152968, cited in Martin et al., 2005). The minimum age for the Collier Group is constrained by a suite of dolerite sills intruded into the Backdoor and Ilgarari Formations (see below; Wingate, 2002).

Establishing stratigraphic relations between the western and eastern parts of the Bangemall Basin has been hindered by the relatively poor exposure and general lack of age control in the latter, and the lack of detailed mapping of rocks between the two areas (Hocking and Jones, 2002). Two groups of rocks have been identified in the eastern Bangemall Supergroup, the Scorpion and Salvation Groups (Hocking and Jones, 1999; Hocking et al., 2000). The Salvation Group comprises the Coonabildie Formation and the overlying Brassey Range Formation. A SHRIMP U-Pb zircon maximum depositional age of 1330 ± 70 Ma has been recorded from a sandstone in the Coonabildie Formation (Nelson, 2002), whereas a maximum depositional age of 1229 ± 85 Ma was obtained from detrital zircons within sandstone of the Brassey Range Formation (Nelson, 2002; Hocking and Jones, 2002). Detrital zircon chronology shows that the Salvation Group was deposited after 1200 Ma, suggesting that it might be a time equivalent of the Collier Group (Nelson, 2002).

The Edmund and Collier Groups contain large volumes of tholeiitic dolerite sills (Muhling and Brakel, 1985). Wingate (2002) reported SHRIMP U–Pb zircon and baddeleyite ages from two suites of sills in the western part of the region at 1465 ± 3 and 1070 ± 6 Ma. Nelson (2001) reported SHRIMP U-Pb zircon and baddeleyite ages for dolerite sills intruding parts of the Edmund Group in the western Bangemall at 1074 ± 17 Ma, 1072 ± 8 Ma, and 1462 ± 3 Ma. Similar though less precise ages were reported for felsic rocks (1080 ± 80 Ma; Rb–Sr isochron; not plotted) by Compston and Arriens (1968), and a Rb–Sr isochron age of 1098 ± 42 Ma (not plotted) has been reported for altered rhyolite by Gee et al. (1976). Goode and Hall (1981) provided a K–Ar age of 1050 Ma for glauconite adjacent to an undated dolerite (not plotted).

In the Eastern Bangemall, K–Ar ages of 917 ± 13 and 968 ± 19 Ma determined for K-feldspar from two samples of granophyric Glenayle Dolerite are interpreted as minimum estimates of the time of dolerite crystallization (Nelson, 2002, not plotted). Compston (1974) and Preiss et al. (1975) reported Rb–Sr and K–Ar ages of c. 1050 Ma for dolerite sills intruding sedimentary rocks of the adjacent Earaheedy Basin. Wingate obtained U–Pb SHRIMP baddeleyite intrusive ages of 1066 ± 14 and 1068 ± 20 Ma for the Glenayle Dolerite. Combination of analyses from these 2 samples yields a mean $^{207}Pb/^{206}Pb$ age of 1066 ± 14 Ma (95% confidence interval), which is interpreted as the best estimate of the age of the Glenayle Dolerite. Nelson (2002) provides a whole-rock K-Ar age of 1058 ± 13 Ma for basalt. A younger whole-rock K–Ar age of 968 ± 19 Ma (not plotted; Nelson, 2002) most likely represent the effects of Ar loss.

The older sills are apparently restricted to the Edmund Group, whereas the younger suite is present in both the Edmund and Collier Groups. The Collier Group was therefore deposited before 1070 Ma. The Edmund Group is older than 1465 Ma (Wingate, 2002), and younger than 1619 ± 15 Ma monzogranite in the underlying Gascoyne Complex (Nelson, 1998; Sheppard and Swager, 1999). The extensive system of dolerite sills that intrude the Collier Group most likely relate to the 1078-1070 Ma Warakurna Large Igneous Province (Martin et al., 2005).

<1000 Ma

Rocks of the Edmund and Collier Groups were folded about arcuate easterly to southeasterly trending folds during the Edmundian Orogeny. The age of the folding is poorly constrained; the maximum age of the Edmundian Orogeny post-dates deposition of the Collier Subgroup (~1070 Ma). Dolerite dykes of the Mundine Well dyke swarm cut the folds and have been dated at 755 ± 3

Ma (U–Pb dating of zircon and baddeleyite, Wingate and Giddings, 2000), and 754 ± 5 Ma (U-Pb dating of zirconolite, Rasmussen and Fletcher, 2004), providing a younger limit on the age of deformation. Thus the Edmundian Orogeny occurred between ~1060 and 755 Ma.

Bryah and Padbury Basins

The Bryah and Padbury Groups make up the western part of the former Glengarry Basin, and are now interpreted to have developed in rift and foreland basins, respectively (Pirajno et al., 1996; Martin, 1994). Strata of the Bryah Basin are in fault contact with both the Yilgarn Craton and Yerrida Basin successions (Pirajno and Occhipinti, 2000; Occhipinti et al., 2004; Reddy and Occhipinti, 2004). The Bryah Group contains the Karalundi, Narracoota, Ravelstone and Horseshoe Formations (Occhipinti et al., 1997; Pirajno et al., 1998), all deformed and metamorphosed to greenschist facies. The Narracoota Formation forms the bulk of the Bryah Group. The formation includes metamorphosed peridotitic and high-Mg basalt, basaltic hyaloclastite, mafic pyroclastic rocks, mafic intrusive rocks, and mafic and ultramafic schist (Pirajno and Occhipinti, 1998; Pirajno et al., 1998; Pirajno and Occhipinti, 2000). The Padbury Group is in fault contact with the Bryah Group (Occhipinti et al., 1998) as well as locally unconformable on the Bryah Group (Martin, 1994; Pirajno and Occhipinti, 2000). The Padbury Group contains quartz wacke, siltstone, conglomerate, iron-formation, hematitic shale, and minor clastic rocks and dolomite (Martin, 1994; Occhipinti et al., 1997), and is subdivided into the Labouchere, Wilthorpe, Robinson Range and Millidie Creek Formations.

The Bryah and Padbury Basins contain orogenic gold, copper–gold volcanogenic massive sulphides, manganese and iron ore. The origin of the gold mineralisation is probably related to tectonothermal activity during the Capricorn Orogeny at ca 1800 Ma (Pirajno and Occhipinti, 2000).

<2100 Ma

The age of the Bryah and Padbury Groups is poorly constrained. A Pb-Pb isochron date of 1920 ± 35 Ma, on assumed syngenetic pyrite from the Narracoota Formation (Bryah Group), was reported by Windh (1992). A Pb-Pb age of 1700 Ma was obtained from galena from the Mikhaburra mine (Narracoota Formation – Bryah Group) (unpublished data, cited in Pirajno and Occhipinti, 1998). These Pb-Pb isochron ages probably represent mineralizing events in the Bryah Basin, rather than minimum depositional ages of the Bryah Group (Pirajno and Occhipinti, 1998). A maximum age of 2014 ± 22 Ma, from SHRIMP U-Pb dating of detrital zircons in the Ravelstone Formation (Bryah Group), was obtained by Nelson (1996).

The maximum age of the Padbury Group is constrained by the interpreted 1920 Ma depositional age of the Narracoota Formation (Windh, 1992; Pb-Pb model age pyrite). The most reliable available estimate of the maximum depositional age of the Padbury Group is provided by SHRIMP U–Pb dating of detrital zircon populations from quartz arenite in the lower Labouchere Formation. The youngest population has been dated at 2000 to 1900 Ma (Windh, 1992) and constrains the maximum depositional age of the Padbury Group to less than 1900 Ma. This age is supported by the 2014 ± 22 Ma maximum age of the Ravelstone Formation.

Nelson (1996) determined a SHRIMP U-Pb in zircon maximum depositional age of the Beatty Park Member (Padbury Group), which overlies the Labouchere Formation, at 1996 ± 35 Ma, whereas Windh (1992) provides a SHRIMP U-Pb age of ~1800 Ma for a leucogranite dyke crosscutting the Padbury Group. A minimum age is provided by the overlying ca 1640 Ma Edmund Group (Nelson, 1995).

Outliers of the Mount Leake Formation (which has been correlated with the Earaheedy Group, see later) unconformably overlie the Bryah Group. Glauconite obtained from quartz arenite outcrops of the Mount Leake Formation returned a K-Ar age of 1573 Ma (not plotted, Bunting, 1986). This age, however, is not considered reliable (Grey, 1994). Nelson (1997) obtained a U–Pb SHRIMP maximum depositional age of 1785 ± 11 Ma for detrital zircons from the Mount Leake Formation, which may correlate with the basal Yelma Formation, but is geographically isolated from the remainder of the group (Hocking et al., 2000).

Yerrida Basin

The Yerrida Basin consists of the Yerrida Group, which lies unconformably overlies the Archaean Yilgarn Craton (Pirajno et al., 1998; Pirajno and Occhipinti, 2000; Pirajno et al., 2004a) but is locally in fault contact with the Marymia Inlier (Bagas, 1999) and is unconformably overlain by the late Palaeoproterozoic Earaheedy Group (Pirajno and Adamides, 2000).

The Yerrida Group (which makes up the eastern part of the former Glengarry Basin) has been divided into the basal Windplain Subgroup and the conformably overlying Mooloogool Subgroup, which developed in sag and rift basins, respectively (Pirajno et al., 1995, 1996). The Windplain Subgroup comprises a thick sequence of siliciclastic, carbonate and evaporitic sedimentary rocks (Juderina Formation), and iron-rich shales (Johnson Cairn Formation). The Mooloogool Subgroup comprises several kilometres of sandstone (Doolgunna Formation), turbidite (Thaduna Formation), mafic extrusive and intrusive rocks (Killara Formation), and carbonaceous shale (Maraloou Formation) (Pirajno et al., 1996; Pirajno and Adamides, 2000).

>2100 Ma

Stromatolitic carbonates in the Bubble Well Member (Juderina Formation) give Pb/Pb isochron dates of 2258 ± 180 Ma (Russell et al., 1994) and 2173 ± 64 Ma (Woodhead and Hergt, 1997), which were interpreted as the age of deposition (not plotted).

<2100 Ma

Rasmussen and Fletcher (2002) determined an age of 1843 ± 14 Ma from monazite in black shale of the Maraloou Formation of the Yerrida Basin. They interpreted that the monazite formed during hydrothermal circulation of fluids during intrusion of sills associated with the volcanic Killara Formation, which also occurs in the upper part of the Yerrida Basin. This date provides a minimum age for the Maraloou Formation, previously only constrained between 2200 Ma and 1800 Ma. The presence of peperites, indicates that the 1843 Ma date probably approximates the depositional age of the Maraloou Formation (Rasmussen and Fletcher, 2002).

Nelson (1997) provides a maximum depositional age of 1764 ± 13 Ma for shale interbedded with basaltic lavas near the stratigraphic base of the Killara Formation of the Yerrida Group. However, given the spread of discordant ages within this sample, and that this age is based solely on a single grain analysis, its reliability as a maximum depositional age is suspect.

Two K–Ar analyses are within error of a single value, corresponding to a weighted mean K–Ar date of 1652 ± 23 Ma (Nelson, 2002), was obtained for a coarse-grained dolerite sill of the Killara Formation (Pirajno and Adamides, 2000) that has intruded clastic sedimentary rocks of the Juderina Formation. In the absence of evidence of thermal metamorphism of the sample, the date of 1652 ± 23 Ma is interpreted as a minimum age for crystallization of the dolerite (Nelson, 2002).

The Yerrida Basin hosts epigenetic lead–carbonate and oxide mineralisation in sandstone and stromatolitic carbonate rocks of the Juderina Formation, at and above the unconformity with the Earaheedy Group. A Pb-Pb model age of 1650 Ma was derived from paragenetically late base-metals in mineralised carbonates of the Finlayson Member (Juderina Formation; Unpublished data of Nelson cited in Pirajno et al., 1995 and Pirajno and Adamides, 2000), whereas galena from veins in the Thaduna Formation give a Pb/Pb model age of ~1800 Ma (Gee, 1990). Also present in the Yerrida Basin are a number of gossans with anomalous Cu, Pd, Ba and Zn values in black shale of the Maraloou Formation (Pirajno and Occhipinti, 2000).

Coarse-grained and silicified arenite, from the Juderina Formation at the base of the Yerrida Group (Pirajno et al., 1996; Pirajno and Adamides, 2000) yielded a youngest U-Pb SHRIMP age population of 1298 ± 29 Ma, interpreted as a maximum age for deposition of the sandstone precursor to the quartzite (Nelson, 2002).

Earaheedy Basin

The Earaheedy Basin lies at the easternmost end of the Capricorn Orogen and unconformably overlies rocks of the Yilgarn Craton, Yerrida Basin (Mooloogool Group), and possibly the Bryah Basin and contains shallow-water shelf deposits of the Earaheedy Group (Pirajno et al., 2004a). These basins are in turn unconformably overlain by the Mesoproterozoic Edmund and Collier Basins and Phanerozoic Officer Basin (Martin, 1998). In the north, basement rocks are exposed in the Imbin Inlier (Pirajno and Hocking, 2001) and the Malmac Dome, within the Stanley Fold Belt.

The Earaheedy Group consists of the lower Tooloo Subgroup and the upper Miningarra Subgroup. In ascending order, the Tooloo Subgroup includes the Yelma, Frere, and Windidda Formations, and the Miningarra Subgroup includes the Chiall and Wongawol Formations, Kulele Limestone, and the Mulgarra Sandstone (Hocking and Jones, 2002).

<2100 Ma

The age of the Earaheedy Group is stratigraphically constrained by the age of the underlying Mooloogool Group (Maraloou Formation ~1840 Ma; Rasmussen and Fletcher, 2002), and by the Malmac (2600 Ma; Nelson, 2002) and Imbin (1990 Ma; Nelson, 2001) Inliers.

U/Pb dating of zircons from Yilgarn granitoids exposed along the southern margin of the basin, within the Shoemaker impact structure, the Goodin Inlier, and just west of the basin within the Marymia Inlier, have yielded a uniform and consistent set of ages in the range 2675-2650 Ma (not plotted; Nelson, 1997, 1998). A rhyodacite from the Imbin Inlier, near the northern margin of the basin has yielded a SHRIMP U–Pb zircon age of 1990 ± 7 Ma (Nelson, 2001), which is close to the age of granitic rocks of the southern Gascoyne Complex at the western end of the Capricorn Orogen (Sheppard et al., 1999). The inlier has been interpreted to unconformably underlie the basin although the contact is not exposed (Pirajno et al., 2004a).

Pb–Pb wholerock dating of stromatolitic carbonate rocks from the unconformably overlying Yelma Formation of the Earaheedy Group gave ages of 2008 ± 68 Ma and 1946 ± 71 Ma (Russell et al., 1994), whereas studies of stromatolite taxa from the unconformably overlying carbonate rocks of the Yelma Formation (Earaheedy Group) suggest ages of between 1900 and 1800 Ma (Grey, 1994).

Lead–lead (galena) mineralisation ages of 1650 Ma and 1770-1740 Ma respectively, are recorded from the Magellan deposit in outliers of Yelma Formation overlying the Yerrida Basin and the Sweetwaters Well Member of the Yelma Formation (Richards and Gee, 1985; Teen, 1996). The

1770-1740 Ma ages may reflect the deformation event that formed the Stanley Fold Belt, which provides a possible further minimum age constraint for the Earaheedy Basin (Pirajno et al., 2004b).

Deformation in the Stanley Fold Belt is tentatively attributed by Pirajno et al. (2000) and Jones et al. (2000) to the second phase of the Yapungku Orogeny (1790 to 1760 Ma; Smithies and Bagas, 1997; Bagas and Smithies, 1998; Bagas et al., 2000). This is consistent with SHRIMP U–Pb dating of zircons and monazite from the Malmac Inlier, which indicate a disturbance event at about 1720 Ma (SHRIMP U-Pb zircon age of 1724 ± 24 Ma for an indistinct granitic phase within the Malmac Granite; Nelson, 2002). SHRIMP U–Pb dating of zircons by Vielreicher and McNaughton (2002) also detected a disturbance, associated with hydrothermal activity, in the Marymia Inlier at about 1.72 Ga. The timing of this deformation ties in reasonably well with the epigenetic Mississippi Valley type mineralisation in the Yelma Formation (1770-1740 Ma; Teen, 1996).

Glauconite from the Yelma Formation (at the base of the Earaheedy Group) gave minimum K–Ar ages of about 1700 Ma (Preiss et al., 1975; recalculated by Richards and Gee (1985) at 1698 ± 12 Ma) and minimum Rb–Sr ages of between 1590 and 1710 Ma (Preiss et al., 1975). Horwitz (1975) reported a K–Ar age of 1688 ± 72 Ma from glauconite in sandstone of the Wandiwarra Member (near the middle of the group). These data suggest glauconite was reset during later deformation (this data is not plotted).

Detrital zircons from an arenite within the Yelma Formation at the base of the Tooloo Subgroup gave a SHRIMP U–Pb maximum depositional age of 2027 ± 23 Ma (Nelson, 1997). The youngest single grain (more than 90% concordant) from the basal Yelma Formation of the Earaheedy Group has been dated at 1983 ± 51 Ma whereas the youngest single grain (101% concordant) in the upper Mulgarra Sandstone is dated at 1808 ± 36 Ma (Halilovic et al., 2004). The youngest population of zircons from arenite of the Mount Leake Formation provides a maximum depositional age of 1785 ± 11 Ma (Nelson, 1997). A second sample from the same formation has a youngest population with a mean $^{207}Pb/^{206}Pb$ ratio corresponding to an age of 1832 ± 37 Ma, providing a maximum age for the deposition of the arenite (Nelson, 1997).

The Pb–Pb whole-rock carbonate ages from the Yelma Formation of ~2010 Ma and ~1950 Ma (Russell et al., 1994) conflict with both the maximum depositional zircon age of 1800 Ma of Halilovic et al. (2004) for the Mulgarra Sandstone, and the U–Pb monazite age of 1843 ± 14 Ma marking regional lithospheric extension and emplacement of mafic sills into Maraloou Formation (Rasmussen and Fletcher, 2002). The inaccuracy of the ‘old’ ages obtained from Pb/Pb dating of carbonates in the Earaheedy Basin is supported by the presence of two detrital zircon grains from the Mount Leake Formation which may correlate with the basal Yelma Formation, but is geographically isolated from the remainder of the group. Nelson (1997) obtained a U–Pb (SHRIMP) maximum depositional age of 1785 ± 11 Ma for this unit.

Detrital grains as young as 1800 Ma, combined with deposition of the unconformably underlying strata in the Yerrida Basin at c. 1840 Ma and deformation of the Earaheedy Group at around 1750 Ma, provide a relatively tight constraint on the depositional age of the Earaheedy Group (Halilovic et al., 2004).

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

The following investigations are recommended to resolve gaps in the current understanding of the time-space evolution of the Capricorn Orogen.

- Establish/refine age constraints for sedimentation and the age of unconformities within the Lower and Upper Wyloo Groups, the Coor-de-Wandy Formation, the Earaheedy Group, and the Bryah and Padbury Groups, all of which are poorly constrained.
- Comparison of the provenance of the lower Ashburton Formation with similar-aged sequences in Proterozoic Australia.
- Geochemical analysis of mafic rocks within the Ashburton Basin.
- Investigation into the relationship of the ~2006 Ma component to the ~2550 Ma components of the Halfway Gneiss.
- Geochemical analysis of Bertibubba Supersuite granites to determine a possible post-collisional signature.
- Further investigation into the mixed geochemical signatures of mafic rocks within the Killara (Mooloogool Group) and Narracoota (Bryah Group) Formations to help unravel their geodynamic setting.
- Establish better depositional constraints and provenance data for the Edmund and Collier Groups in the western part of the Bangemall Basin. Detailed chronology of sequences in the eastern Bangemall Basin (e.g., Scorpion and Salvation Groups) to establish their time equivalence to the Edmund and Collier Groups.
- Re-sampling and SHRIMP analysis of the Tangadee rhyolite may establish a more reliable maximum depositional age for the Edmund Group.
- Re-assessing the Capricorn age of collision between the Yilgarn and Pilbara Cratons.
- The timing of mineral deposits in the Capricorn Orogen are poorly constrained, if at all. SHRIMP xenotime and monazite geochronology and geochemistry to determine ages of mineralisation and fluid flow events would be viable.

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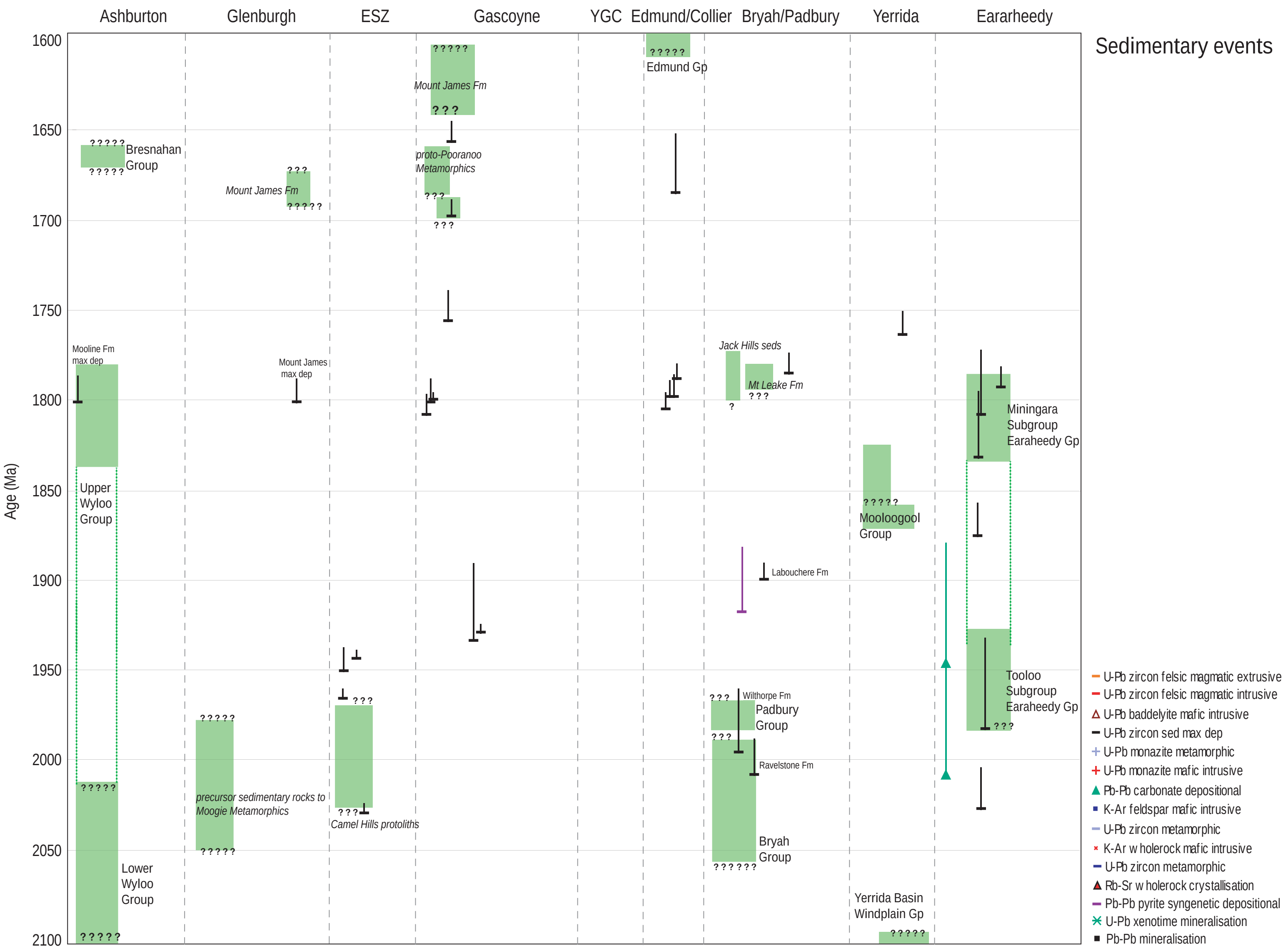
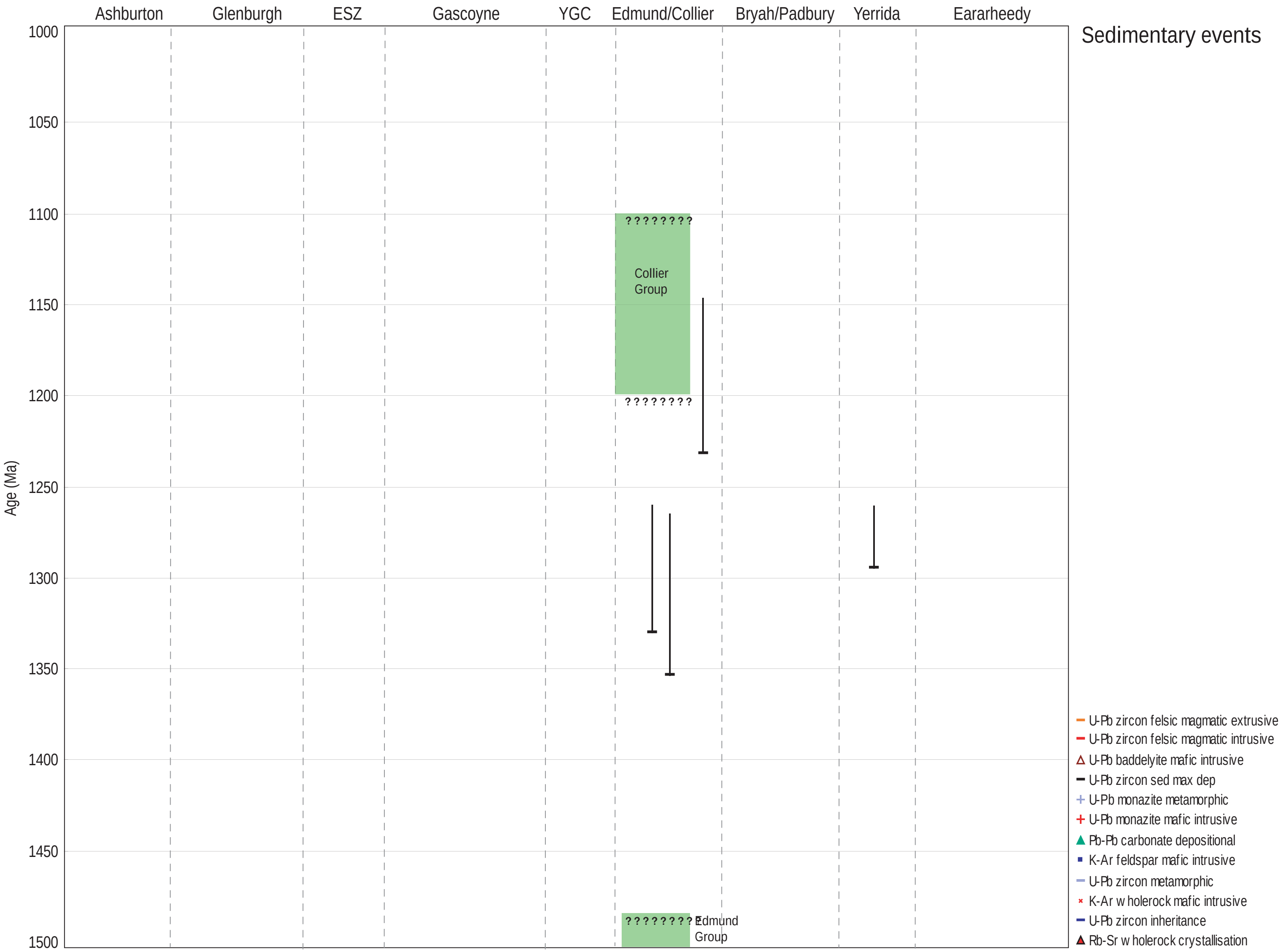
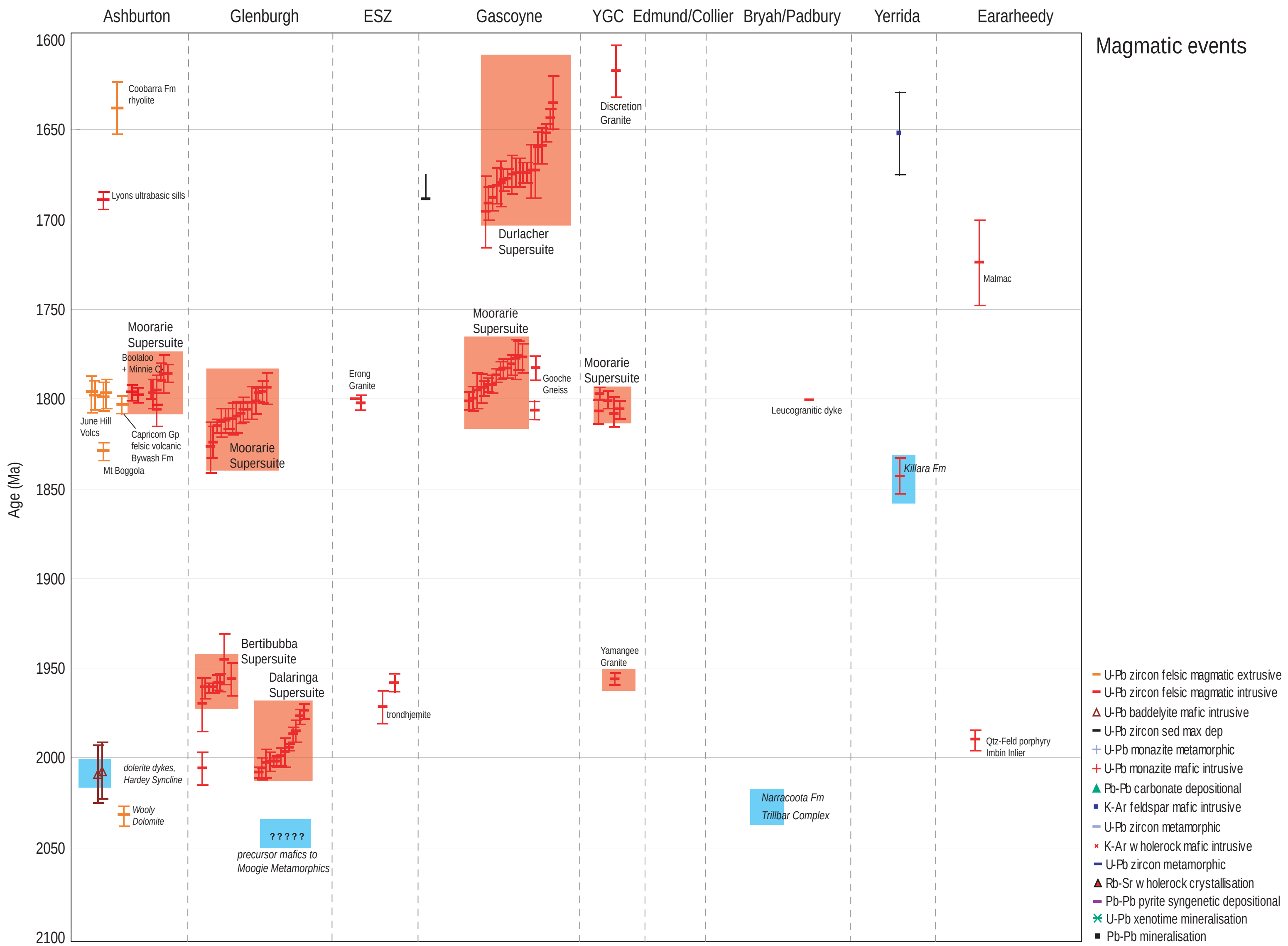
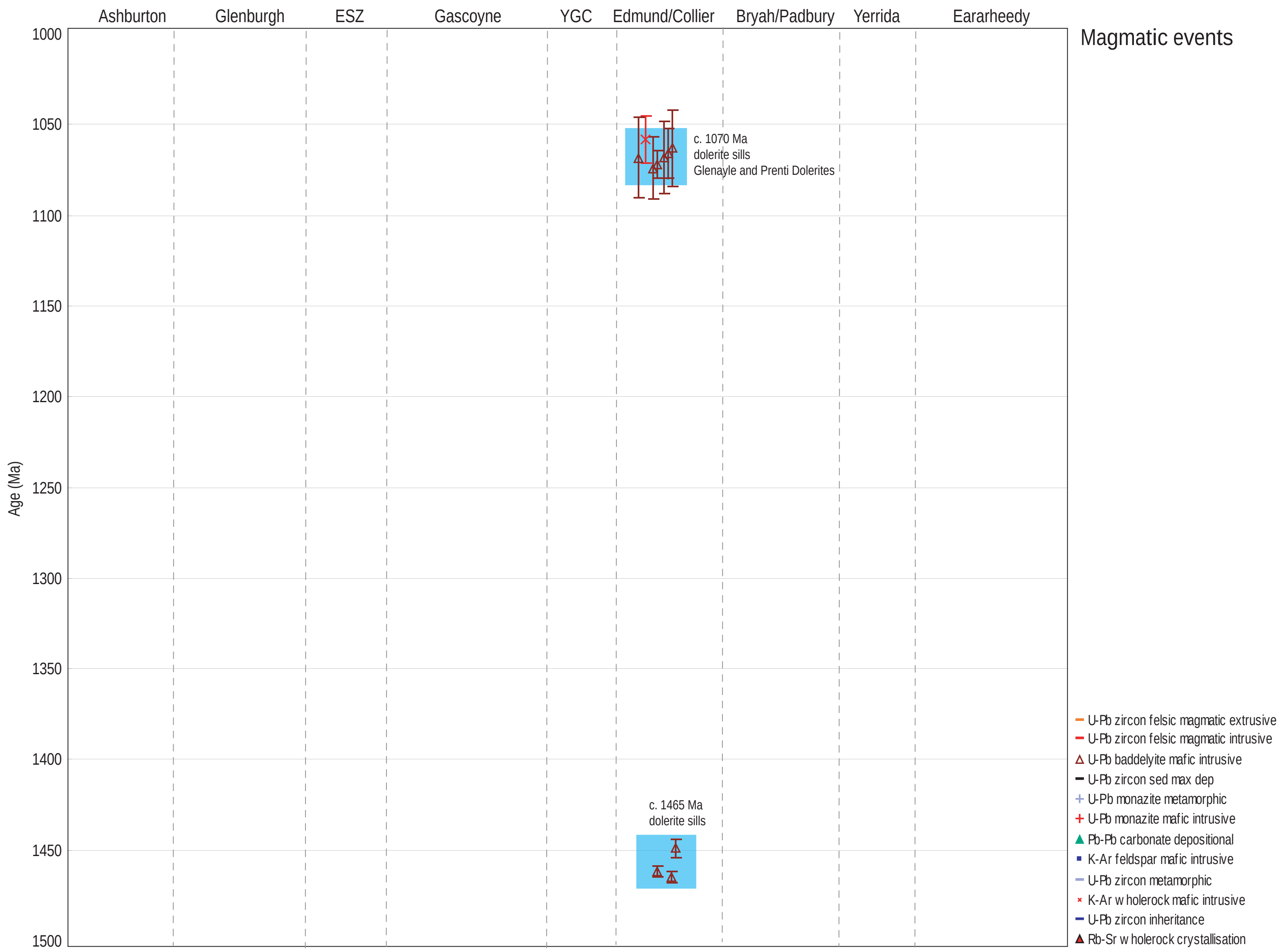
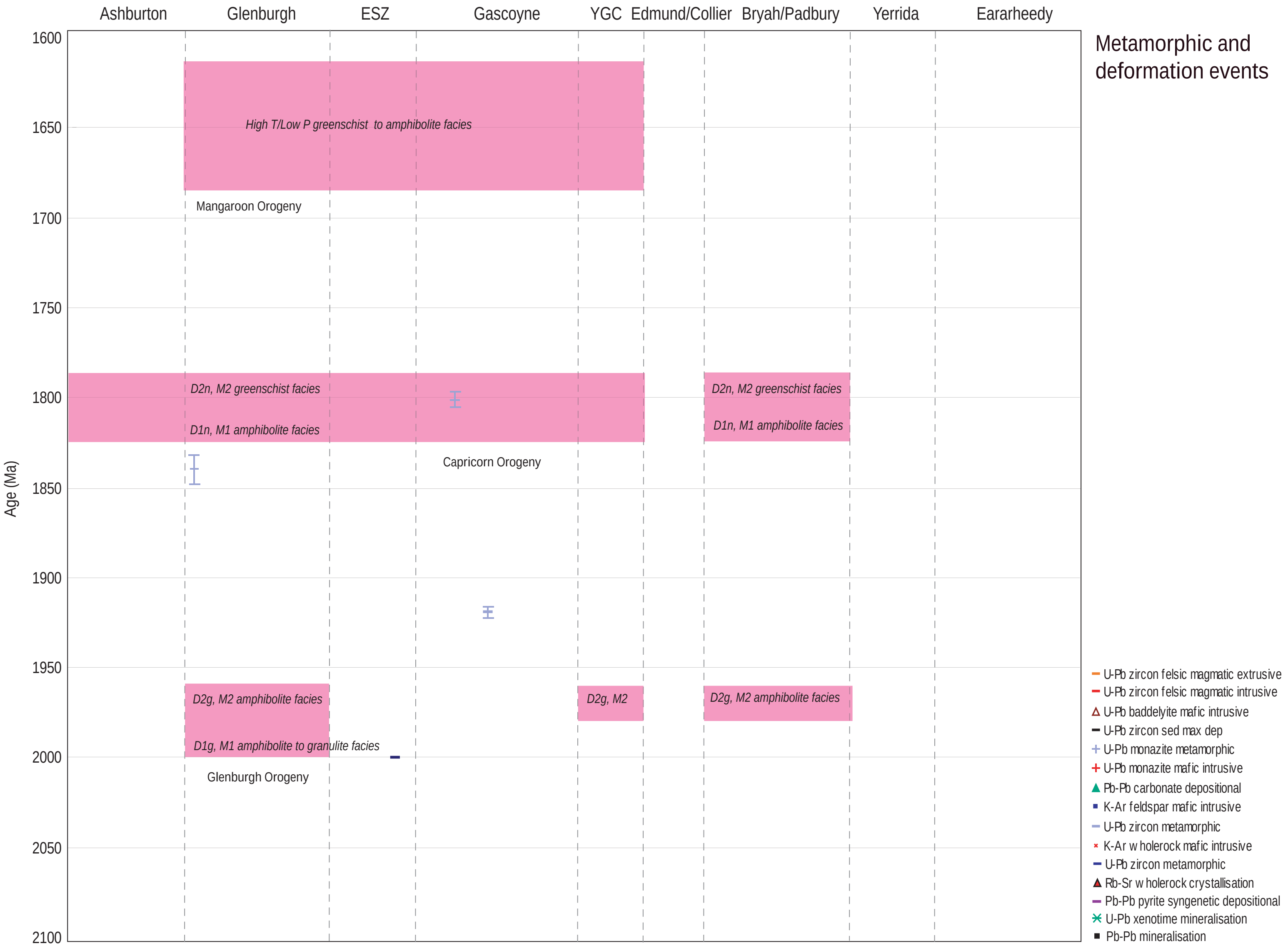
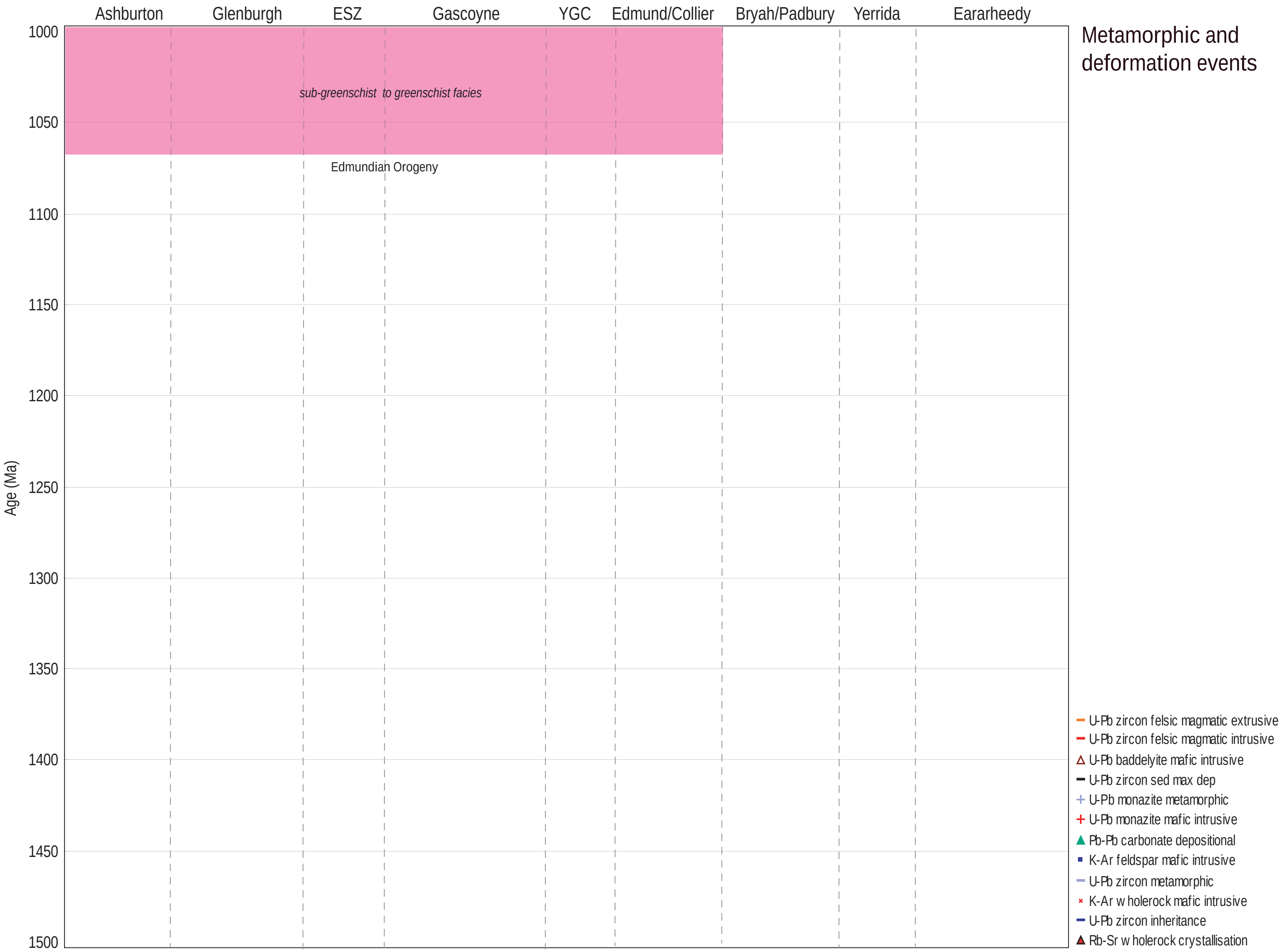

Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Sedimentary events
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Bresnahan Group
Mooline Fm max dep
Upper Wyloo Group
Lower Wyloo Group
Mount James Fm
Mount James max dep
precursor sedimentary rocks to Moogie Metamorphics
Camel Hills protoliths
Mount James Fm
proto-Pooranoo Metamorphics
Edmund Gp
Jack Hills seds
Mt Leake Fm
Labouchere Fm
Wilthorpe Fm
Padbury Group
Ravelstone Fm
Bryah Group
Mooloogool Group
Yerrida Basin Windplain Gp
Miningara Subgroup Earaheedy Gp
Tooloo Subgroup Earaheedy Gp
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon metamorphic
Rb-Sr w holerock crystallisation
Pb-Pb pyrite syngenetic depositional
U-Pb xenotime mineralisation
Pb-Pb mineralisation


Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Sedimentary events
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
????????
Collier Group
????????
????????
Edmund Group
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon inheritance
Rb-Sr w holerock crystallisation


Magmatic events
Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Coobarra Fm rhyolite
Lyons ultrabasic sills
Moorarie Supersuite
Boolaloo + Minnie Ck
June Hill Volcs
Capricorn Gp felsic volcanic Bywash Fm
Mt Boggola
dolerite dykes, Hardey Syncline
Wooly Dolomite
Moorarie Supersuite
Bertibubba Supersuite
Dalaringa Supersuite
? ? ? ? ?
precursor mafics to Moogie Metamorphics
Erong Granite
trondhjemite
Durlacher Supersuite
Moorarie Supersuite
Gooche Gneiss
Discretion Granite
Moorarie Supersuite
Yamangee Granite
Leucogranitic dyke
Narracoota Fm
Trillbar Complex
Killara Fm
Malmac
Qtz-Feld porphyry Imbin Inlier
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar wholerock mafic intrusive
U-Pb zircon metamorphic
Rb-Sr wholerock crystallisation
Pb-Pb pyrite syngenetic depositional
U-Pb xenotime mineralisation
Pb-Pb mineralisation


Magmatic events
Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
c. 1070 Ma
dolerite sills
Glenayle and Prenti Dolerites
c. 1465 Ma
dolerite sills
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon inheritance
Rb-Sr w holerock crystallisation


Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Metamorphic and deformation events
High T/Low P greenschist to amphibolite facies
Mangaroon Orogeny
D2n, M2 greenschist facies
D1n, M1 amphibolite facies
D2n, M2 greenschist facies
D1n, M1 amphibolite facies
Capricorn Orogeny
D2g, M2 amphibolite facies
D1g, M1 amphibolite to granulite facies
D2g, M2
D2g, M2 amphibolite facies
Glenburgh Orogeny
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar wholerock mafic intrusive
U-Pb zircon metamorphic
Rb-Sr wholerock crystallisation
Pb-Pb pyrite syngenetic depositional
U-Pb xenotime mineralisation
Pb-Pb mineralisation


Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Earaheedy
Metamorphic and deformation events
sub-greenschist to greenschist facies
Edmundian Orogeny
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon inheritance
Rb-Sr w holerock crystallisation


Mineralisation events
Ashburton
Glenburgh
ESZ
Gascoyne
YGC
Edmund/Collier
Bryah/Padbury
Yerrida
Eararheedy
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
SHRIMP U-Pb xenotime Au
Pb-Pb
Pb-carbonate
Pb-Pb
Pb-carbonate
Pb-Pb galena
Pb-Pb galena
Pb-Pb pyrite
U-Pb zircon felsic magmatic extrusive
U-Pb zircon felsic magmatic intrusive
U-Pb baddelyite mafic intrusive
U-Pb zircon sed max dep
U-Pb monazite metamorphic
U-Pb monazite mafic intrusive
Pb-Pb carbonate depositional
K-Ar feldspar mafic intrusive
U-Pb zircon metamorphic
K-Ar w holerock mafic intrusive
U-Pb zircon metamorphic
Rb-Sr w holerock crystallisation
Pb-Pb pyrite syngenetic depositional
U-Pb xenotime mineralisation
Pb-Pb mineralisation

Time-Space evolution of the Albany-Fraser Orogen

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OVERVIEW

The Albany–Fraser Orogen, traditionally divided into the east-striking Albany Mobile Belt and northeast-striking Fraser Mobile Belt (Myers, 1990), is characterised by high-grade gneisses and granitic rocks and low- to medium-grade metasedimentary rocks that extend along the southern and southeastern margin of the Yilgarn Craton (Figure 21). The Orogen is in fault contact with the Archaean Yilgarn Craton to the northwest and extends eastwards under the Eucla Basin to the Coompana Block and western margin of the Gawler Craton. It is regarded as a collisional suture zone between these two cratons (Myers et al., 1996), recording the Mesoproterozoic collision of the Yilgarn Craton, the Mawson Craton of East Antarctica and South Australia between 1345 and 1140 Ma (Bunting et al., 1976; Baksi and Wilson, 1980; Nelson et al., 1995; Myers et al., 1996; Clark et al., 1999, 2000; Dawson et al., 2002; Duebendorfer, 2002; Fitzsimons, 2003). The orogen is truncated to the west and northeast by the Neoproterozoic Pinjarra and Paterson Orogens, respectively. To the south, the orogen was previously contiguous with outcrops on the Wilkes Land coast of Antarctica. The Albany–Fraser Orogen is unconformably overlain by the Jurassic to Holocene sedimentary rocks of the Bremer Basin, which is largely offshore and was initiated during rifting along the future margins of Australia and Antarctica (Fitzsimons and Buchan, 2005).

The Albany–Fraser Orogen (Figure 21) was divided into four lithotectonic domains by Myers (1990), defined using differences in structural style apparent from aeromagnetic data (Beeson et al., 1988; Myers, 1990; Fitzsimons, 2003) and confirmed by field and isotopic studies:

- The Northern Foreland, largely comprising thermally and structurally reworked late Archaean (3000-2600 Ma) granitoids of the southeastern Yilgarn Craton;
- The Biranup Complex, dominated by the felsic Munglinup and Dalyup orthogneisses (with protolith ages of 2640-2575 Ma and 1700-1630 Ma respectively; Nelson et al., 1995), but also including the high-strain Coramup Gneiss along its eastern margin;
- The Fraser Complex, comprising fault-bounded mafic granulite intruded by minor 1300-1280 Ma granitoids (Clark et al., 1999; Condie and Myers, 1999); and
- The Nornalup Complex, composed of ortho- and paragneisses with pre-1450 Ma protolith ages (Myers, 1995), extensively intruded by granitoids with ages in the ranges 1330-1280 Ma and 1190-1135 Ma (Nelson et al., 1995).

Geochronological studies of the Albany–Fraser Orogen have focused primarily on U–Pb zircon dating of early, syn-, and post-tectonic felsic plutonic rocks of the Biranup, Fraser and Nornalup Complexes (Black et al., 1992; Clark, 1995; Nelson et al., 1995; Clark et al., 1999, 2000; Love, 1999; Bodorkos and Clark 2004a, b). This work has identified two distinct phases of Mesoproterozoic magmatism and metamorphism, an older event at 1345-1260 Ma and a younger event at 1215-1140 Ma (Stages I and II of Clark et al., 2000), with local evidence for a third event at ~1030 Ma (Stage III; Fitzsimons et al., 2005). Each of these events was associated with a discrete episode of metamorphism and north–south to northwest–southeast shortening, and Stages I and II are separated by a phase of regional extension characterized by mafic dyke emplacement and sediment deposition. Clark et al. (2000) and Bodorkos and Clark (2004b) correlated Stage I with ocean closure and collision of a combined Western–Northern Australian Craton with the Mawson Craton of southern Australia and Antarctica, and Stage II with intracratonic reactivation of the already-assembled orogen during renewed shortening.

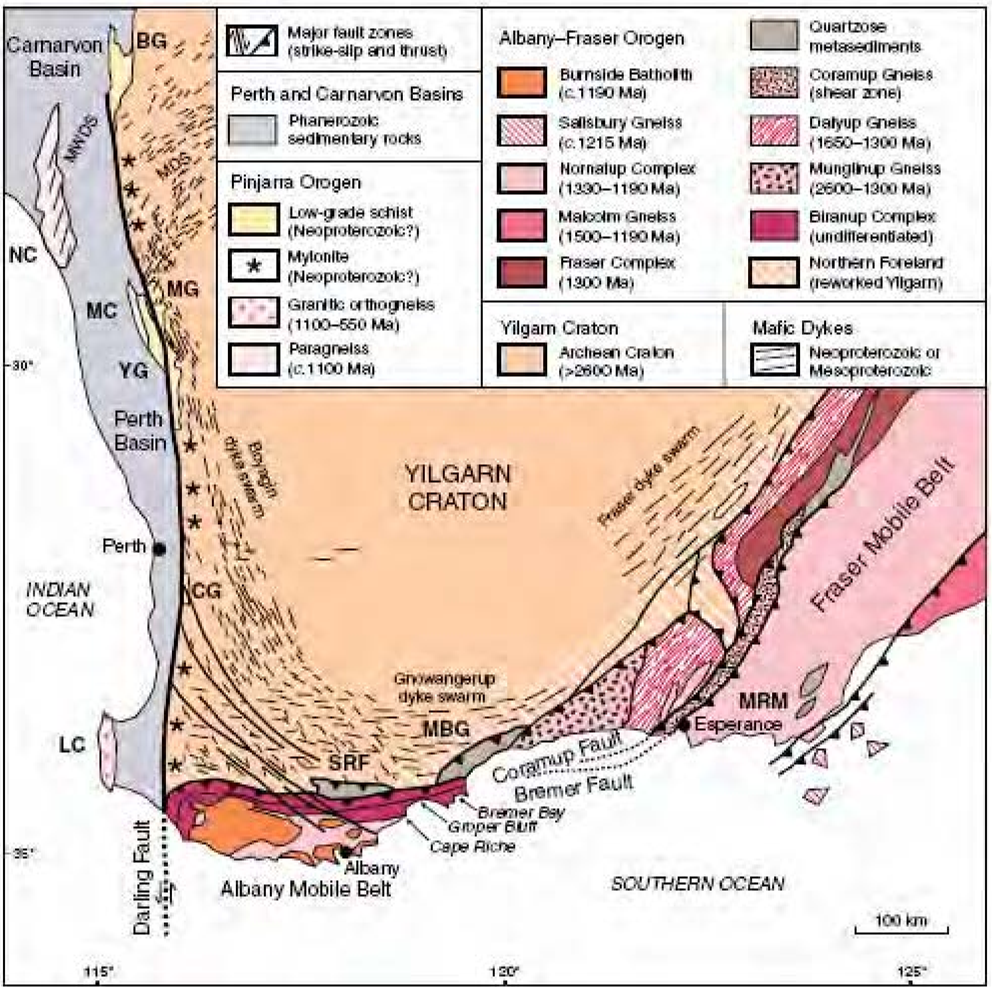


Figure 21: *Geology of southwestern Australia (from Fitzsimons and Buchan, 2005). BG, Badgeradda Group; CG, Cardup Group; LC, Leeuwin Complex; MBG, Mount Barren Group; MC, Mullingarra Complex; MDS, Muggamurra dyke swarm; MWDS, Mundine Well dyke swarm; MG, Moora Group; MRM, Mount Ragged metasedimentary rocks; NC, Northampton Complex; SRF, Stirling Range Formation; YG, Yandanooka Group*

Domain Subdivision

In the following sections, geological domains of the Albany-Fraser Orogen are discussed with an emphasis on geochronological constraints, as plotted in the accompanying Time-Space plots. The four geological domains of the Albany-Fraser Orogen are discussed in the order in which they are plotted, from left to right across the plots. The geochronological data are plotted in two 500 million year intervals (2100-1600 Ma and 1500-1000 Ma; Figure 22), although an overview of geochronological data not encompassed in these time intervals is provided where applicable.

Geochronological data compilation involved merging data extracted from Geoscience Australia's OZCHRON database with pre-existing data available from the literature and unpublished reports where available. Data interpretations have focussed on U-Pb SHRIMP data, with less emphasis placed on whole rock Rb-Sr and K-Ar data.

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Northern Foreland

Following the terminology of Myers (1990), the Northern Foreland comprises the southern margin of the Late Archaean Yilgarn Craton that was structurally and thermally reworked to produce amphibolite facies gneisses during the development of the Albany–Fraser Orogen. It comprises 3000-2600 Ma gneiss and granite, younger dolerite dykes, and fault-bound quartz-rich metasedimentary rocks (Fitzsimons et al., 2005).

The Munglinup Gneiss was derived from Archaean monzogranite and biotite tonalite with SHRIMP U–Pb zircon crystallization ages of 2640–2575 Ma (four samples: 2639 ± 37 Ma, 2631 ± 8 Ma, 2595 ± 11 and 2577 ± 9 Ma; Nelson, 1996; Nelson et al., 1995). Metamorphic zircon growth at ~1250 Ma was recorded in one sample of Munglinup Gneiss (Nelson et al., 1995).

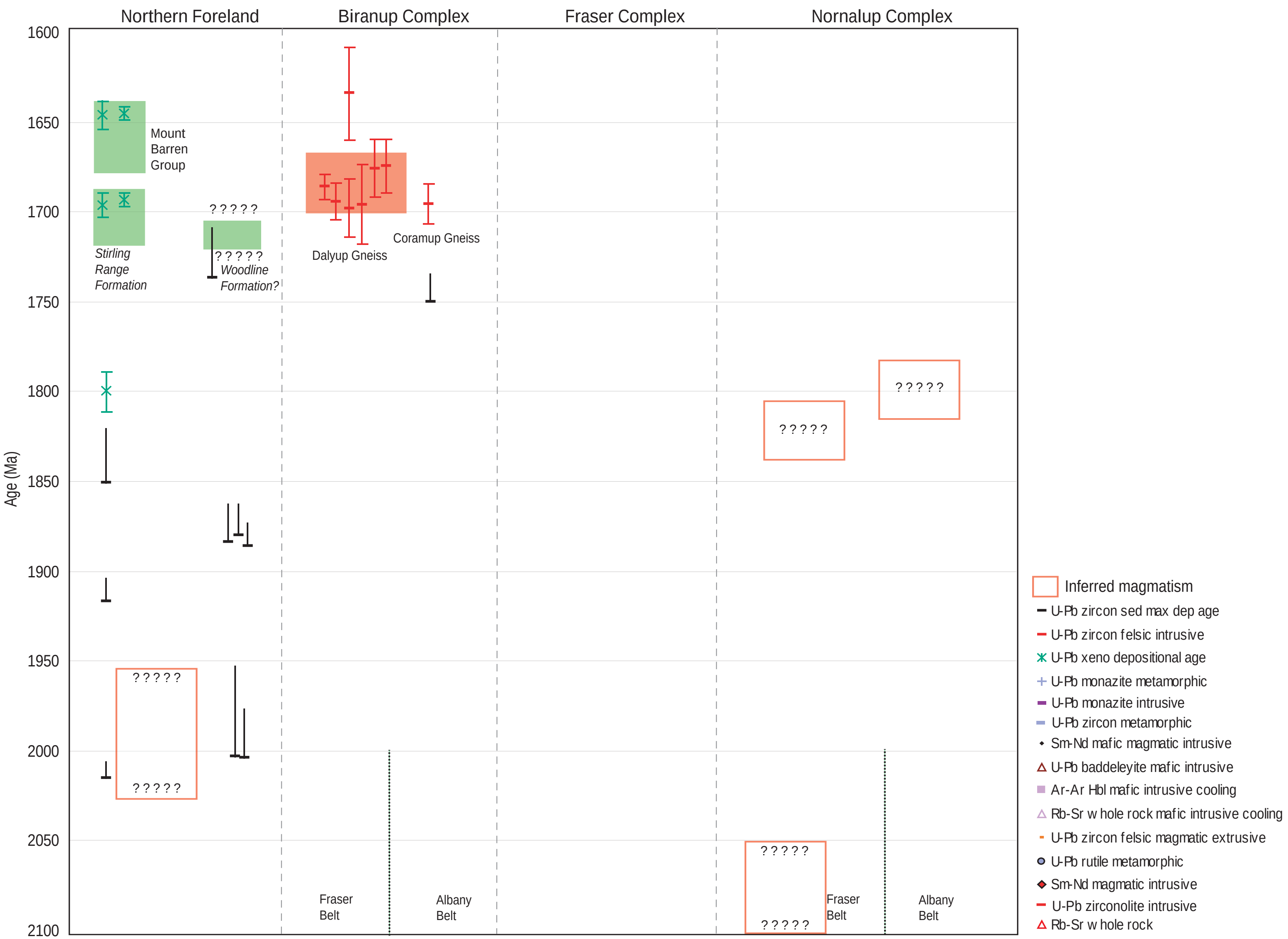
The Munglinup Gneiss was originally considered to be part of the Biranup Complex (Myers, 1995). However, magnetic anomalies within the gneisses suggest the presence of remnant greenstones and, in some instances, these can be traced across the Northern Foreland boundary and into the craton interior (Spaggiari et al., 2007). More recently, Spaggiari et al. (2007) report new SHRIMP U–Pb zircon dating of Munglinup Gneiss samples which yielded felsic igneous protolith ages of 2681 ± 5 Ma, 2661 ± 15 Ma and 2658 ± 21 Ma, which are similar to typical Yilgarn granite ages, and slightly older than those previously reported for the unit (Nelson, 1996; Nelson et al., 1995). Some of these orthogneisses record a thermal disturbance at ~1190 Ma, consistent with reworking during Stage II of the Albany–Fraser Orogeny. Spaggiari et al. (2007) therefore interpret the Munglinup Gneiss to be part of the Northern Foreland (i.e. reworked Yilgarn Craton).

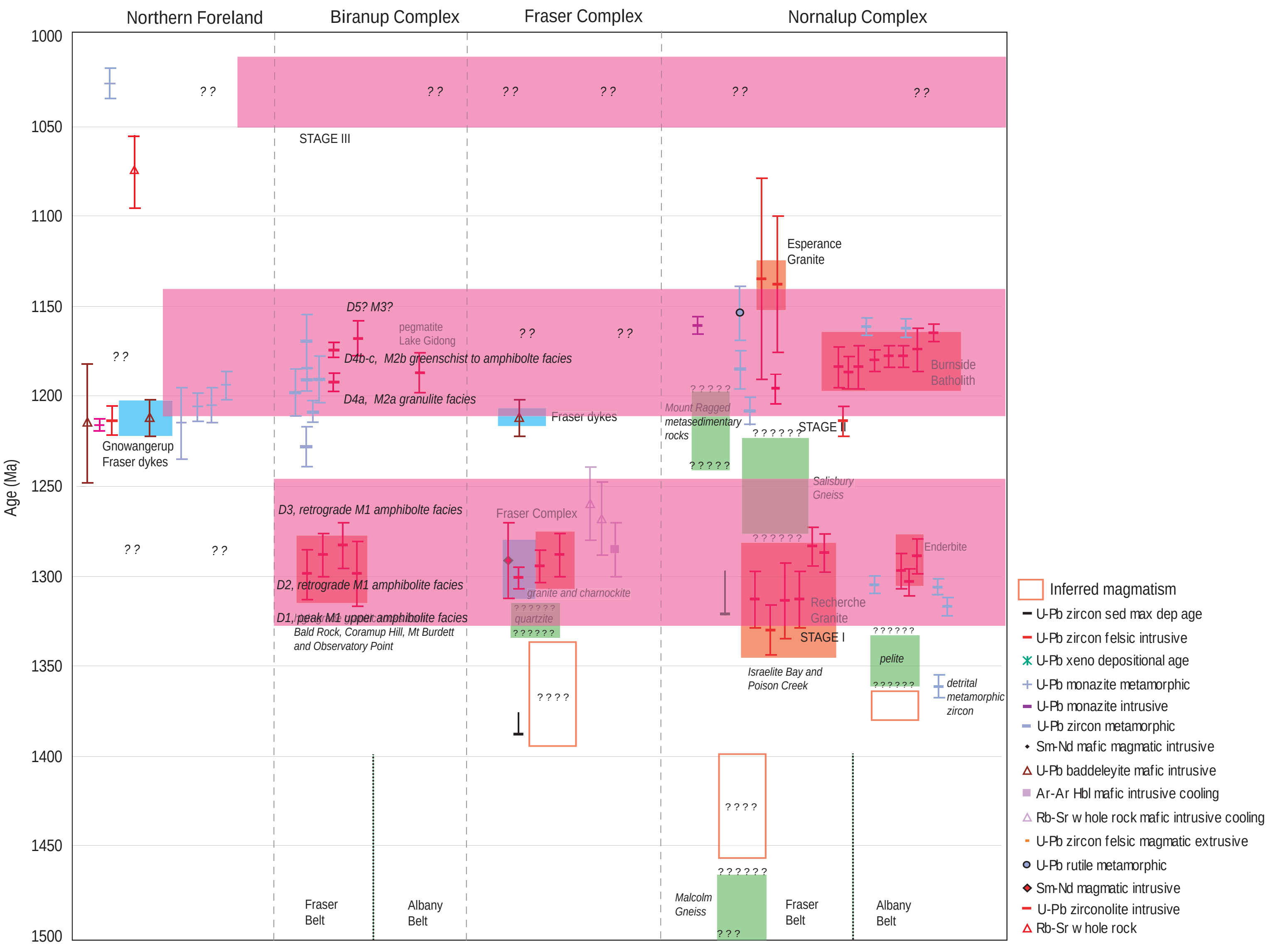
Proterozoic sedimentary rocks of the Woodline Formation, Mount Barren Group and Stirling Range Formation are thought to be part of the Northern Foreland (Jones and Hall, 2004; Jones, 2006). These formations may represent foreland sediments (Griffin, 1989), or older sediments deposited prior to the Albany–Fraser Orogeny (Hall and Jones, 2005). Alternatively, they could be allochthonous sedimentary units thrust onto the Yilgarn Craton (Myers, 1990).

The Proterozoic Woodline Formation unconformably overlies the Archaean rocks and comprises quartz sandstone, quartz conglomerate, chert breccia and interlayered mudstone (Jones, 2003; Hall and Jones, 2005). Six samples of coarse-grained quartz sandstone have yielded maximum depositional ages of 2004 ± 27 Ma, 2003 ± 50 Ma, 1886 ± 13 Ma, 1884 ± 21, 1880 ± 17 and 1737 ± 28 Ma (Jones, in prep.). A maximum depositional age of 1737 Ma for the Woodline Formation is indicated by SHRIMP U–Pb analysis of detrital zircons (Hall and Jones 2005; Jones in prep). A whole-rock Rb–Sr isochron age of 1620 ± 100 Ma (not plotted) was interpreted by Turek (1966) to represent a depositional age. The Woodline Formation could be of similar age to the Mt Barren Group in the southern part of the Albany–Fraser Orogen, recently dated by Vallini et al. (2002, see below).

The Stirling Range Formation preserves an approximately 1600 m-thick succession of sub-greenschist to lower greenschist-facies quartzite, shale, slate and phyllite that has undergone several episodes of deformation (Muhling and Brakel, 1985). Detrital zircons from this unit are dominated by a population aged 2016 ± 6 Ma (SHRIMP U-Pb, Rasmussen et al., 2002), which has no obvious source in the Yilgarn Craton and provides a maximum constraint on the depositional age. A minimum constraint on the time of deposition is provided by 1800 ± 14 Ma Pb–Pb SHRIMP ages for diagenetic xenotime (Rasmussen et al., 2004).

Figure 22 (overleaf): *Geochronological data and summary Time-Space plot for the Albany-Fraser Orogen, subdivided into the (a) 2100-1600 and (b)1500-1000 Ma timeslices.*


Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Mount Barren Group
Stirling Range Formation
?????
Woodline Formation?
Dalyup Gneiss
Coramup Gneiss
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr w hole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr w hole rock


Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
STAGE III
STAGE II
STAGE I
D5? M3?
pegmatite
Lake Gidong
D4b-c, M2b greenschist to amphibolte facies
D4a, M2a granulite facies
Gnowangerup
Fraser dykes
Fraser dykes
Esperance
Granite
Burnside
Batholith
Mount Ragged
metasedimentary
rocks
Salisbury
Gneiss
D3, retrograde M1 amphibolte facies
Fraser Complex
D2, retrograde M1 amphibolte facies
D1, peak M1 upper amphibolite facies
Bald Rock, Coramup Hill, Mt Burdett
and Observatory Point
granite and charnockite
quartzite
Enderbite
Recherche
Granite
Israelite Bay and
Poison Creek
pelite
detrital
metamorphic
zircon
Malcolm
Gneiss
Fraser
Belt
Albany
Belt
Fraser
Belt
Albany
Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr whole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr whole rock

The Mount Barren Group, in the Albany–Fraser Belt, crops out near the boundary between the Albany and Fraser Provinces. It comprises conglomerates, sandstones, pelites and stromatolitic carbonates that vary in metamorphic grade from lower greenschist in the north to upper amphibolite in the south (Witt, 1998). Metasedimentary rocks of the Mount Barren Group are dominated by quartzite (Kundip Quartzite) and psammitic to pelitic schist (Kybulup Schist) with subordinate dolomite and metaconglomerate. U–Pb geochronology of detrital zircon (Nelson, 1997) from two samples of Kundip Quartzite provide SHRIMP U-Pb maximum depositional ages of 1917 ± 13 Ma and 1851 ± 30 Ma for the sandstone precursors to the quartzite (Nelson, 1997). Detrital zircon populations aged ~2980, 2650, 2290, 2020, 1860, and 1790 Ma (Wetherley, 1998; Dawson et al., 2002) indicate that the Mount Barren Group must have been derived from sources other than the Yilgarn Craton (Dawson et al., 2002).

SHRIMP U-Pb analysis of xenotime from the Kundip Quartzite by Vallini et al. (2002) yielded two age populations: 1696 ± 7 Ma for cement adjacent to detrital zircon grains, and 1646 ± 8 Ma for outer zones. Preserved textures show that initial xenotime growth was early diagenetic, establishing the ~1700 Ma age as a proxy for the depositional age of the Mount Barren Group. The younger age (~1650 Ma) is regarded as burial related. Thus, U–Pb geochronology of detrital zircon (Nelson, 1997; Dawson et al., 2002) and diagenetic xenotime (Vallini et al., 2002) indicates that the Mount Barren Group was deposited after c. 1790 Ma but before c. 1700 Ma. Krapez and Martin (1999) have suggested that the Mount Barren Group was a foreland-basin sequence that formed as a consequence of Late Palaeoproterozoic collision between the Yilgarn and Gawler Cratons.

Stage II of the Albany–Fraser Orogeny commenced with emplacement of the Fraser dyke swarm into the Northern Foreland and the Biranup Complex. SHRIMP dating of baddeleyite from a granophyric segregation in the centre of one dyke yielded a mean $^{207}Pb/^{206}Pb$ age of 1212 ± 10 Ma (Wingate et al., 2000). The Stirling Range Formation is intruded by a series of east-trending dolerite dykes which give a zirconolite SHRIMP $^{207}Pb/^{206}Pb$ age of 1218 ± 3 Ma, indistinguishable from the less precise dates obtained from zircon (1215 ± 10 Ma) and baddeleyite (1217 ± 39 Ma) (Rasmussen and Fletcher, 2004), indicating that they are part of the Gnowangerup/Fraser dyke swarm.

Metamorphic monazite from the Stirling Range Formation yields a similar U–Pb SHRIMP age of 1215 ± 20 Ma (Rasmussen et al., 2002), suggesting a link between dyke emplacement and metamorphism. Kyanite-bearing schists from Barrens and West beaches yield SHRIMP U–Pb ages for xenotime and monazite of 1206 ± 8 Ma and 1194 ± 8 Ma respectively, and have been interpreted as dating peak syn-D2 metamorphism in the Mount Barren Group (Dawson et al., 2003).

The age of the Stirling dykes (1218 ± 3 Ma) corresponds with dates from other dyke swarms (1215 ± 11 Ma to 1204 ± 10 Ma) in the adjacent Yilgarn Craton (Evans, 1999; Qiu et al., 1999; Wingate et al., 2000; Pidgeon and Nemchin, 2001; Pidgeon and Cook, 2003). The timing of dyke emplacement also coincides with monazite growth in quartzite from the Stirling Range Formation (1215 ± 20 Ma; Rasmussen et al., 2002) and the formation of metamorphic xenotime and monazite in pelitic schist from the nearby Mount Barren Group (1205 ± 10 Ma; Dawson et al., 2003). Rasmussen and Fletcher (2004) suggest the growth of peak thermal metamorphic minerals is a likely consequence of crustal heating during mafic magmatism and intrusion.

Fitzsimons et al. (2005) obtained a SHRIMP U–Pb monazite age of 1027 ± 8 Ma for garnet–staurolite schist from West Beach, and argued that this age represented the true timing of syn-D2 amphibolite facies metamorphism in the Mount Barren Group. This interpretation clearly conflicts with the interpretation of Dawson et al. (2003). Fitzsimons et al. (2005) indicates that the older ages reported by Dawson et al. (2003) were obtained from monazite inclusions in biotite, and thus pre-date peak metamorphism.

The c. 1030 Ma monazite age reported by Fitzsimons et al. (2005) is the only robust evidence for a possible third stage of contractional tectonism in the Albany–Fraser Orogen, although a Rb–Sr whole-rock and mica isochron for pelitic samples from Barrens Beach yielded an imprecise age of 1077 ± 22 Ma (Thom et al., 1981) and suggests that these rocks were recrystallized during a post-1100 Ma thermal event. Fitzsimons et al. (2005) suggests the ~1200 Ma xenotime and monazite ages probably reflect an earlier metamorphic event that is unlikely to have exceeded greenschist facies. As noted by Dawson et al. (2003), the timing of this event is within error of the ~1210 Ma dyke swarm emplaced over much of southwestern Australia (Evans, 1999; Wingate et al., 2000; Pidgeon and Nemchin, 2001), consistent with this event resulting from the thermal influence of mafic intrusions.

Biranup Complex

The metasedimentary rocks of the Northern Foreland are in steep tectonic contact with granulite-facies orthogneisses of the Biranup Complex that dominate the northern part of the Albany-Fraser Orogen. This complex comprises a tectono-stratigraphic sequence of intensely deformed ortho- and paragneiss, including quartzite and BIF, and layered-gabbro intrusions (Myers, 1990).

The Dalyup Gneiss is dominated by granulite facies orthogneisses. It extends from at least the Bremer Bay area in the west, to inboard of the Fraser Complex in the east, and forms the main suture to the craton margin (Nelson et al., 1995).

The Dalyup Gneiss comprises biotite–hornblende granodiorite and monzogranite gneiss with SHRIMP U–Pb zircon crystallization ages of 1695-1634 Ma (Nelson et al., 1995). Five samples of orthogneiss of the Dalyup Gneiss have yielded SHRIMP U-Pb zircon protolith crystallisation ages of 1670 ± 15 Ma (Ten Mile Rocks), 1671 ± 16 Ma (Lake Gidong), 1634 ± 26 Ma (Lake Gidong), 1692 ± 22 Ma (Dalyup Creek) and 1695 ± 16 Ma (Mt Andrew) (Nelson, 1996). A mean $^{207}Pb/^{206}Pb$ age of 1184 ± 12 Ma determined from two analyses in one sample may date the time of metamorphic zircon growth (Nelson, 1996). More recent age data have been reported by Spaggiari et al. (2007). Boudinaged Dalyup Gneiss samples have yielded SHRIMP U-Pb protolith igneous crystallization ages of 1680 ± 7 and 1689 ± 11 Ma, with the latter undergoing new metamorphic zircon growth at 1197 ± 12 Ma. Crystallized melts within the boudin necks yielded crystallization ages of 1178 ± 4 and 1187 ± 5 Ma, with the latter preserving evidence of subsequent metamorphism at 1167 ± 15 Ma (Spaggiari et al., 2007). The 1700-1630 Ma protoliths to the Dalyup Gneiss (and the Coramup Gneiss, see below) are exotic to the late Archaean southeastern WAC (Nelson et al., 1995; Bodorkos and Clark, 2004b).

The Coramup Gneiss is a 10 km wide ductile shear zone developed between the Coramup and Bremer Faults at the southeastern margin of the Biranup Complex (Bodorkos and Clark, 2004a, b). Myers (1995) assigned its southernmost exposures to the western Nornalup Complex, whereas Clark et al. (1999) considered the Coramup Gneiss to be the easternmost unit of the Biranup Complex.

Recent SHRIMP U–Pb zircon dates indicate that garnet-bearing granodioritic gneiss of the Coramup Gneiss has an igneous crystallization age of 1688 ± 12 Ma (indistinguishable from the Dalyup Gneiss), and underwent metamorphism at 1231 ± 9 Ma (Spaggiari et al., 2007). Metamorphosed quartz sandstone (in the Coramup Gneiss) from the same area has a U-Pb zircon maximum depositional age of ~1750 Ma, was metamorphosed at 1215 ± 5 Ma, and preserves evidence for post-metamorphic resetting at 1184 ± 7 Ma. Structurally, most of the Dalyup and Coramup Gneisses are contained within major shear zones that wrap around the craton margin and these have been interpreted to represent the remnants of terrane amalgamation, possibly during Stage I of the Albany–Fraser Orogeny (1345-1260 Ma). The metamorphic ages recorded in Biranup Complex rocks between ~1210 and 1140 Ma represent reworking during Stage II (Spaggiari et al., 2007).

Bodorkos and Clark (2004b) reported SHRIMP U-Pb zircon ages of 1731 ± 25 Ma and 1602 ± 20 Ma (not plotted) from two analyses from two zircons from the Coramup Gneiss, interpreted to be related to magmatic crystallisation of the tonalitic precursor to the gneiss. A pegmatite dyke crosscutting the dominant foliation in the Coramup gneiss has a SHRIMP U-Pb age of 1168 ± 12 Ma, interpreted as the magmatic crystallisation age of the pegmatitic dyke. This age from a syn-D2 pegmatite provides direct evidence for 1215-1140 Ma tectonism during Stage II of the Albany-Fraser Orogeny outside of the Nornalup Complex (Clark et al., 2000).

A magmatic event in the Biranup Complex occurred at ~1300 Ma, based on U-Pb SHRIMP dates obtained for high-grade orthogneisses from Bald Rock (1299 ± 14), Coramup Hill (1283 ± 13), Mount Burdett (1299 ± 18), and Observatory Point (1288 ± 12), which record the crystallisation ages of the granitic protoliths to the gneisses (Nelson, 1996). The $^{207}Pb/^{206}Pb$ age of 1288 ± 12 Ma for charnockite is interpreted as the crystallization age of the precursor leucogranite. The granite probably crystallized during or shortly following the peak of metamorphism, and this date may therefore also provide an estimate of the time of granulite-facies metamorphism (Nelson, 1996).

A pegmatite dyke intruding the Dalyup orthogneiss has a SHRIMP U-Pb zircon crystallisation age of 1187 ± 12 Ma (Nelson, 1996), which constrains the timing of Stage II tectonism (Nelson et al., 1996; Bodorkos and Clark, 2004b).

Fraser Complex

The Fraser Complex (Myers, 1985) forms a major component of the northeastern part of the Albany–Fraser Orogen, and comprises several fault-bound slices of mafic granulite derived from at least three separate magma sources, all of which have subduction-related geochemical anomalies consistent with an oceanic arc origin (Condie and Myers, 1999).

A mineral Sm-Nd isochron date of 1291 ± 21 Ma, interpreted as an igneous crystallisation age, was obtained by Fletcher et al. (1991) on a sample of gabbro from the Fraser Complex. The same sample gave a biotite, whole-rock 2-point Rb-Sr isochron date of 1268 ± 20 Ma. Bunting et al. (1976) reported a whole rock Rb-Sr isochron data of 1262 ± 21 Ma on muscovite-bearing dykes from shear zones in granulite-facies gneiss adjacent to the Fraser Complex. An Ar/Ar date of 1285 ± 15 Ma was determined by Baksi and Wilson (1980) by the incremental heating of hornblende isolated from a granulite from the Fraser Range. The isotopic evidence suggests that Fraser Complex gabbros crystallised, underwent high-grade metamorphism and deformation, and were tectonically emplaced into the middle crust all in a relatively short time span (~30 million years; Fletcher et al., 1991). The Rb-Sr and Ar-Ar cooling ages between 1285 and 1262 Ma for the Fraser Complex have also been interpreted to date the termination of high-grade metamorphism throughout the eastern part of the orogen (Nelson et al., 1995). Granulite facies M1a metamorphism in the Fraser Complex was synchronous with charnockite emplacement (Clark et al., 1999). Orthogneiss yielded a single population with a $^{207}Pb/^{206}Pb$ age of 1301 ± 6 Ma, interpreted as the igneous crystallisation age of the charnockite (Clark et al., 1999). The age provides an estimate for the timing of high-grade activity in the Fraser Complex (M1a/D1), and also provides a minimum intrusion age for the metagabbros that the charnockite intrudes (Fletcher et al., 1991).

Monzogranite records a mean $^{207}Pb/^{206}Pb$ crystallisation age of 1293 ± 9 Ma (Clark et al., 1999), while an undeformed aplite dyke intruding basic granulites yielded a SHRIMP U-Pb zircon crystallisation age of 1288 ± 12 Ma (Clark et al., 1999). High-grade metamorphism at 1301 ± 6 Ma, was followed by a high-P amphibolite facies event temporally bracketed by the 1293 ± 9 Ma granite and the 1288 ± 12 Ma aplite (Clark et al., 1999).

Quartzo-feldspathic metasedimentary gneiss interleaved with the Fraser Complex contains a single population of well-preserved 1388 ± 12 Ma detrital zircons (Clark et al., 1999). The Fraser Complex supracrustal sequence is significantly younger than metasedimentary rocks occurring elsewhere in the eastern Biranup Complex, which predate orthogneisses with U–Pb SHRIMP zircon ages of 1700–1600 Ma (Nelson et al., 1995). The spectrum of detrital ages in the paragneiss is exclusively Mesoproterozoic, and does not correspond to any known basement rocks in the Biranup Complex or the WAC. These zircon crystals may have been derived from Nornalup Complex basement (i.e. the Malcolm Gneiss and its earliest intrusions, see below; Nelson et al., 1995).

Ion-microprobe baddeleyite $^{207}Pb/^{206}Pb$ results are reported for a northeast-trending dyke swarm intruded into Archaean rocks of the eastern Yilgarn Craton by Wingate et al. (2000). The age of 1212 ± 10 Ma obtained for the Fraser Dyke Swarm is similar to a SHRIMP zircon age of 1215 ± 11 Ma reported by Qiu et al. (1999) for a quartz diorite dyke located 400 km to the west. Evans (1999) reported SHRIMP zircon ages between 1216 and 1202 Ma (mean 1210 Ma) for five dolerite and quartz diorite dykes in the central (Wheatbelt swarm) and southern (Gnowangerup swarm) parts of the Yilgarn Craton.

Nornalup Complex

Further to the south and east of the Biranup Complex, the deeper part of the Albany-Fraser Orogen comprises a completely different group of ortho- and paragneisses, largely of Proterozoic origin, intruded by younger granites (Myers, 1990). The Nornalup Complex can be subdivided into the Recherche Granite and Esperance Granite complexes and the Malcolm Gneiss.

In the Nornalup Complex, pre-orogenic basement rocks crop out only in the Malcolm Gneiss, which comprises paragneiss units, dominated by psammite and quartzite with minor garnet–biotite–sillimanite pelite, intruded by felsic and mafic orthogneiss, and all cut by dykes of the Recherche Granite (Clark et al., 1999; 2000). It was generally strongly, but heterogeneously, deformed by D1 and D2. Zircons from metasedimentary gneiss from near Point Malcolm yielded a wide spectrum of detrital ages. Two distinct populations at 1560 ± 40 and 1807 ± 35 Ma, and single grain analyses ranging in age from 2033 to 2734 Ma, suggest that the sedimentary precursors to these rocks were not derived from the vicinity of the Albany–Fraser Orogen (Nelson et al., 1995). Zircons of the youngest group, comprising ten analyses, with $^{207}Pb/^{206}Pb$ ratios indicating an age of 1560 ± 40 Ma, sets a limit on the earliest time of deposition of the sediments that formed the protolith of the paragneiss (Nelson, 1996). A poorly defined 1500–1400 Ma zircon population from a granitic orthogneiss within the Malcolm Gneiss has been interpreted as an emplacement age (Myers, 1995) and provides a minimum age for deposition.

The Malcolm Gneiss is intruded by Recherche Granite and numerous generations of felsic and mafic dykes. The Recherche Granite is subdivided into even-grained units and porphyritic units. It was intruded as sheets together with syn-plutonic mafic dykes, and was boudinaged during D1. Samples of granitic gneiss representative of the widely-distributed Recherche Granite (Myers, 1990) yield crystallisation ages between ~1330 and 1283 Ma (Nelson, 1996). These include: a porphyritic granodiorite from Israelite Bay, 1314 ± 21 Ma; a porphyritic granite at Poison Creek east of Cape Arid, 1330 ± 14 Ma; a fine, even-grained granite on the headland north of Observatory Island west of Esperance, 1288 ± 12 Ma; a granite gneiss from Coramup Hill, north of Esperance, 1283 ± 13 Ma; and a granite from Mount Burdett, north of Esperance, 1299 ± 18 Ma (Nelson, 1996). An aplite dyke which cuts the Recherche Granite yields a SHRIMP U-Pb age of 1313 ± 16 Ma (Clark et al., 2000). These rocks intruded during a period of high-grade metamorphism and intense deformation recognised throughout the eastern Albany–Fraser Orogen (Stage I Albany-Fraser Orogeny; Myers, 1995; Nelson et al., 1995).

In the eastern Fraser Mobile Belt, 1280-1215 Ma extension and erosion of the crust thickened during Stage I of the Albany–Fraser Orogeny resulted in the deposition of the protoliths to the Mount Ragged and Salisbury metasedimentary sequences, which unconformably overlie pre-1313 Ma rocks of the Nornalup Complex (Clark et al., 2000).

The Salisbury Gneiss comprises garnet–cordierite migmatite and mafic granulite outcropping on a series of islands at the southeast margin of the Nornalup Complex (Clark et al., 2000). Zircon cores aged 1214 ± 8 Ma in the leucosome are interpreted as dating metamorphism and melting, which pre-dates Stage II tectonism elsewhere in the orogen and is synchronous with the emplacement of the Gnowangerup and Fraser dyke swarms into the southeastern Yilgarn Craton (Evans, 1999; Wingate et al., 2000). Zircon rims in the Salisbury Gneiss are dated at 1182 ± 13 Ma and are assumed to date high temperature exhumation along ductile thrust zones, which are thus the same age as similar structures developed throughout the Nornalup Complex. Clark et al. (2000) proposed that thrusting of the Salisbury Gneiss over the Nornalup Complex at this time was responsible for metamorphism of the Mount Ragged metasedimentary rocks, but had little metamorphic effect on other units that had already developed Stage I high-grade assemblages. Conversely, widespread evidence for 1214 Ma partial melting in the Salisbury Gneiss implies that this unit was not previously metamorphosed in Stage I (Clark et al., 2000) and suggests a setting similar to the Mount Ragged metasedimentary rocks (i.e. a cover succession deposited onto Nornalup basement after Stage I tectonism).

The Mount Ragged metasedimentary rocks, and the Mount Ragged schist (Myers, 1995), are a sequence of massive quartzites and subordinate metapelites recrystallised in upper greenschist-lower amphibolite facies that crop out northwest of the Malcolm Gneiss. The Mount Ragged Quartzite yields a youngest zircon population of 1321 ± 24 Ma which sets a maximum age for the deposition of the sediments that formed the protolith of the quartzite. This succession of quartzite with minor pelite was deposited in deep water conditions, and detrital zircon populations at ~1780 and c. 1320 Ma are consistent with local derivation from the Dalyup Gneiss and Recherche Granite (Clark et al., 2000). SHRIMP U-Pb analysis of rutile from Mount Ragged mica schist yielded an age of 1154 ± 15 Ma, providing a minimum estimate for the timing of peak amphibolite facies metamorphic conditions in the Mount Ragged metasedimentary rocks (Clark et al., 2000). This age is consistent with metamorphism resulting from Stage II crustal thickening, which occurred at 1190-1160 Ma in the gneissic basement (Clark et al., 2000).

A pegmatite within the Malcolm Gneiss yielded a SHRIMP U-Pb monazite age of 1165 ± 5 Ma which records the age of crystallisation of the host pegmatite and provides an estimate for the timing of movement in shear zones in the Malcolm Gneiss (Clark et al., 2000), an age indistinguishable from the age of Stage II thrusting in the Coramup Gneiss (Bodorkos and Clark, 2004b).

The western part of the Albany–Fraser Orogen is dominated by late to post-kinematic granite plutons (Burnside Batholith). These rocks occur mainly within the Nornalup Complex, but locally occur across the Nornalup–Biranup Complex boundary (Myers, 1995).

U-Pb zircon crystallisation ages of Burnside Batholith plutons range between ~1170 and 1190 Ma (Pidgeon, 1990; Black et al., 1992). Black et al. (1992) provides U-Pb zircon protolith emplacement ages of 1184 ± 11 and 1184 ± 12 Ma for orthogneiss of the Burnside Batholith. These orthogneisses are cut by aplite dykes, with an emplacement age of 1182 ± 12 Ma (Black et al., 1992). A crystallisation age of 1180 ± 6 Ma was derived from zircons in pegmatite from a layered mafic gneiss and pegmatite, while a sample of porphyritic granite yielded an emplacement age of 1189 ± 9 Ma. A second sample of pegmatite (Groper Bluff) yielded a crystallisation age of 1196 ± 8 Ma (Black et al., 1992). Pidgeon (1990) reported single- and multi-grain U-Pb zircon dates of 1174 ± 12 Ma and 1178 ± 6 Ma, respectively, for post-tectonic adamellites (Albany Adamellite) of the Burnside Batholith.

Evidence for Stage I magmatism is limited to U–Pb zircon emplacement ages of 1289 ± 10 Ma for enderbite (Pidgeon, 1990) and 1296 ± 10 and 1302 ± 7 Ma for tonalite (Love, 1999) at Albany. The 1289 ± 10 Ma enderbitic gneiss is adjacent to the 1178 ± 6 Ma old Albany Adamellite and interpreted as dating the emplacement of the granodioritic parent of the gneiss, probably during granulite facies metamorphism (Pidgeon, 1990). Clark (1995) obtained U-Pb SHRIMP dates of 1304 ± 5 Ma and 1167 ± 7 Ma on metamorphic zircons from granulite-facies metasedimentary migmatitic gneiss sampled near the Albany Enderbite.

Metasedimentary rocks are subordinate, and include garnet–sillimanite migmatites and quartzite. Pelitic migmatites from Ledge Beach (Clark, 1995) and Albany (Love, 1999) contain 1750-1720 Ma detrital grains, consistent with erosion of a Dalyup Gneiss source, and the Albany migmatite also contains a dominant population of detrital metamorphic zircon aged 1364 ± 8 Ma (Love, 1999), constraining the depositional age to 1360–1300 Ma. U–Pb metamorphic zircon ages of 1304 ± 3 Ma and 1314 ± 5 Ma for the Ledge Beach and Albany migmatites respectively (Clark, 1995; Love, 1999), reflect Stage I metamorphism. The Ledge Beach migmatite contains a second generation of metamorphic zircon dated at 1169 ± 8 Ma (Clark, 1995), synchronous with the emplacement of the Burnside Batholith and the main episode of Stage II thrusting in the Fraser Belt.

Late- to post-tectonic Esperance Granite plutons (Myers, 1995) were emplaced into the Nornalup Complex and Mount Ragged metasedimentary rocks at c. 1140 Ma. Two outcrops of undeformed granite gave imprecise U-Pb zircon crystallisation ages of 1138 ± 38 Ma and 1135 ± 56 Ma (Nelson, 1996). These ages were interpreted by Myers (1995) as dating a second period of tectonism and metamorphism correlating with the major ~1190–1170 Ma orogenic episode identified in the western part of the orogen. Although Esperance Granite plutons have not been recognised in the Biranup Complex, the 1187 ± 12 Ma pegmatite dyke intruding Palaeoproterozoic gneisses at Lake Gidong (Nelson et al., 1995) may be related to this second thermo-tectonic event.

OUTSTANDING QUESTIONS AND SCOPE OF FUTURE PROJECTS

The following geochronological investigations are recommended to resolve gaps in the current understanding of the time-space evolution of the Albany-Fraser Orogen.

- A more detailed study combining systematic geochronology with phosphate petrography and metamorphic reaction histories across the full spectrum of bulk compositions is needed to fully characterize the controls on monazite growth in the Mount Barren Group.
- Further geochronological evidence for a possible third (~2030 Ma) stage of contractional tectonism in the Albany–Fraser Orogen (i.e. Fitzsimons et al., 2005).
- Similar xenotime and monazite studies of the Woodline Formation to test its proposed equivalence with the Mount Barren Group.
- Detailed detrital provenance studies of sedimentary units to better constrain their stratigraphic position (e.g., protoliths to the Mount Ragged and Salisbury metasedimentary sequences).
- Reanalysis of the Malcolm Gneiss may provide a more accurate maximum depositional age for the sediments that formed the protolith to the paragneiss.
- Establish/refine age constraints for the Esperance granites, and investigate the possible presence of similar-aged intrusives in the Biranup Complex.
- There is no isotopic evidence of Stage I tectonism in the Biranup Complex of the Albany Belt, but this could reflect a lack of data rather than a significant difference between the Albany and Fraser Belts.
- Clark et al. (2000) and Bodorkos and Clark (2004b) have argued that the Recherche Granite was emplaced within a continental magmatic arc above a southeast-dipping subduction zone. Limited chemistry on the Recherche granites does not seem to support this, although further geochemistry is warranted.
- Further granite geochemistry, petrology and geochronology will undoubtedly refine the subdivision of the granites in the Biranup and Nornalup Complexes, and will possibly alter the understanding of their metallogenic potential, which currently is low.
- Dating of mineral deposits at Tropicanna and Trilogy.

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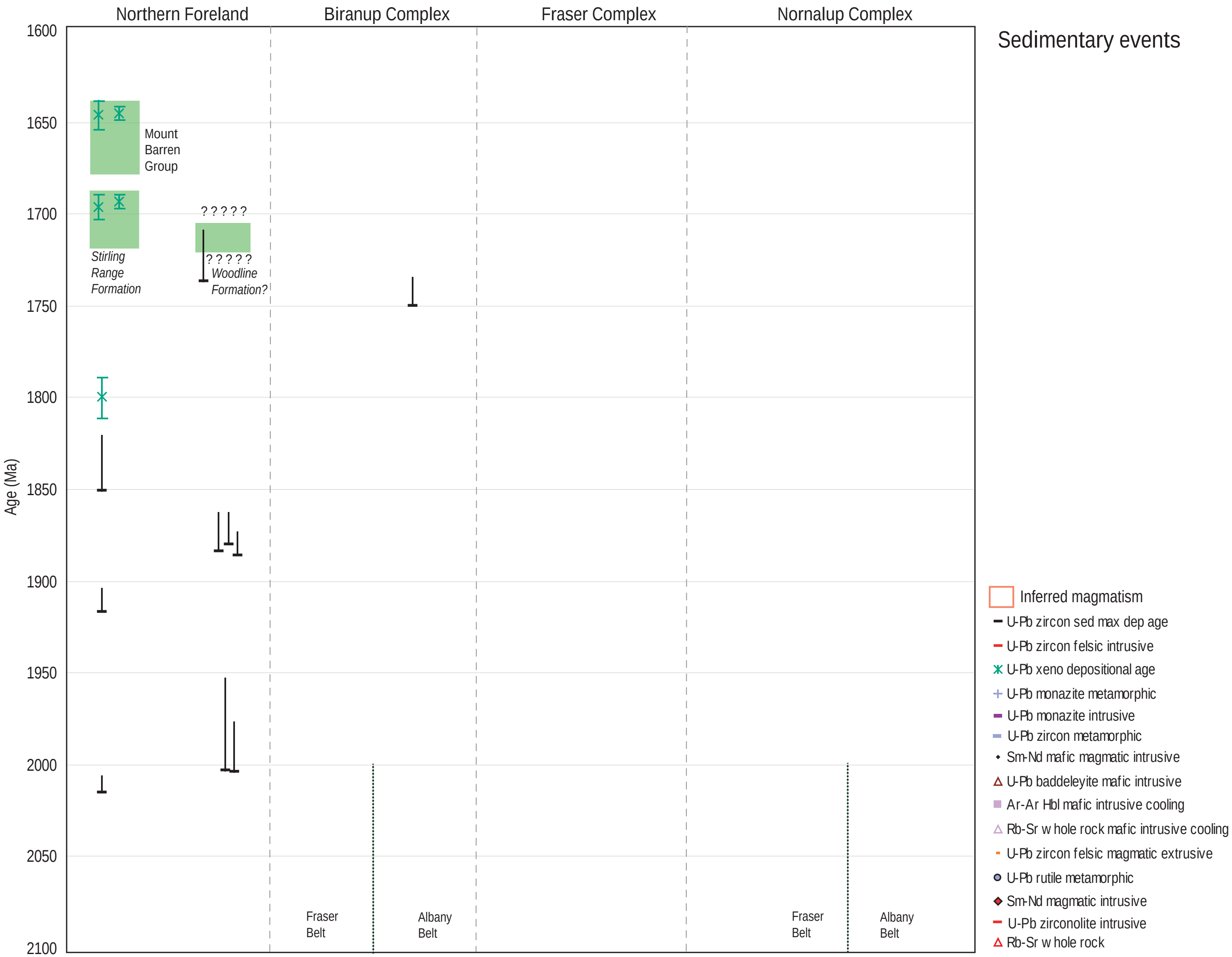
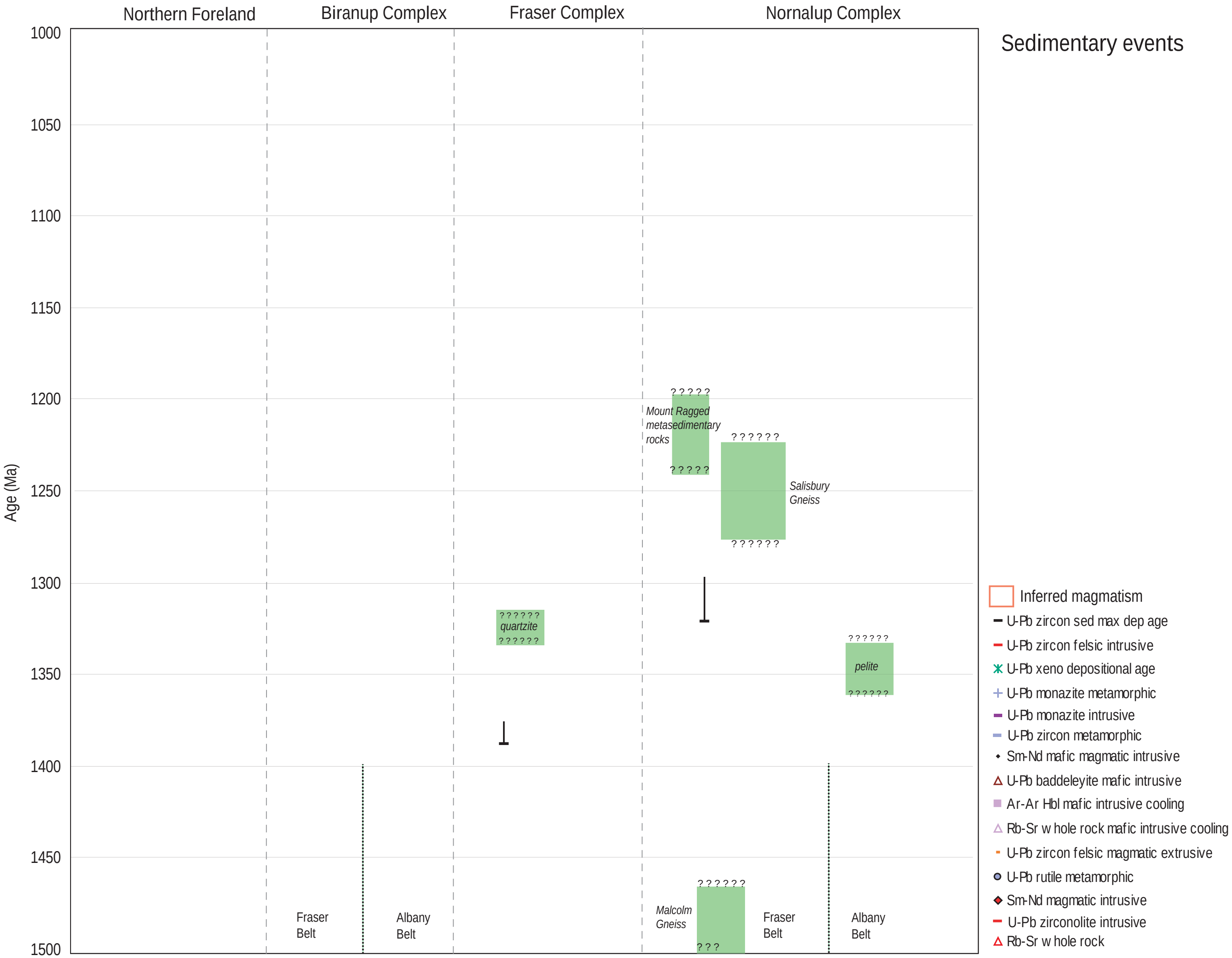
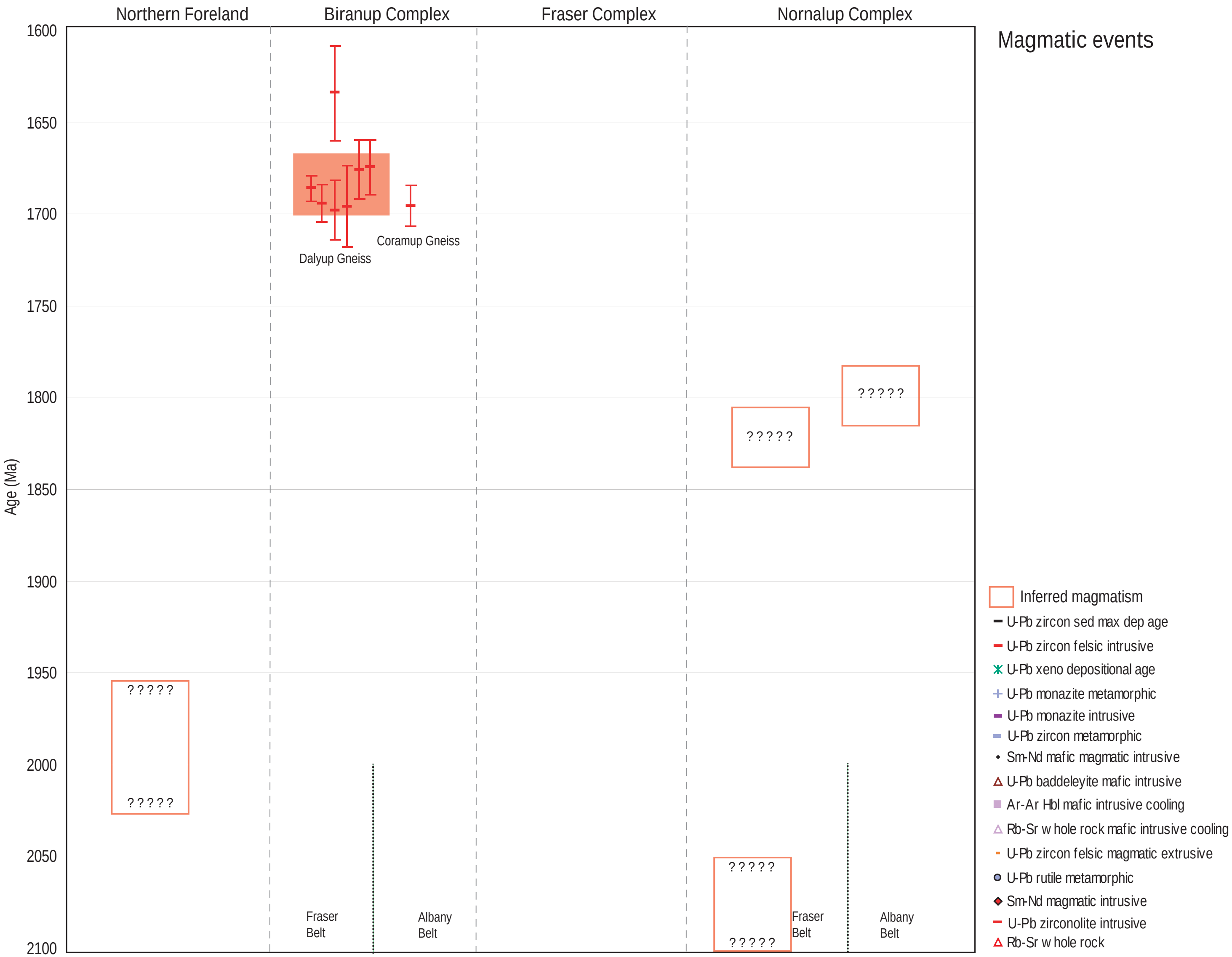
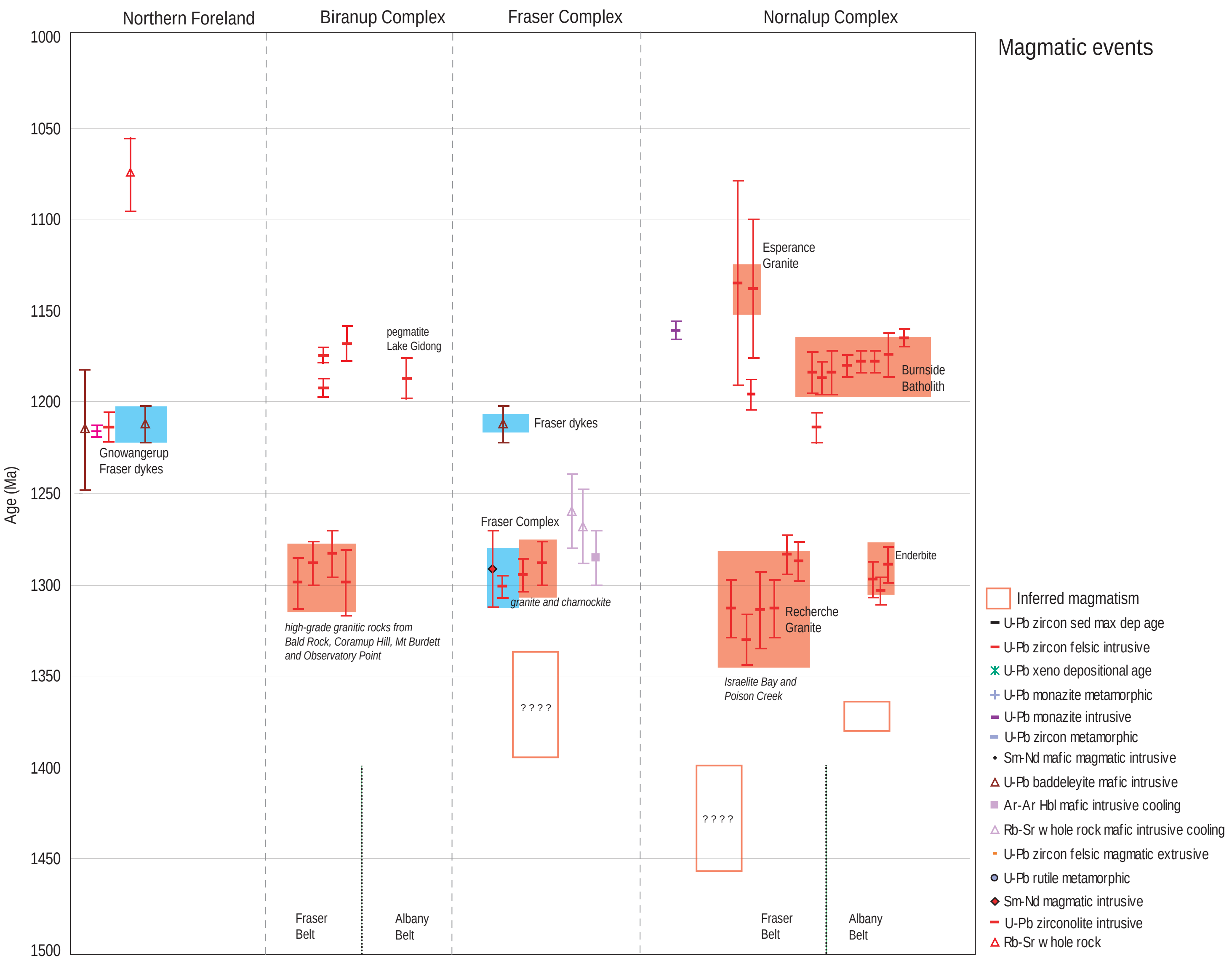

Sedimentary events
Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Mount Barren Group
Stirling Range Formation
? ? ? ? ?
? ? ? ? ?
Woodline Formation?
Fraser Belt
Albany Belt
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr whole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr whole rock


Sedimentary events
Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Mount Ragged metasedimentary rocks
Salisbury Gneiss
quartzite
pelite
Malcolm Gneiss
Fraser Belt
Albany Belt
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr w hole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr w hole rock


Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Magmatic events
Age (Ma)
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
Dalyup Gneiss
Coramup Gneiss
?????
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr whole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr whole rock


Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Magmatic events
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Gnowangerup Fraser dykes
pegmatite Lake Gidong
high-grade granitic rocks from Bald Rock, Coramup Hill, Mt Burdett and Observatory Point
Fraser dykes
Fraser Complex
granite and charnockite
? ? ? ?
Esperance Granite
Burnside Batholith
Enderbite
Recherche Granite
Israelite Bay and Poison Creek
? ? ? ?
Fraser Belt
Albany Belt
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr whole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr whole rock


Northern Foreland
Biranup Complex
Fraser Complex
Nornalup Complex
Metamorphic and deformation events
Age (Ma)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
STAGE III
D5? M3?
D4b-c, M2b greenschist to amphibolte facies
D4a, M2a granulite facies
STAGE II
D3, retrograde M1 amphibolte facies
D2, retrograde M1 amphibolte facies
D1, peak M1 upper amphibolite facies
STAGE I
detrital metamorphic zircon
Fraser Belt
Albany Belt
Fraser Belt
Albany Belt
Inferred magmatism
U-Pb zircon sed max dep age
U-Pb zircon felsic intrusive
U-Pb xeno depositional age
U-Pb monazite metamorphic
U-Pb monazite intrusive
U-Pb zircon metamorphic
Sm-Nd mafic magmatic intrusive
U-Pb baddeleyite mafic intrusive
Ar-Ar Hbl mafic intrusive cooling
Rb-Sr w hole rock mafic intrusive cooling
U-Pb zircon felsic magmatic extrusive
U-Pb rutile metamorphic
Sm-Nd magmatic intrusive
U-Pb zirconolite intrusive
Rb-Sr w hole rock

Time-Space evolution of the Musgrave Province

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OVERVIEW

The Musgrave Province is located in north-western South Australia, south-western Northern Territory and eastern Western Australia (Figure 23). The province forms an east-west trending Palaeo-Mesoproterozoic crystalline basement inlier that is well exposed in several ranges (e.g. Tomkinson, Mann, Musgrave and Petermann Ranges) but elsewhere is largely covered by sands of the Great Victoria Desert. The Musgrave Province is surrounded by Neoproterozoic-Palaeozoic basins, namely the Amadeus Basin to the north, the Canning Basin to the northwest, the Officer Basin to the south and west, and the Warburton Basin to the east. The major geological events to have affected the Musgrave Province are the Musgrave Orogeny (~1200-1160 Ma), the magmatic Giles Event at ~1080-1040 Ma, and the Petermann Orogeny (~570-530 Ma). The Musgrave Province is divided into two domains which are separated by the Woodroffe Thrust; the Mulga Park Domain in the north, and the Fregon Domain in the south (Camacho et al., 1991).

For this compilation, the geochronology of the Musgrave Province is discussed according to state and territory boundaries, with the Northern Territory geology further subdivided into the Mulga Park and Fregon Domains. The geochronological data are plotted in two 500 million year intervals (1900-1400 Ma and 1400-900 Ma; Figure 24). Although this compilation focuses on the Proterozoic record, the geochronological constraints on the ~570-530 Ma Petermann Orogeny are also briefly discussed.

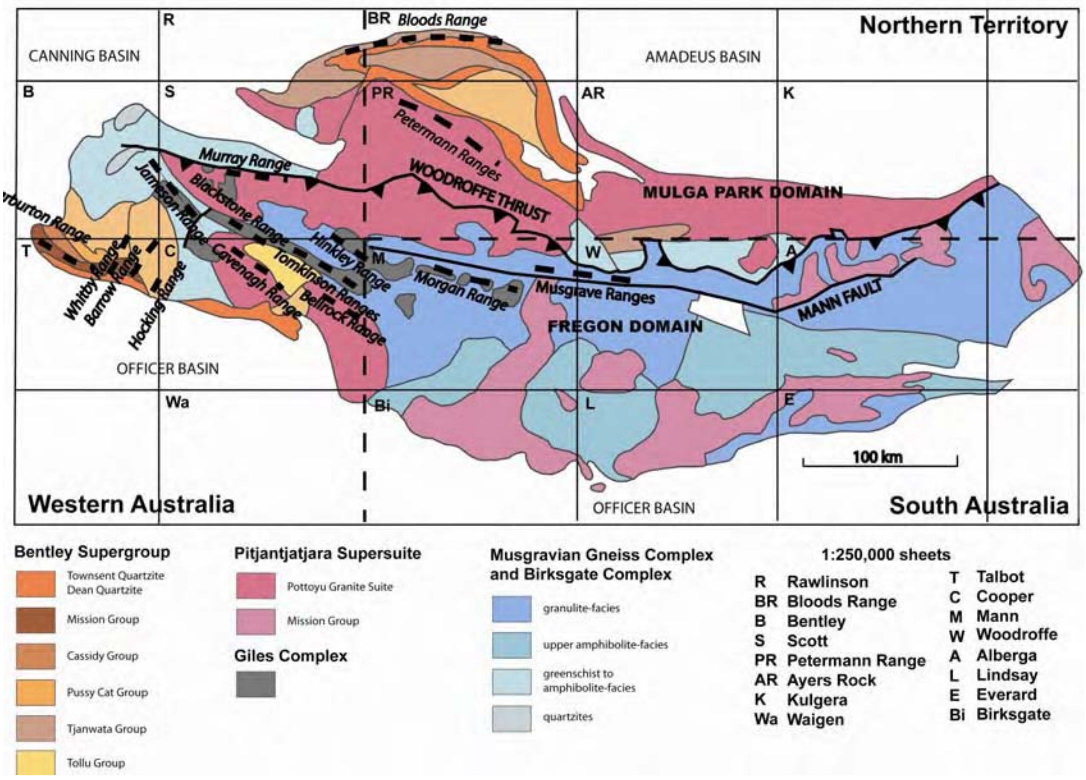


Figure 23: *Simplified solid geology of the Musgrave Province, showing the Mulga Park and Fregon Domains, and the state-territory borders.*

REVIEW OF GEOLOGY AND GEOCHRONOLOGY BY GEOLOGICAL DOMAIN

Mulga Park Domain

Stratigraphy

The Mulga Park Domain is dominated by felsic orthogneisses with less common mafic rocks and paragneisses. These rocks were metamorphosed in the Musgrave Orogeny, but contain an earlier record with zircon ages mostly in the range 1600 – 1540 Ma, as well as some zircon components as old as ~2000 Ma (Camacho and Fanning, 1995; Edgoose et al., 2004). Some of these older ages have been interpreted as magmatic ages, and include U-Pb SHRIMP zircon ages of 1591 ± 9 Ma (igneous xenocrysts in granite; Edgoose et al., 2002), 1591 ± 30 Ma (felsic gneiss at Allanah; Young et al., 2002), 1584 ± 23 Ma (amphibolite-facies gneiss, Olia Chain; Scrimgeour et al., 1999), 1563 ± 22 Ma (felsic granulite from Britten Jones; Young et al., 2002), 1555 ± 28 Ma (amphibolite gneiss; Camacho and Fanning, 1995), and 1539 ± 23 Ma (gneiss, Olia Chain; Young et al., 2002). Consequently, most authors regard the Mulga Park Domain to consist largely of igneous rocks intruded in the period ~1600-1540 Ma.

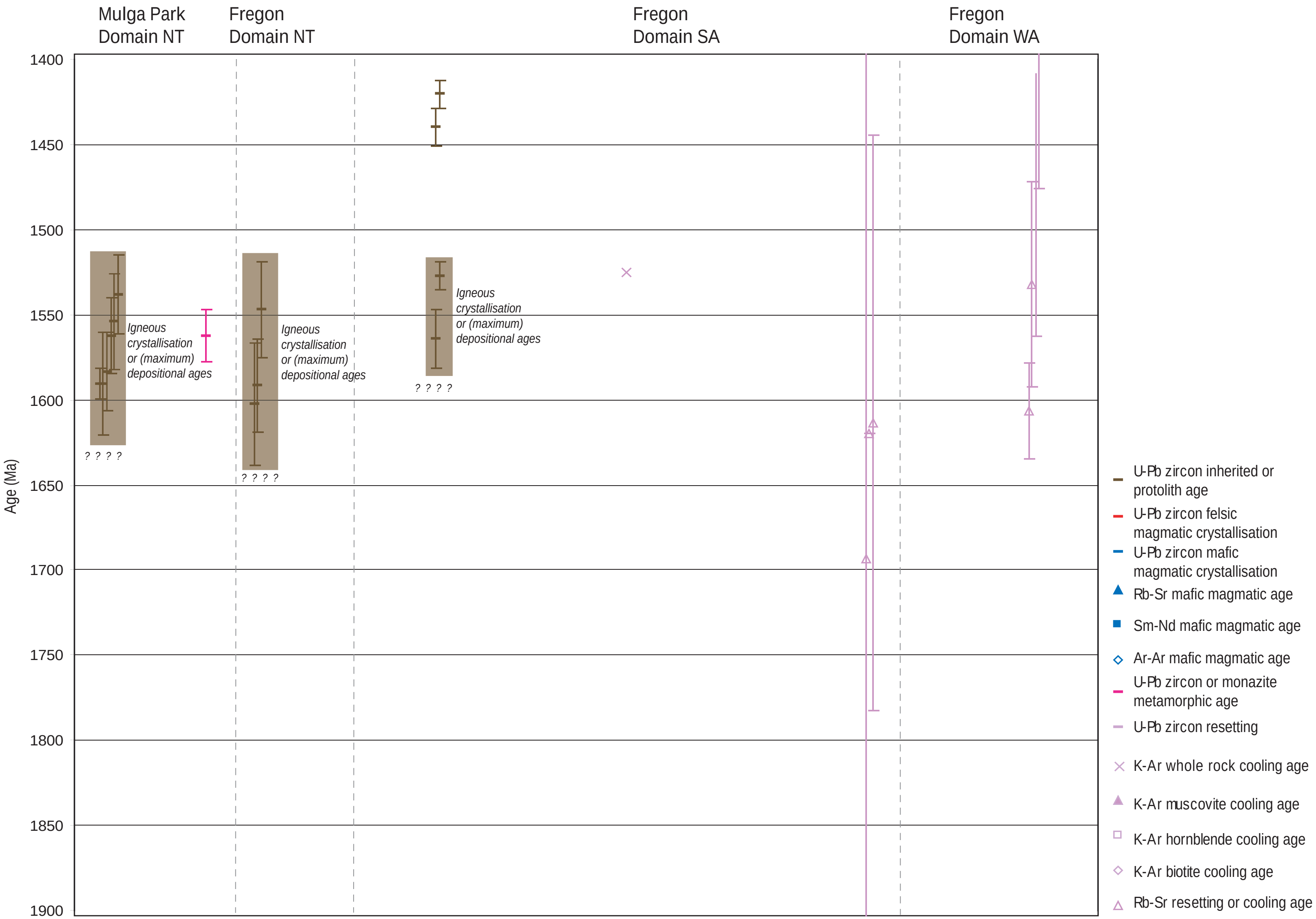
In the Bloods Range area in the northern Musgrave Province, a succession of rift-related sediments and bimodal volcanics, the Tjauwata Group, are correlated with similar sediments south of the Woodroffe Thrust in Western Australia, known as the Bentley Supergroup. The Tjauwata Group includes the Tjuninata Formation, the Mount Harris Basalt, and the Puntitjata Rhyolite. A minimum age constraint for the Mount Harris Basalt is provided by the cross-cutting Walu Granite with a SHRIMP U-Pb zircon age of 1084 ± 9 Ma (Close et al., 2003). The overlying Puntitjata Rhyolite has a Kober Pb-Pb zircon age of 1075 ± 3 Ma (Close et al., 2003). These syn-sedimentary magmatic rocks are synchronous with the Giles Event (see below).

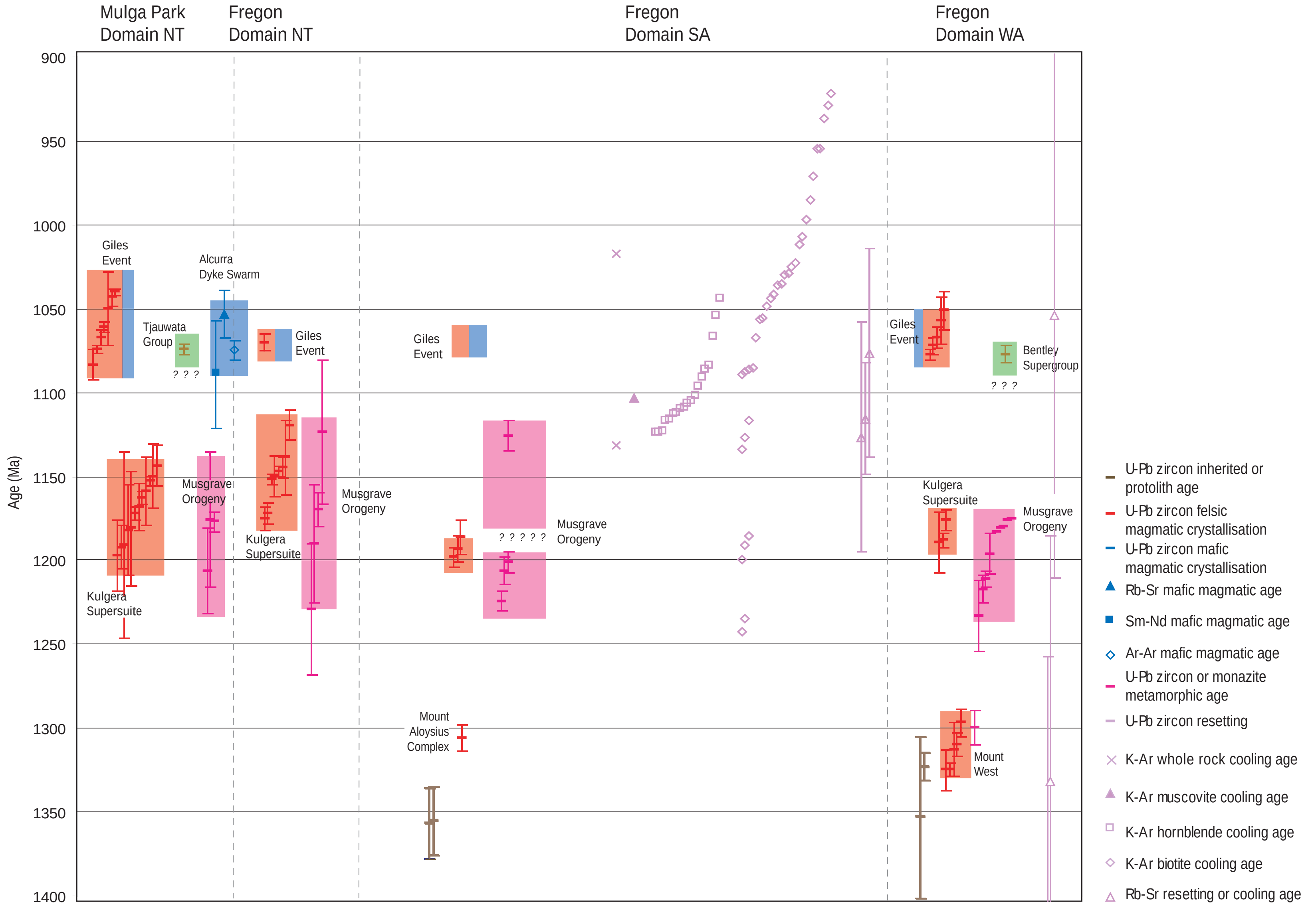
Metamorphism and deformation

Basement rocks in the Mulga Park Domain were metamorphosed to greenschist- to upper-amphibolite-facies during the ~1200-1160 Ma Musgrave Orogeny (Gray and Compston, 1978). The timing of this event is constrained by U-Pb SHRIMP zircon ages from metamorphic zircon rims and monazite ages including; 1206 ± 25 Ma (Mulga Park; Camacho and Fanning, 1995), 1177 ± 6 Ma (Mulga Park; Camacho, 1997), 1176 ± 40 Ma, (Olia Chain; Scrimgeour et al., 1999).
An earlier metamorphism was suggested by Camacho (1997) who separated zircons from leucosome with intercalated biotite-rich layers within a migmatitic metasediment. The zircons consist of cores and rims and the rims yield a SHRIMP U-Pb age of 1563 ± 15 Ma, interpreted as the time of migmatisation of the sediments (Camacho, 1997; Edgoose et al., 2004).

Metamorphism during the Musgrave Orogeny was followed by upper-greenschist-facies to upper-amphibolite-facies metamorphism during the Petermann Orogeny. Maboko et al. (1992) determined $^{40}Ar/^{39}Ar$ muscovite ages of 550-530 Ma in the Fregon Domain which they considered syntectonic with the Petermann Orogeny. They also determined $^{40}Ar/^{39}Ar$ muscovite ages of ~550 Ma from a shear-zone in the Mulga Park Domain. Given that these ages are identical within analytical error, Maboko et al. (1992) concluded they dated the juxtaposition of the two domains along the Woodroffe Thrust during the Petermann event. Camacho and Fanning (1995) measured Rb-Sr and K-Ar ages of muscovites and biotite in the Mulga Park Domain ranging in age from ~558 Ma to ~530 Ma, in agreement with the ages of Maboko et al. (1992).

Figure 24 (overleaf): *Geochronological data and summary Time-Space plot for the Musgrave Province, subdivided into the (a) 1900-1400 and (b)1400-900 Ma timeslices.*


Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Igneous crystallisation or (maximum) depositional ages
Igneous crystallisation or (maximum) depositional ages
Igneous crystallisation or (maximum) depositional ages
? ? ? ?
? ? ? ?
? ? ? ?
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age



Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Age (Ma)
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
Giles Event
Tjauwata Group
? ? ?
Alcurra Dyke Swarm
Giles Event
Giles Event
Kulgera Supersuite
Musgrave Orogeny
Kulgera Supersuite
Musgrave Orogeny
? ? ? ? ?
Musgrave Orogeny
Mount Aloysius Complex
Giles Event
Bentley Supergroup
? ? ?
Kulgera Supersuite
Musgrave Orogeny
Mount West
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age

Magmatism

The ~1190-1120 Ma Pitjantjatjara Supersuite (also known as the Kulgera Supersuite) includes mainly granites and charnockites (Edgoose et al., 2004). They range in composition from alkali granite to diorite, and include extensive biotite granite gneiss. In the Mulga Park Domain these include the Pottoyu Suite, Mantarurr Suite, Kulpitjata Suite and unfoliated garnet granite west of Kulgera. U-Pb SHRIMP igneous zircon ages for the Pottoyu Suite range from 1192 ±13 Ma to 1144 ± 12 Ma (Scrimgeour et al., 1999), and from 1197 ± 21 Ma to 1150 ± 19 Ma for the Kulpitjata Suite (Young et al., 2002). Similar ages have also been determined for the Pitjantjatjara Supersuite in the Fregon Domain, as discussed below.

Although the Giles Event (1080-1040 Ma) is represented largely in the Fregon Domain, a number of intrusives and volcanics in the Mulga Park Domain are also considered part of this event. Felsic intrusives include the Hull Suite, Michell Nob Granite and the Nulchara Charnockite. The age of the Hull Suite is constrained by two units within the suite, the Walu Granite which has a SHRIMP U-Pb zircon age of 1084 ± 9 Ma (Close et al., 2003), and the Rowley Granophyre with a Kober Pb-Pb zircon age of 1075 ± 2 Ma (Close et al., 2003). The Michell Nob Granite has a SHRIMP U-Pb zircon igneous age of 1068 ± 6 Ma (Camacho, 1997). The Nulchara Charnockite has a SHRIMP U-Pb zircon crystallization age of 1044 ± 5 Ma (Camacho, 1997).

The Alcurra Dyke Swarm (also referred to as the Kulgera Dyke Swarm) occurs as unmetamorphosed shallow dipping dykes and sills that intrude Musgravian gneiss and Pitjantjatjara Supersuite granites in both the Mulga Park and the Fregon Domains (Edgoose et al., 2004). Camacho et al. (1991) report a Rb-Sr age of 1054 ± 14 Ma, and Zhao and McCulloch (1993) determined a Sm-Nd wholerock-mineral isochron age of 1090 ± 32 Ma for a dolerite dyke in the same area. More recently, Schmidt et al. (2006) reported a weighted mean Ar-Ar biotite age of 1076 ± 6 Ma for a sample from the Alcurra Dyke Swarm. As reported above, bimodal volcanics within sedimentary rocks of the Tjauwata Group are also of this age (Edgoose et al., 2004).

Fregon Domain

Stratigraphy

As with the Mulga Park Domain the Fregon Domain comprises gneisses metamorphosed by the Musgrave Orogeny. In the Fregon Domain these gneisses are referred to as the Birksgate Complex and are of higher metamorphic grade than gneisses in the Mulga Park Domain. Although metamorphosed to upper-amphibolite to granulite-facies during the Musgrave Orogeny, many of these gneisses preserve older ages between 1600 and 1540 Ma, as well as zircon components as old as 2000 Ma (Edgoose et al., 2004). For example, xenocrystic zircon in a granite from the Mann Ranges yields a U-Pb SHRIMP age of 1592 ± 27 Ma (Scrimgeour et al., 1999), a felsic granulite from Kulgera yields a U-Pb SHRIMP zircon age of 1557 ± 24 Ma interpreted as the intrusive age (Camacho and Fanning, 1995), a felsic granulite from the Mann Ranges yields a U-Pb SHRIMP zircon age of 1548 ± 28 Ma (Scrimgeour et al., 1999) and inherited zircons from sediments in the Kelly Hills yield a U-Pb SHRIMP zircon age of 1603 ± 36 Ma (Young et al., 2002).

In the eastern Musgrave Province LA-ICPMS analyses of detrital zircons have yielded ages as young as ~1400 Ma (Wade et al., pers. comm., quoted in Scrimgeour et al., 2005). This implies deposition of a sedimentary package after ~1400 Ma and prior to subsequent metamorphism during the Musgravian Orogeny at ~1200 Ma.

Sediments of the Bentley Supergroup (Daniels, 1974) are synchronous with the Giles Event. These include basalt, rhyolite, rhyodacite, and lesser dolomite and conglomerates. The age of the Bentley Supergroup is constrained by a U-Pb SHRIMP zircon age of 1078±5 Ma (Sun et al., 1996) from the Smoke Hill Volcanics.

Metamorphism and Deformation

Rocks of the Fregon Domain were metamorphosed during the Musgrave Orogeny (Gray and Compston, 1978) reaching upper-amphibolite-facies to granulite-facies. White et al. (1999) report U-Pb SHRIMP ages from metamorphic zircon rims in orthogneisses of 1233 ± 21 Ma, 1217 ± 8 Ma and 1211 ± 5 Ma. Similarly, Edgoose et al. (2002) reported an age of 1229 ± 39 Ma from metamorphic zircon rims. Younger metamorphic ages of 1190 ± 35 Ma and 1170 ± 10 Ma have been reported from the Mann Ranges by Scrimgeour et al. (1999). Camacho and Fanning (1995) report an age of 1124 ± 43 Ma from metamorphic zircon rims from a metaluminous gneiss south of Kulgera.
The final major event to affect the Musgrave Province was the late-Neoproterozoic Petermann Orogeny (~570-530 Ma). North-directed thrusting along the south-dipping Woodroffe Thrust juxtaposed granulite-facies gneisses of the Fregon Domain with the generally lower metamorphic grade rocks of the Mulga Park Domain. The steeply north-dipping Mann Fault to the south of the Woodroffe Thrust was also generated during this event. Timing of this event is constrained by $^{40}Ar/^{39}Ar$ muscovite ages of 550-530 Ma (Maboko et al.,1992), considered syntectonic with the Petermann Orogeny. Sub-eclogitic rocks occur in mylonite zones in the Mount Aloysius area in the western Musgrave Province and yield Sm-Nd mineral-pair ages of 536 ± 16 Ma (garnet-plagioclase) and 533 ± 16 Ma (hornblende-clinopyroxene) (Clarke et al., 1995).

Magmatism

White et al. (1999) identified a magmatic event at ~1325 to 1300 Ma in the Mount West region, which predates the Pitjantjatjara Supersuite. This is based on U-Pb SHRIMP ages from zircon cores interpreted to represent the timing of igneous intrusion of orthogneisses that were subsequently metamorphosed during the Musgrave Orogeny. Interpreted ages for this magmatic event range between 1324 ± 12 Ma and 1296 ± 8 Ma (White et al., 1999).

Pitjantjatjara Supersuite/Kulgera Supersuite rocks (1190-1120 Ma) also occur in the Fregon Domain where they include the Umutju Suite, Walal Granite, Kulgera Granite and the Umbeara Granite, which have similar well constrained ages to suites occurring in the Mulga Park Domain. Pb-Pb Kober ages from the Umutju Suite range in age from 1175 ± 7 Ma to 1120 ± 9 Ma (Young et al., 2002). The Ayers Range Adamellite yields a U-Pb TIMS zircon age of 1152 ± 3 Ma (Camacho and Fanning, 1995). Similar ages were obtained by Maboko et al. (1991) and Camacho (1997) for granites in the southern regions of the Fregon Domain.

The Giles Event (1080-1040 Ma) includes felsic intrusives and the more mafic and ultramafic Giles Complex. The Giles Complex is part of the Warakurna Large Igneous Province (e.g. Wingate et al., 2004) and in the Fregon Domain comprises a suite of layered mafic and ultramafic intrusions. There is some exposure in the Northern Territory but most outcrop occurs in South Australia and Western Australia to the south and southwest of the Mann Ranges. Sun et al. (1996) analysed zircon from a granophyre in the Giles Complex yielding a U-Pb SHRIMP age of 1078 ± 3 Ma. The Angatja Granite has a Kober Pb-Pb zircon age of 1071 ± 5 Ma (Scrimgeour et al., 1999).

Also discussed in the Mulga Park Domain section, dolerite rocks of the Alcurra Dyke Swarm also occur within the Fregon Domain, and are equivalent in age to the Giles Event (Edgoose et al., 2004). Younger dolerites are also found in the Mann Ranges. Edgoose et al. (2004) report an unnamed olivine dolerite and suggest this may be related to dolerite dykes in the Mount Webb area of the

Arunta Inlier in Western Australia, which have SHRIMP U-Pb zircon ages of 976 ± 3 Ma and 972 ± 8 Ma (Wyborn et al., 1998).

The Amata Dolerite is exposed in the Tomkinson Ranges and yields a U-Pb baddeleyite age of 824 ± 4 Ma (Sun, S-s., unpublished data in Glikson et al., 1996). Zhao and McCulloch (1993) report Sm-Nd ages for the Amata Dolerite of 790 ± 40 Ma and 797 ± 49 Ma.

Metallogeny of the Musgrave Province

Mineral exploration in the Musgrave Province has been hampered by limited land access. The Giles Complex is one of the largest layered mafic-ultramafic intrusive complexes in the world and is related to the continental-scale Warakurna Large Igneous Province. Similar large intrusive complexes elsewhere host magmatic Ni-Cu-PGE deposits (e.g. Voisey's Bay, Canada and Duluth, USA). Western Mining Corporation, discovered podiform copper hosted in sheared basalts in the Warburton Range, and the Wingelinna nickel laterite resource. The Nebo-Babel deposit occurs in a gabbronorite intrusion associated with the Giles Complex (Seat et al., 2007). In South Australia companies are targeting nickel, copper cobalt and gold associated with ultramafic rocks. Metasedimentary rocks associated with the Birksgate Complex are also considered prospective for Broken Hill style base metal Pb-Zn-Ag deposits. In Northern Territory copper and base metal occurrences occur in the Tjauwata Group. Secondary Pb, Cu, Ag and Au have been found in quartz veins in the Mount Harris Basalt south of Bloods Range (Scrimgeour et al., 2005).

OUTSTANDING QUESTIONS AND SCOPE FOR FUTURE PROJECTS

Compared with other parts of Proterozoic Australia, the Musgrave Province has received relatively little geological and geochronological attention, largely to due limited land access. This is reflected in considerable uncertainty regarding the nature and timing of major sedimentary, magmatic and metamorphic events in the region. Some of these uncertainties are highlighted here.

The pre-Musgrave Orogeny geological history of the Musgrave Province is poorly understood. As outlined above, there is some geochronological evidence for significant magmatism, and possibly metamorphic and sedimentary activity, between ~1600 Ma and ~1550 Ma. The nature, extent and detailed timing of this event remain uncertain. There is also some recent unpublished geochronological evidence to suggest that previously unrecognised sedimentary, magmatic and metamorphic events may have occurred in the period between ~1550 Ma and ~1200 Ma. The extent to which any rocks in the region preserve a pre-1600 Ma history remains an open question with important implications for possible correlations with other parts of Proterozoic Australia.

Constraints on the timing of the Musgrave Orogeny are relatively blurry despite several geochronological studies. There are at least two inter-related reasons for this. Firstly, the late Mesoproterozoic to early Neoproterozoic part of the geological time-scale is problematic for U-Pb geochronology. Older events are generally best-constrained by $^{207}Pb/^{206}Pb$ ages, and younger events best-constrained by $^{206}Pb/^{238}U$ ages. However, in the period from ~1400-800 Ma U-Pb isotopic analyses tend to smear along the Concordia curve in the presence of isotopic inheritance and/or Pb-loss, hindering the identification of a tightly-constrained age. In the case of Musgrave Orogeny gneisses, both isotopic inheritance and subsequent Pb-loss are almost ubiquitous. These methodological problems provide at least a partial explanation for the wide range in reported U-Pb ages for the Musgrave Orogeny, and limit confidence in the geological interpretation of the reported ages. Improved geochronological constraints will require careful sampling specifically targeting samples with minimal inheritance or Pb-loss. For example, targeting Musgrave Orogeny age magmatic rocks with little or no inherited zircon, and which have not been affected by close proximity to Giles Event magmatism.

The Musgrave Province is currently the focus of mapping projects by the GSWA and PIRSA, and significant new geochronological datasets are being generated in association with those projects. It is expected that the geochronological constraints depicted here in the Time-Space plot will be augmented, and perhaps superseded, in the near future by new and improved constraints.

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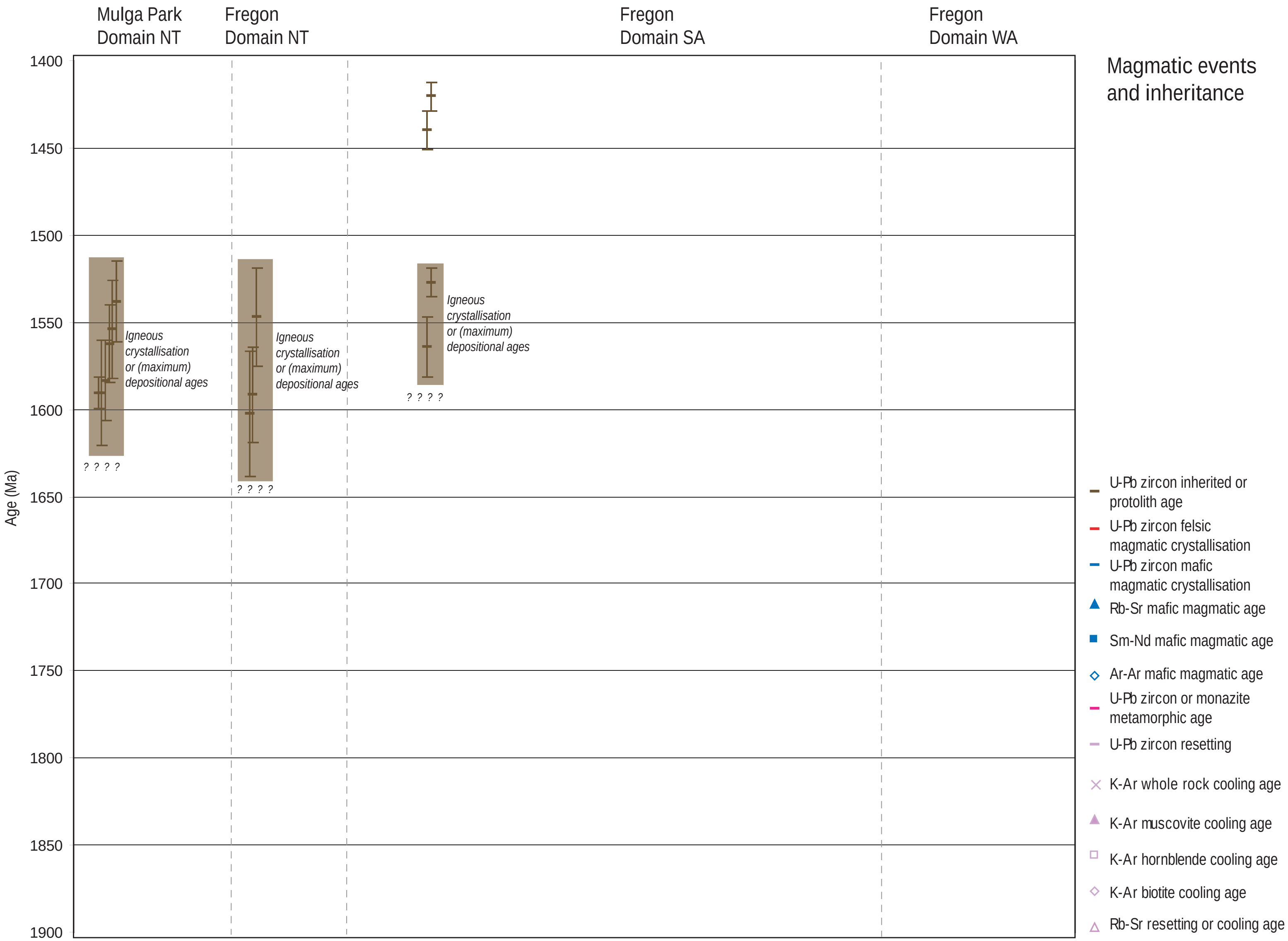
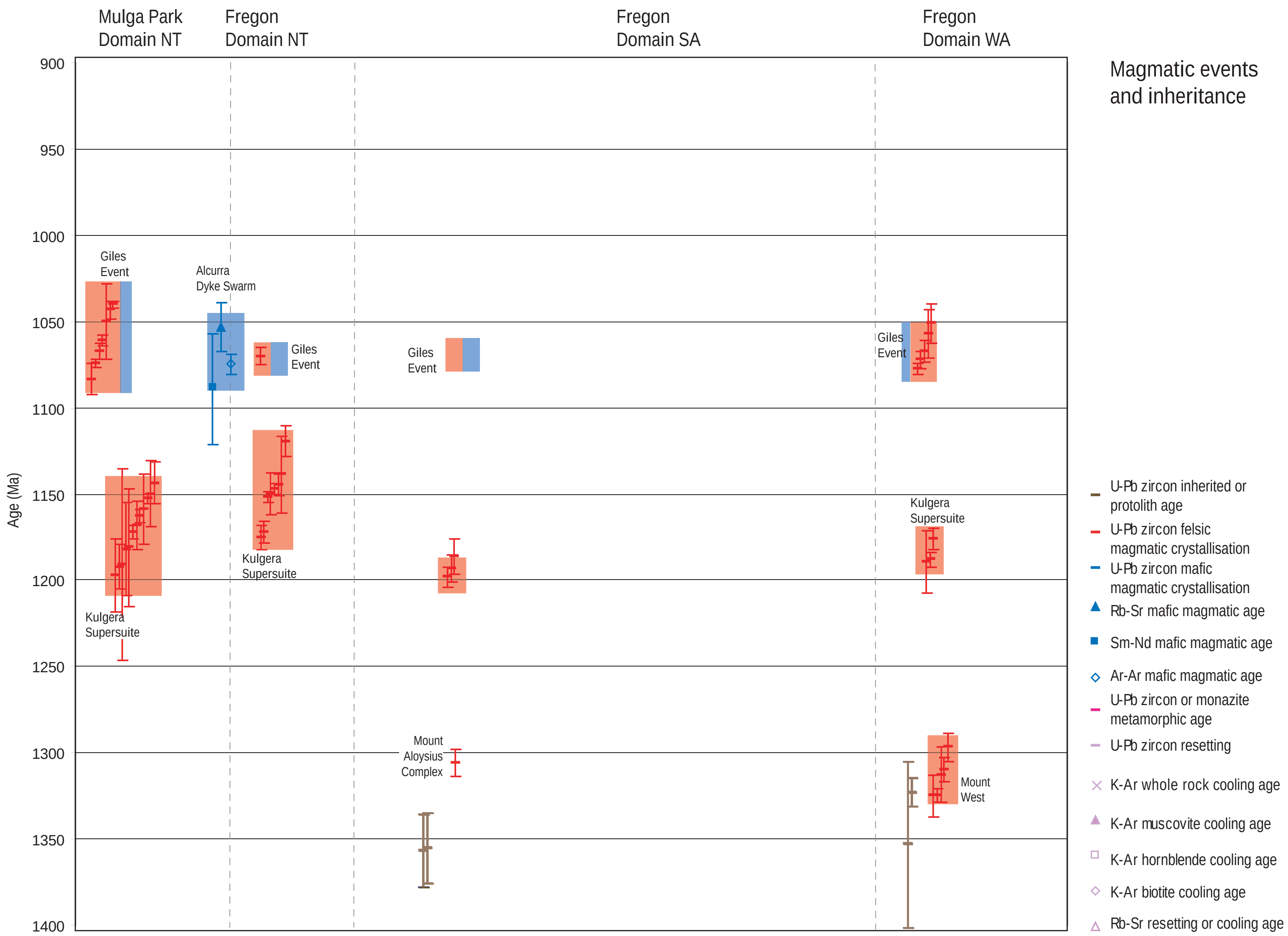
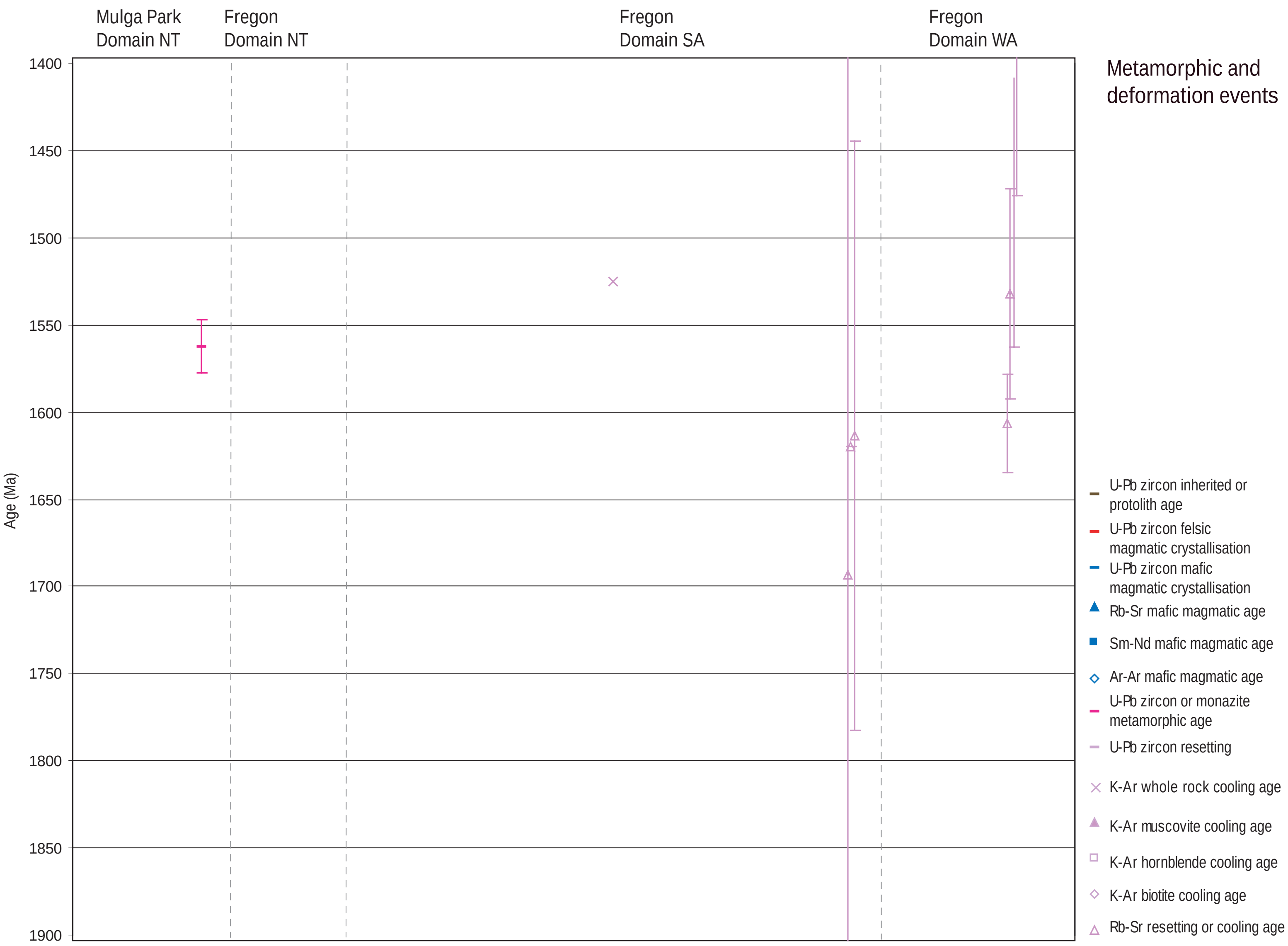
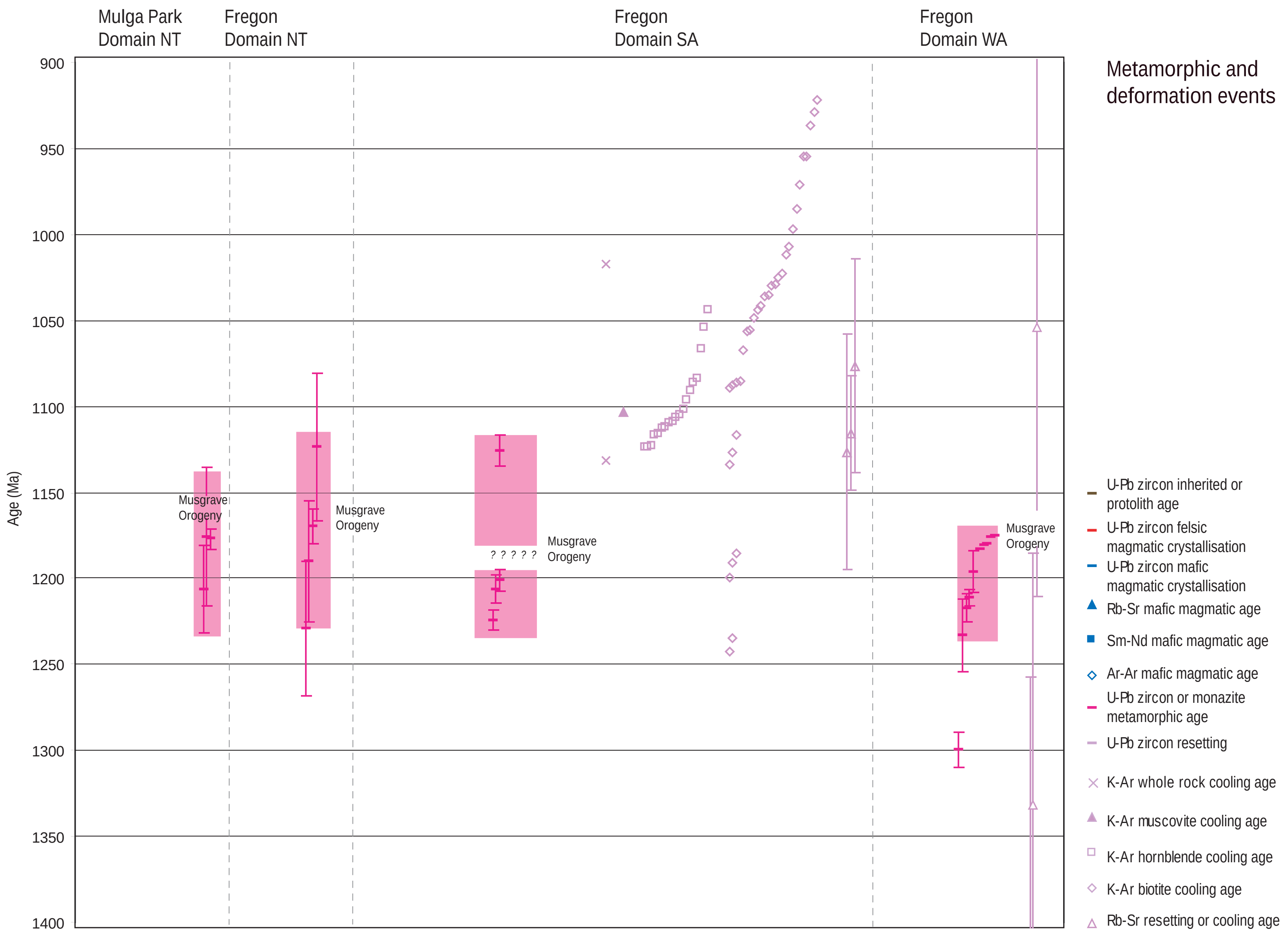
Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Sedimentary events
Age (Ma)
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
Tjauwata Group
? ? ?
Bentley Supergroup
? ? ?
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age


Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Magmatic events and inheritance
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Igneous crystallisation or (maximum) depositional ages
Igneous crystallisation or (maximum) depositional ages
Igneous crystallisation or (maximum) depositional ages
? ? ? ?
? ? ? ?
? ? ? ?
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age


Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Age (Ma)
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
Giles Event
Alcurra Dyke Swarm
Giles Event
Giles Event
Giles Event
Kulgera Supersuite
Kulgera Supersuite
Kulgera Supersuite
Mount Aloysius Complex
Mount West
Magmatic events and inheritance
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age


Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Metamorphic and deformation events
Age (Ma)
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age


Mulga Park Domain NT
Fregon Domain NT
Fregon Domain SA
Fregon Domain WA
Age (Ma)
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
Musgrave Orogeny
Musgrave Orogeny
Musgrave Orogeny
? ? ? ? ?
Musgrave Orogeny
Metamorphic and deformation events
U-Pb zircon inherited or protolith age
U-Pb zircon felsic magmatic crystallisation
U-Pb zircon mafic magmatic crystallisation
Rb-Sr mafic magmatic age
Sm-Nd mafic magmatic age
Ar-Ar mafic magmatic age
U-Pb zircon or monazite metamorphic age
U-Pb zircon resetting
K-Ar whole rock cooling age
K-Ar muscovite cooling age
K-Ar hornblende cooling age
K-Ar biotite cooling age
Rb-Sr resetting or cooling age