Geological framework of the Albany–Fraser Orogen

by

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Introduction

The margins of the Archean Yilgarn Craton record a long and variable geodynamic history, from at least the latest Neoarchean. These margins are either truncated or reworked, or were formed by a combination of these processes. For example, the western margin of the Yilgarn Craton is truncated by the late Mesoproterozoic to Neoproterozoic Darling Fault Zone, whereas the northern margin of the Yilgarn Craton is truncated by the c. 2000 Ma collision of the Glenburgh Terrane, and also reworked during several episodes of tectonism following that collision (Johnson et al., 2011). While the history of the eastern margin of the Yilgarn Craton is obscure due to thick cover of the Officer Basin, the southern and southeastern margins of the Yilgarn Craton record a long history of reworking, which has become increasingly evident in the Albany–Fraser Orogen. Hence, the Albany–Fraser Orogen not only provides insight into Paleoproterozoic and Mesoproterozoic tectonic events and supercontinent configurations (e.g. Johnson, 2013), but through the analysis of that reworking, provides insight into the history of more distal or previously unrecognized components of the Yilgarn Craton (e.g. Kirkland et al., 2014).

This review summarizes the tectonic framework and history of the Albany–Fraser Orogen to provide context for the various contributions in this volume, including: interpretations of the four deep reflection seismic lines (Spaggiari et al., 2014a; Occhipinti et al., 2014; Korsch et al., 2014); the potential field modelling (Brisbout et al., 2014; Murdie et al., 2014); the geochronology, isotope geology, and geochemistry (Kirkland et al., 2014a; Smithies et al., 2014a); and the mineral systems (Tyler et al., 2014). The interpreted bedrock geology of the eastern part of the central Albany–Fraser Orogen, and the east Albany–Fraser Orogen, is presented in the three plates that accompany this volume. Plate 4 contains cross-sections of the geology in these maps constrained by the interpretations of the seismic data. This review does not attempt to summarize historical work — such material can be found elsewhere (e.g. Spaggiari et al., 2009, 2011).

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The Albany–Fraser Orogen comprises two main tectonic units that reflect its relationship to the Yilgarn Craton — the Northern Foreland and the Kepa Kurl Booya Province (Figs 1 and 2). The Northern Foreland originated as part of the Archean Yilgarn Craton, and in general overlies the non-reworked part of the craton in various thrust sheets (Plate 4). The Kepa Kurl Booya Province (Spaggiari et al., 2009; 2011) is defined as the crystalline basement of the Albany–Fraser Orogen. It includes four fault-bound geographical and structural zones (Tropicana, Biranup, Fraser, and Nornalup) that contain rocks with variable protolith ages and geological histories (Spaggiari et al., 2009, 2011; Occhipinti et al., 2014; Kirkland et al., 2014). Three sedimentary basins are present: the 1815–1600 Ma Barren Basin; the 1600–1305 Ma Arid Basin; and the 1280–1215 Ma Ragged Basin (Spaggiari et al., 2014b; Waddell, 2014). Within the Biranup Zone and throughout the Nornalup Zone Mesoproterozoic granitic intrusions belong to either the 1330–1280 Ma Recherche Supersuite or to the 1200–1125 Ma Esperance Supersuite, coinciding with Stages I and II of the Albany–Fraser Orogeny, respectively (Fig. 2). A single occurrence of Recherche Supersuite granite occurs in the Northern Foreland near Bald Rock dated at 1299 ± 14 Ma (GSWA 83690, Nelson, 1995). The eastern extent of the Albany–Fraser Orogen coincides with the Rodona Shear Zone, which separates the orogen from the Madura Province (Fig. 1; Plates 2 and 3). These units, and the tectonic events that formed them, are described briefly below, followed by a summary of recently proposed tectonic models (Spaggiari et al., 2014b). Further details and references can be found in Spaggiari et al. (2009, 2011, 2012, 2014b), Kirkland et al. (2011a,b), and Smithies et al. (2013).

Northern Foreland

The Northern Foreland is defined as the portion of the Archean Yilgarn Craton that was intruded by Paleoproterozoic magmatic rocks, and reworked during the Mesoproterozoic Albany–Fraser Orogeny (Fig. 2; Plates 1, 2 and 3). Its position reflects its proximity to the Yilgarn Craton during orogenesis; hence, the term ‘foreland’. It consists of greenschist and amphibolite to granulite facies, Archean gneisses and granites, remnant greenstones, and younger dolerite dykes. The Munglinup

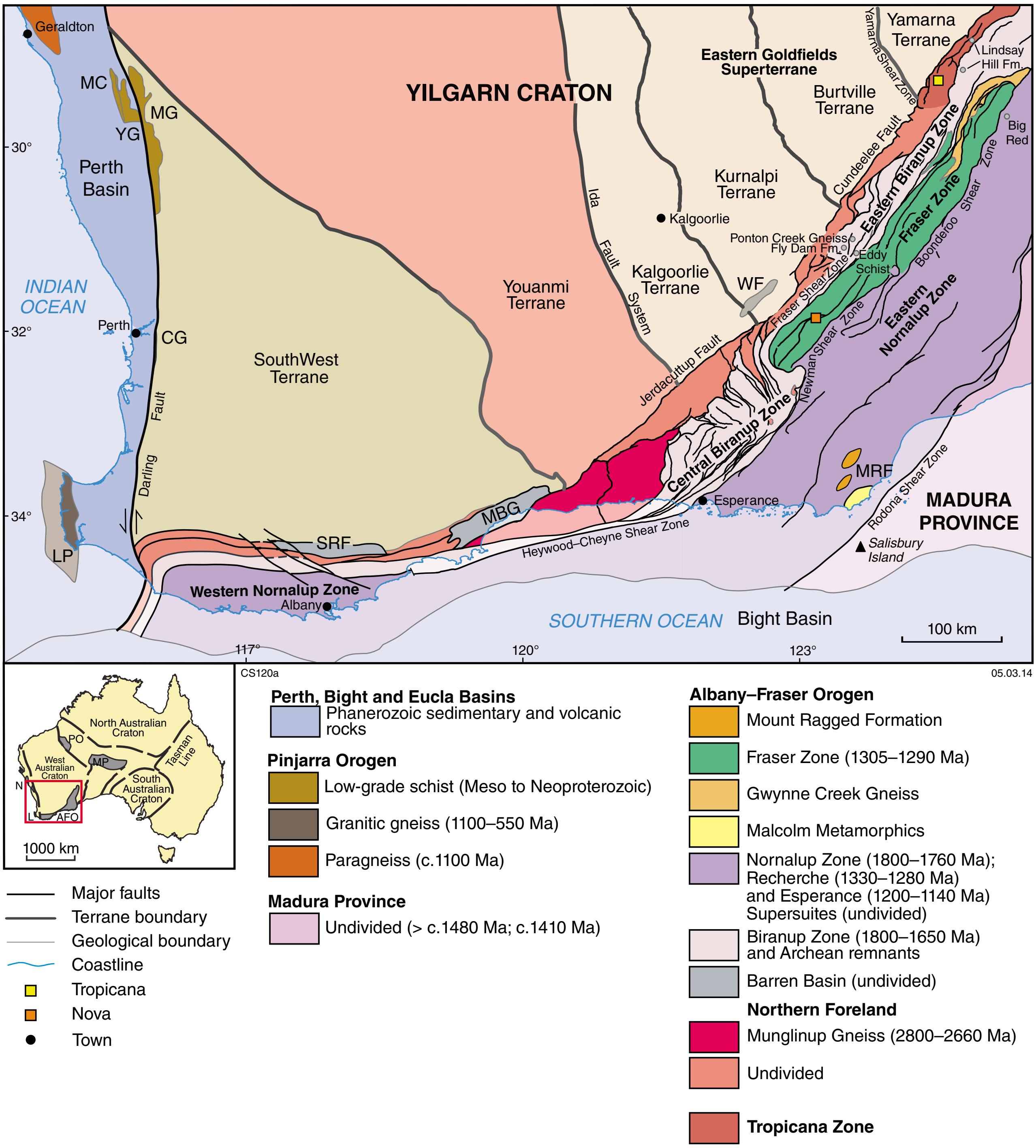

Figure 1. **Simplified, pre-Mesozoic interpreted bedrock geology of the Albany–Fraser Orogen and tectonic subdivisions of the Yilgarn Craton (from Spaggiari et al., 2014b). Abbreviations used: SRF – Stirling Range Formation; MBG – Mount Barren Group; WF – Woodline Formation; MRF – Mount Ragged Formation; CG – Cardup Group; LP – Leeuwin Province; MC – Mullingarra Complex; MG – Moora Group. Inset: AFO – Albany–Fraser Orogen; MP – Musgrave Province; PO – Paterson Orogen; L – Leeuwin Province; N – Northhampton Province.**

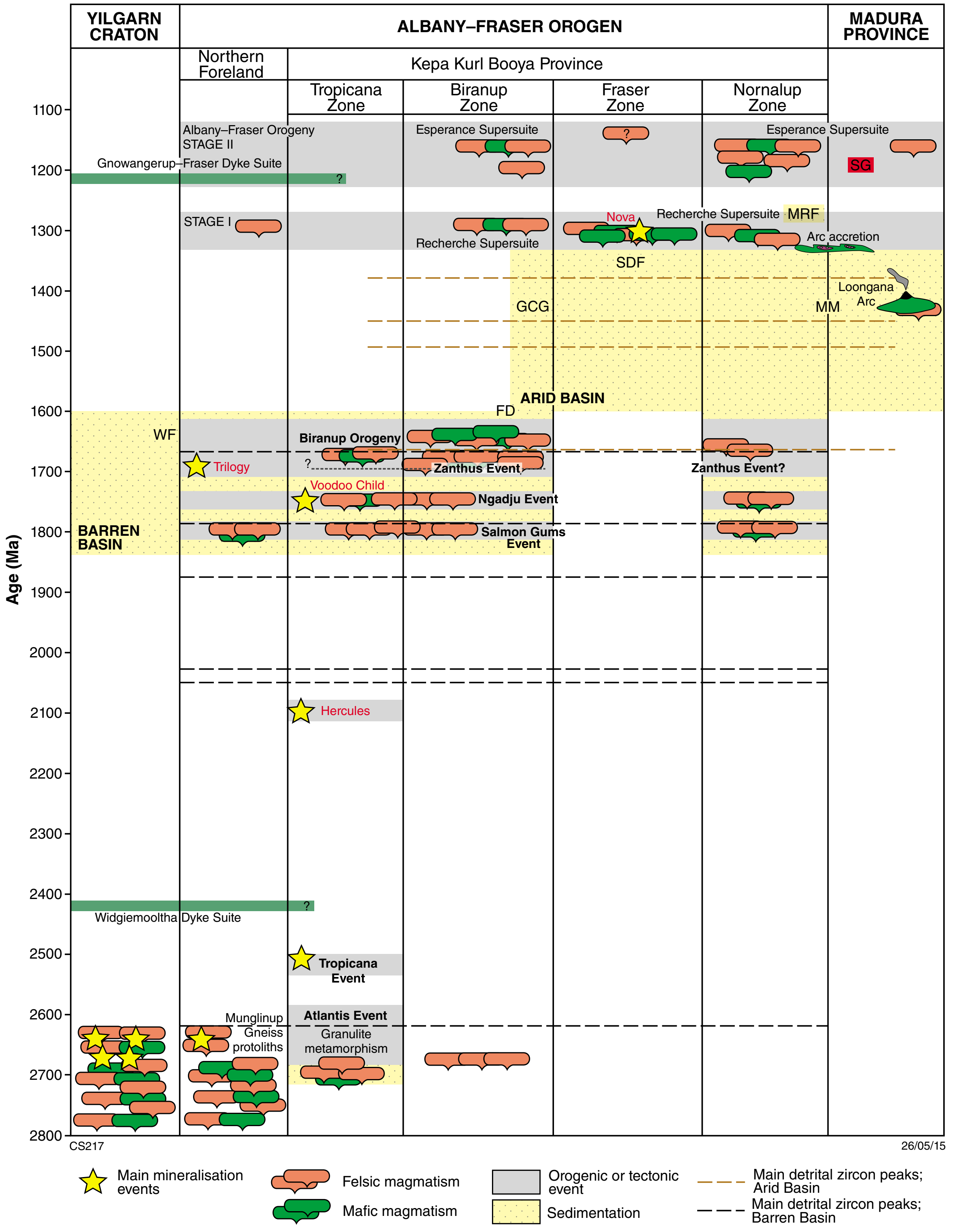

Figure 2. **Time–space plot of the Albany–Fraser Orogen and Madura Province. Abbreviations used: FD – Fly Dam Formation; GCG – Gwynne Creek Gneiss; MM – Malcolm Metamorphics; MRF – Mount Ragged Formation; SDF – Snowys Dam Formation; SG – Salisbury Gneiss; WF – Woodline Formation.**

Gneiss, with protolith ages of 2717–2640 Ma, is a major component of the Northern Foreland and is preserved in thrust sheets in the central part of the orogen (Plates 3 and 4). It is bounded to the east by the Red Island Shear Zone, which is interpreted as the major boundary between the Munglinup Gneiss (Northern Foreland) and Biranup Zone rocks of the Kepa Kurl Booya Province (Fig. 1; see line 12GA-AF2 on Plate 4). The Munglinup Gneiss comprises amphibolite- to granulite-facies orthogneiss interlayered with lenses of metamorphosed mafic rocks, some of which are interpreted as metamorphosed mafic dykes or sills. Minor banded metachert (jaspilite), amphibolitic schist, serpentinite, and metamorphosed ultramafic rocks are interpreted as remnants of Archean greenstone sequences.

Deformation in the Northern Foreland varied from moderate- to high-strain ductile conditions under amphibolite- to granulite-facies conditions in the Munglinup Gneiss (and the southern part of the Mount Barren Group of the Barren Basin), to low to moderate strain, brittle to semibrittle, under greenschist to amphibolite facies conditions. This variation generally reflects lower strain conditions and lower metamorphic grade with increasing distance towards the craton, as well as the exhumation of different crustal levels. Geochronological data indicate metamorphism and deformation occurred between 1210 and 1180 Ma, during Stage II (1225–1140 Ma) of the Albany–Fraser Orogeny, although early deformation may be as old as Archean. At least three phases of folding are recognized in the Munglinup Gneiss, which is also locally sheared and boudinaged. Megascale fold interference patterns are well defined in aeromagnetic imagery, due to the presence of magnetite in the metamorphic fabrics. The northern limit of the Northern Foreland is defined by the presence of discontinuous and widely spaced shear zones. Mafic dykes in the central Albany–Fraser Orogen also show the effects of increased deformation intensity, from north to south, within the Northern Foreland. In the north, magmatic textures and clear intrusive relationships are preserved, whereas towards the south, the mafic dykes are metamorphosed and rotated parallel to the regional trend of the orogen.

Kepa Kurl Booya Province

Archean to Paleoproterozoic units

Tropicana Zone

The newly named Tropicana Zone (Fig. 2; Plate 1; Occhipinti et al., 2014) contains Archean rocks that have an affinity to the Yilgarn Craton, but their geological evolution is distinct, and cannot be readily correlated with adjacent terranes, such as the adjacent Yamarna Terrane (Occhipinti et al., 2014; Kirkland et al., 2014a). Differences include the presence of c. 2700 Ma sanukitoid granites (Kirkland et al., 2014; Smithies et al., 2014a), and Archean gneisses that underwent upper amphibolite to granulite facies metamorphism over a prolonged period from c. 2718 to 2554 Ma (Kirkland et al., 2014; Doyle et al., 2014). Furthermore, the Tropicana Zone has been emplaced an unknown distance into its current position overlying the Yamarna Terrane of the Yilgarn Craton via the c. 2500 Ma Plumridge Detachment (Plate 4; Occhipinti et al., 2014). It is for this reason that it is not included in the Northern Foreland of the Albany–Fraser Orogen, i.e. because it formed in a different structural position. Hence, the Tropicana Zone is defined as part of the Kepa Kurl Booya Province.

Two units have been defined in the Tropicana Zone: the Tropicana Gneiss and the Hercules Gneiss (Plate 1). The Tropicana Gneiss includes interlayered granitic gneiss that incorporates tonalitic and dioritic compositions, mafic gneiss (including metagabbro and metamorphosed ultramafic rocks), garnet gneiss, and minor metachert and meta-iron formation (see also Spaggiari et al., 2011 and Doyle et al., 2014). Locally, the Tropicana Gneiss is intruded by Paleoproterozoic granite of Biranup Zone affinity (Fig. 2). The Hercules Gneiss is only known from diamond drillcores from the Neale Project area (Atlantis and Hercules prospects), and is dominated by Neoarchean metadiorite and quartz metamonzodiorite gneiss (Kirkland et al., 2014). This gneissic fabric is locally crosscut by microgranite veins dated at 1783 ± 3 Ma (GSWA 192550, Kirkland et al., 2014), and fine- to medium-grained mafic rocks.

The Tropicana Zone shares a similar geological history to the Northern Foreland and Biranup Zone from at least 1800 Ma, with deposition of Barren Basin sediments (Lindsay Hill Formation), and intrusion of Paleoproterozoic granitic rocks such as the c. 1800 Ma Black Dragon Formation, the c. 1763 Ma McKay Creek Metasyenogranite (associated with the Voodoo Child Formation), the c. 1710 Ma Bobbie Point Metasyenogranite, and most likely 1690–1670 Ma metagranitic and metagabbroic rocks similar to those dated in the adjacent Pleiades Lakes area of the Biranup Zone (Fig. 2; Plate 1; Spaggiari et al., 2011; Occhipinti et al., 2014).

Biranup and Nornalup zones

The Biranup Zone is dominated by strongly deformed orthogneiss, with lesser amounts of metagabbroic and hybrid rocks that range in age from 1810 to 1625 Ma, and which flank the entire southern and southeastern margin of the Yilgarn Craton (Figs 1 and 2). Isolated remnants of Archean granite with Yilgarn Craton affinity occur within the Biranup Zone and this, combined with the isotopic and geochemical affinities of the Paleoproterozoic intrusive rocks, indicates a direct association with the Yilgarn Craton during their emplacement. The Paleoproterozoic magmatic rocks intrude metasedimentary rocks of the Barren Basin (see below). The Nornalup Zone is the southern- and easternmost unit of the Albany–Fraser Orogen and also spans its entire length (Fig. 1), although much of the original basement appears to be masked by intrusions of the Recherche and Esperance Supersuites.

In the east Albany–Fraser Orogen, the Nornalup Zone is separated from the Biranup and Fraser Zones by the Newman and Boonderoo Shear Zones and from the Madura Province by the Rodona Shear Zone.

Salmon Gums Event

The oldest dated Paleoproterozoic intrusive rocks are 1810–1800 Ma granitic gneisses that occur in both the Biranup and Nornalup Zones, marking the earliest phase of Paleoproterozoic magmatic activity recognized so far. This event, here named the Salmon Gums Event (after the locality Salmon Gums; Fig. 2), coincided with deposition of the Stirling Range Formation (Rasmussen et al., 2004), which corresponds to the earliest recognized period of formation of the Barren Basin. Metagranodiorite and metadiorite of the Black Dragon Gneiss is dated at c. 1800 Ma and occurs adjacent to the Tropicana Zone (Plate 1; Doyle et al., 2014). In the central Biranup Zone two diamond drillcores from south of Salmon Gums (Hopkinson, 2010) intersected layered, mafic and felsic granitic gneiss that yielded 1806 ± 6 Ma and 1804 ± 6 Ma zircon U–Pb dates, interpreted to reflect magmatic crystallization (hole SGD001, GSWA 192502, Kirkland et al., 2014b; hole SGD002, GSWA 192504, preliminary data, respectively). In the eastern Nornalup Zone migmatitic, monzogranitic gneiss containing angular mafic inclusions is exposed about 12 km east of Boingaring Rocks, and has yielded a zircon U–Pb date of 1809 ± 8 Ma, interpreted as the age of magmatic crystallization (GSWA 194785, Kirkland et al., 2014). All of these granites contain mafic enclaves.

Ngadju Event

The 1810–1800 Ma magmatic event was followed by a second phase of magmatic activity between 1780 and 1760 Ma, here named the Ngadju Event after the Ngadju people (Fig. 2). This event is recorded in the Biranup and Nornalup Zones, as well as the Tropicana Zone, and coincided with widespread sediment deposition and the formation of various sub-basins of the Barren Basin (Spaggiari et al., 2014b). In the central Biranup Zone, the diamond drillcores from south of Salmon Gums (Hopkinson, 2010) also intersected granitic gneiss that yielded a date of 1779 ± 7 Ma, interpreted as the magmatic crystallization age (hole SGD003, GSWA 192505, Kirkland et al., 2014c). In the eastern Nornalup Zone, strongly deformed metamonzogranite in the Newman Shear Zone yielded a date of 1763 ± 11 Ma, interpreted as the magmatic crystallization age (Kirkland et al., 2012a). The similarity in magmatic ages in both the Biranup and Nornalup zones implies that these zones shared the Paleoproterozoic (and likely Archean) substrate, prior to intrusion of the Fraser Zone and Recherche Supersuite during Stage I of the Albany–Fraser Orogeny (Fig. 2). Thus, the large shear zone system that separates the Biranup and Nornalup Zones (Coramup and Heywood–Cheyne Shear Zones, Fig. 1; Plate 3) is interpreted as a long-lived, reactivated structure that reflects an earlier history of rift-related extension (see also Spaggiari et al., 2014a,b).

Biranup Orogeny

Several phases of mildly alkaline granite magmatism produced widespread syenogranitic rocks throughout the eastern Biranup Zone from c. 1710 Ma through to at least 1650 Ma, during the Biranup Orogeny (Spaggiari et al., 2011). During this period sedimentation and formation of the Barren Basin was ongoing, with deposition of units such as the Woodline Formation and the Fly Dam Formation (Spaggiari et al., 2014b). The c. 1680 Ma Zanthus Event (Fig. 2) is a compressional phase of the Biranup Orogeny that produced folding under upper amphibolite to granulite facies conditions in Biranup Zone granitic gneiss that intruded Barren Basin psammitic gneiss (Ponton Creek Gneiss, Fig. 1; Kirkland et al., 2011a). Younger igneous rocks produced during the Biranup Orogeny include the c. 1660 Ma Eddy Suite, which is dominated by rapakivi-textured metagranodiorite mingled with metagabbro. These rocks have intruded Barren Basin semipelitic schist.

Other metagranitic rocks of both the central and eastern Biranup Zone include metamonzogranite, metagranodiorite, and rare tonalitic gneiss, with most ages falling in the range 1690–1660 Ma (Nelson et al., 1995; Kirkland et al., 2011a; Spaggiari et al., 2009). The central and eastern Biranup Zone are dominated by Paleoproterozoic gneisses that contain evidence of partial melting and migmatization, and have therefore undergone upper amphibolite to granulite facies metamorphism. Most homogeneous zircon overgrowths in these rocks indicate that high-grade metamorphism occurred during Stage II from c. 1225 to 1150 Ma, although some Stage I metamorphic dates of c. 1300 Ma occur in the Nornalup Zone (Kirkland et al., 2011a, 2014a; Spaggiari et al., 2014b).

Mesoproterozoic units

Fraser Zone

The Fraser Zone is bounded by the Fraser Shear Zone (previously named the Fraser Fault; Myers, 1985) along its northwestern edge and southern tip, and by the Newman and Boonderoo Shear Zones along its southeastern edge (Fig. 1; Plates 1, 2 and 3). It is dominated by high-grade metamorphic rocks that have a strong, distinct geophysical signature in both aeromagnetic and gravity data — the latter reflecting high density attributed to the dominance of metagabbroic rocks. All of the northern part of the Fraser Zone is obscured by Cretaceous to Cenozoic cover rocks of the Bight and Eucla Basins, but the gravity data indicate that it is an approximately 425 km long, northeasterly trending, fault-bound unit that is up to 50 km wide. The Fraser Zone contains the 1305–1290 Ma Fraser Range Metamorphics (Spaggiari et al., 2009), which comprise thin to voluminous sheets of metagabbroic rocks that range in thickness from several centimetres up to several hundred metres, interlayered with sheets of metamonzogranitic to metasyenogranitic gneisses, pyroxene-bearing granitic gneisses, and hybrid magmatic rocks. All are interlayered at various scales with amphibolite to granulite facies pelitic, semipelitic, and psammitic gneiss, and locally calc-silicate and iron-rich metasedimentary rocks of the Snowys Dam Formation, which forms part of the Mesoproterozoic Arid Basin (Fig. 2; Spaggiari et al., 2014b). Metagranitic rocks range in composition from metamonzogranite to metasyenogranite. Whole-rock geochemical data for felsic rocks within the Fraser Zone permits these rocks to be subdivided into two broad groups; one compositionally similar to granites representing the majority of the 1330–1280 Ma Recherche Supersuite, the other likely reflecting melts derived locally through melting of the metasedimentary components of the Fraser Zone (Smithies et al., 2013).

Much of the northwestern side of the Fraser Zone is dominated by tightly to isoclinally folded, strongly foliated to mylonitic rocks, whereas the least deformed and thickest examples of metagabbroic sheets occur in the southeast, reflecting a significant difference in strain until the Newman Shear Zone is reached along the southeastern boundary (Fig.1; see also Brisbout et al., 2014). Aeromagnetic and gravity data indicate a repetition of this architecture along strike to the northeast beneath the Eucla Basin, where the Fraser Zone is crossed by seismic line 12GA-AF3.

Peak metamorphic temperatures and pressures recorded in the metapelitic rocks of the Snowys Dam Formation reached approximately 850°C at pressures of 7–9 kbars at c. 1290 Ma, followed by a period of isobaric cooling at pressures of about 9 kbars (Clark et al., 2014). All isotopic results from the Fraser Zone indicate a short time interval for both mafic and felsic igneous crystallization, predominantly between 1305 and 1290 Ma, and essentially coeval granulite-facies metamorphism (Fig. 2). The close temporal correspondence between mafic to felsic magmatism and the age of granulite-facies metamorphism implies that magmatism provided the thermal impetus for metamorphism (Clark et al., 2014). All U–Pb zircon geochronology in the Fraser Zone indicates tectonothermal activity during Stage I of the Albany–Fraser Orogeny, with no evidence of Stage II. This suggests that the Fraser Zone had cooled and strengthened sufficiently to inhibit zircon growth during Stage II, and that the Fraser Zone behaved as a resistant lozenge at that time (Clark et al., 2014). This is consistent with the interpretation that during Stage II the Fraser Zone was translated to the southwest, as indicated by the differential kinematics on its bounding shear zones (Spaggiari et al., 2011, 2013, 2014a).

The Fraser Zone is interpreted to represent a structurally modified, middle- to deep-crustal 'hot zone', formed by the repeated intrusion of gabbroic magma from a mantle upwelling into quartzofeldspathic country rock, either beneath an intercontinental rift, or in a distal back-arc setting (Spaggiari et al., 2011; Smithies et al., 2013; Clark et al., 2014). Whole-rock geochemical data indicate that an oceanic-arc setting, as interpreted by Condie and Myers (1999), is unlikely because the enriched crustal component of the gabbroic rocks of the Fraser Zone is better explained by assimilation from an older, felsic basement that included a Sr-depleted component of Archean — or reworked Archean — crust (Smithies et al., 2013). This interpretation is supported by previous and recent Nd- and Hf-isotopic data (Fletcher et al., 1991; Kirkland et al., 2011b), and the presence of Paleoproterozoic basement rocks in the eastern Nornalup Zone.

Sedimentary Basins

Barren Basin

The Barren Basin evolved over a period of more than 200 million years (1815–1600 Ma) and is interpreted to have extended at least 1000 km along the southern and southeastern Yilgarn Craton margin. It comprises Paleoproterozoic metasedimentary rocks belonging to the Stirling Range Formation, Mount Barren Group, Lindsay Hill Formation, Woodline Formation (Woodline Sub-basin), Fly Dam Formation, and unnamed occurrences of psammitic to semipelitic schist and gneiss (Fig. 1; Plates 1, 2 and 3; Spaggiari et al., 2011, 2014b). These units overlie the Yilgarn Craton, the Northern Foreland, the Biranup Zone, and the Nornalup Zone, and are interpreted to be the structural and erosional remnants of a much larger basin system that evolved along, and in the distal reaches of, the southern and southeastern Yilgarn Craton margin.

At least three main depositional phases are recognized, each closely following magmatic events (Fig. 2). The first commenced prior to c. 1800 Ma with deposition of the Stirling Range Formation, followed by deposition of the Mount Barren Group by 1693 ± 4 Ma (Vallini et al., 2005), and deposition of the Coramup Gneiss, the Ponton Creek psammitic gneiss, Big Red paragneiss, and the Lindsay Hill Formation between 1710 and 1650 Ma, coincident with the Biranup Orogeny. This was followed shortly afterwards by deposition of the Woodline and Fly Dam Formations, possibly in the late stages of, or shortly after, the Biranup Orogeny (Spaggiari et al., 2014b).

Depositional environment

The majority of sedimentary units of the Barren Basin comprise quartz-rich lithologies including cross-bedded sandstones, pure sandstones (now quartzites), pebbly sandstones, and siltstones. For the most part, the preserved units indicate moderate to high energy, fluvial to shallow marine (tidal or deltaic) conditions, indicative of broad, relatively shallow basins. However, a potential bias may exist due to the dominance of units sampled on or adjacent to the Yilgarn Craton. The Big Red paragneiss, which occurs in the Nornalup Zone and is the farthest outboard Barren Basin unit (Fig. 1), is interlayered with metamorphosed iron-rich layers, perhaps indicative of a deeper marine setting. The interbedded sandstone and mudstone protoliths of the Fly Dam Formation may also be indicative of deeper water. The relationships suggest on- or near-craton fluvial to shallow marine deposition, with the basin system gradually deepening away from the craton as time progressed — from c. 1727 Ma, based on the conservative estimate of the maximum depositional age of the Big Red paragneiss (Spaggiari et al., 2014b, and references therein).

Detrital zircon ages and provenance

The most dominant age component of Barren Basin detritus is Neoarchean, mostly spanning the range 2750–2600 Ma (Fig. 2). The Neoarchean ages are consistent with the ages of granites and greenstones of the Yilgarn Craton (Cassidy et al., 2006, and references therein), and given its close proximity and uncomformable contact relationships with some units, the Yilgarn Craton is regarded as the most likely source (Spaggiari et al., 2014b). The Barren Basin also contains several significant age components of zircon detritus spanning 2550–1900 Ma that imply sources distal to the Albany–Fraser Orogen, or alternatively, unrecognized or destroyed basement components. The largest detrital zircon age maxima in the 2550–1900 Ma range occur at c. 2250 and 2035 Ma. Barren Basin metasedimentary rocks from drillcore from the Big Red prospect in the Nornalup Zone (Fig. 1) yielded significant detrital age components between 2575 and 2450 Ma, with a probability peak at c. 2457 Ma. The 2575–2450 Ma age range also appears as minor age components in the Woodline Formation and the Coramup Gneiss (Spaggiari et al., 2014b, and references therein; Kirkland et al., 2014).

After the Neoarchean component, the second largest detrital zircon age component in much of the Barren Basin spans the range 1900–1600 Ma, with the largest probability peak defined between 1700 and 1650 Ma (Fig. 2). Subsidiary probability peaks are defined between 1800 and 1750 Ma, and a smaller peak at c. 1875 Ma. The 1700–1650 Ma age range matches that observed from magmatic rocks emplaced during the Biranup Orogeny, and the 1800–1750 age range matches granitic magmatism in the Biranup and Nornalup Zones during the Salmon Gums and Ngadju Events (Fig. 2). The c. 1875 Ma peak is unknown, and may indicate an as yet unrecognized magmatic event in the Albany–Fraser Orogen, or alternatively, detritus from a distal source (Spaggiari et al., 2014b).

The magmatic episodes appear to have provided substantial amounts of detritus to the basin system, much of which was mixed with detritus sourced from the Yilgarn Craton (Spaggiari et al., 2014b). These interpretations are supported by Lu–Hf data (Kirkland et al., 2011b, 2014a). There appears to have been a close link in the timing between depositional phases and pulses of magmatism, potentially indicative of relatively rapid, cyclical uplift and erosion releasing detritus into the evolving basin system. Although not constrained, potential coeval volcanism may also have supplied detritus to the basin.

Arid Basin

Several successions of metasedimentary rocks have maximum depositional ages younger than the youngest Biranup Zone magmatism (c. 1625 Ma), but have been affected by Stage I tectonism. These sedimentary successions belong to the Arid Basin and include the Malcolm Metamorphics of the eastern Nornalup Zone (formerly the Malcolm Gneiss; Myers, 1995), the Gwynne Creek Gneiss in the northeastern part of the orogen, and the Snowys Dam Formation of the Fraser Zone (Figs 1 and 2; Spaggiari et al., 2011, 2014b). Also included are paragneissic rocks from the western Nornalup Zone such as those found at Whalehead Rock near Albany (Fig. 1; Love, 1999).

The Malcolm Metamorphics are dominated by siliciclastic metasedimentary rocks, but also include layers of mafic amphibolitic schist and less abundant calc-silicate rocks. Two samples of upper amphibolite, migmatitic semipelitic schist yielded maximum depositional ages of 1455 ± 16 Ma (upper intercept age in sample PM-11-011) and 1456 ± 21 Ma (upper intercept age in GSWA 194867, preliminary data), constraining the maximum depositional age to c. 1450 Ma (Adams, 2012). Although part of the Arid Basin, the Malcolm Metamorphics may have originated in the Madura Province, potentially as a fore-arc deposit to the Loongana Arc (see below), they occur in a fault slice close to the Rodona Shear Zone, and may represent an interleaved unit on the Nornalup Zone – Madura Province boundary.

The Gwynne Creek Gneiss occurs in the northeastern part of the Albany–Fraser Orogen, between the Fraser and Biranup Zones, east of the Tropicana gold deposit (Fig. 1; Plate 1). The unit is dominated by psammitic and semipelitic gneiss, and also includes layered, finely laminated, quartzofeldspathic gneiss with layer-parallel leucosome rocks. Minor metagranitic, metamafic, and meta-ultramafic rocks intrude the metasedimentary rocks, and are possibly related to the Fraser Zone intrusions (Spaggiari et al., 2011). Alternatively, they may represent earlier magmatic activity during deposition of the Arid Basin. The metasedimentary rocks are also intruded by late, coarse to very coarse, K-feldspar-rich pegmatites. The Gwynne Creek Gneiss has a maximum depositional age of 1483 ± 12 Ma (based on one analysis), with a more conservative estimate of 1533 ± 11 Ma based on six analyses (Kirkland et al., 2011a).

The Snowys Dam Formation is part of the Fraser Range Metamorphics of the Fraser Zone and is typically intercalated with layers of mafic granulite or amphibolite that are interpreted as sills or sheets of the Fraser Zone gabbroic intrusions, although it is possible that some may represent earlier magmatic activity. The southwestern exposures of the Snowys Dam Formation are predominantly garnet-rich pelitic and semipelitic gneisses, with locally iron-rich metasedimentary rocks, and quartz-rich psammitic gneiss (e.g. the Gnamma Hill and Mount Malcolm areas). Locally, these rocks are interlayered with metasedimentary rocks that have calc-silicate affinities, and may represent metamorphosed marls, or volcaniclastic protoliths.

Maximum depositional ages of the Snowys Dam Formation indicate that deposition occurred not long before mafic magmatism. Garnet–biotite semipelitic gneiss from near Mount Malcolm yielded the youngest maximum depositional age of 1332 ± 21 Ma (single zircon analysis), or the more conservative estimate of 1363 ± 9 Ma (24 youngest analyses; GSWA 194778, Kirkland et al., 2012b). Zircon rims from the same sample yielded a metamorphic date of 1298 ± 12 Ma, identical to metamorphic zircons from mafic granulite at the American Quarry (1292 ± 6 Ma; GSWA 194718, Kirkland et al., 2011c).

Depositional environment

The depositional environment of the Arid Basin is difficult to interpret based on the limited data available and highly variable basin fill. This includes interbedded sandstone and mudstone, calcareous rocks or marls, iron-rich horizons, and probable volcaniclastic or volcanic successions. In contrast to the Barren Basin, there is no evidence of fluvial deposits, and the sequences appear to be generally finer grained, less quartz-rich and less mature (Spaggiari et al., 2014b).

Detrital zircon ages and provenance

The most dominant age component of Arid Basin zircon detritus is Mesoproterozoic, spanning the range 1425–1375 Ma, with slightly lesser volumes in the ranges 1475–1425 Ma and 1375–1325 Ma (Fig. 2; Spaggiari et al., 2014b). The dominant age component of 1425–1375 Ma is found in the Snowys Dam Formation of the Fraser Zone, although this unit is also where the majority of the data comes from. The second most dominant detrital age component in the Arid Basin spans the range 1700–1650 Ma, with minor components in the ranges 1825–1725 Ma and 1625–1600 Ma. The 1700–1650 Ma age range occurs in the Snowys Dam Formation, but is most dominant in the Gwynne Creek Gneiss. All three Arid Basin units contain minor age components in the range 1600–1475 Ma. The smallest age components in all units occur between 2750 and 2600 Ma, 2550 and 2450 Ma, and from 2075 to 2025 Ma (Spaggiari et al., 2014b).

Detrital zircon analysis shows that the Snowys Dam Formation and the Malcolm Metamorphics have an unusual provenance, and that the dominant age range of detritus from c. 1455 Ma through to 1375 Ma does not correspond with any known sources from the Albany–Fraser Orogen (Spaggiari et al., 2014b). Furthermore, zircons of this age have the most juvenile Lu–Hf isotopic signature recorded in the Albany–Fraser Orogen, pointing to an exotic source with newly formed crust of different character. That source is interpreted as the c. 1410 Ma Loongana oceanic-arc, with which this detritus shares a similar isotopic and age signature (Spaggiari et al., 2014b; Kirkland et al., 2014a).

The second largest age component in the Arid Basin spans the range 1700–1650 Ma and can be readily correlated with known sources produced by the Biranup Orogeny. The flanking age range of 1825–1725 Ma also correlates well with known ages of magmatic rocks of the Biranup and Nornalup Zones. This detritus is likely to have shed from uplifted portions of these zones, and/or from the earlier deposition or recycling of these sediments into the Arid Basin, before being mixed with the c. 1455 to 1375 Ma sediments (Spaggiari et al., 2014b). The small number of both Neoarchean detrital zircons and Paleoproterozoic zircon detritus in the age range 2550–1900 Ma in the Arid Basin indicates that recycling from the Barren Basin was minimal, based on the prevalence of detrital zircons of these age groups in the Barren Basin. The small volume of Neoarchean detrital zircons also implies that input from the adjacent Yilgarn Craton was minimal at this time (Spaggiari et al., 2014b).

Ragged Basin

The Ragged Basin represents a restricted sequence of which the only known unit is the Mount Ragged Formation, which is exposed in the eastern Nornalup Zone (Figs 1 and 2). The Mount Ragged Formation is interpreted to have been deposited sometime between Stages I and II of the Albany–Fraser Orogeny (Clark et al., 2000). The metasedimentary component of the Salisbury Gneiss, which is exposed on Salisbury Island (Fig. 1), is interpreted as having been deposited at a similar time to the Mount Ragged Formation; however, there is little constraint on its depositional age. It lies within the Madura Province, and is not considered part of the Ragged Basin.

The Mount Ragged Formation comprises upper-greenschist to lower-amphibolite facies metasedimentary rocks dominated by pale grey, medium-grained, well-sorted, planar cross-bedded quartzite, locally interbedded with pelite or metasiltstone. Poorly sorted, quartz-pebble conglomerates interbedded with thick layers of well-sorted granular, quartz-dominated gritstones also occur locally (Waddell, 2014). The succession has been interpreted as deposited in a shallow intracratonic basin (Clark et al., 2000), although more recent work has refined this interpretation as a shallow basin fed by a large fluvial system dominated by a shifting complex of sandy braided channels (Waddell, 2014). The sequence is interpreted to gradually coarsen upwards, which implies a distal fluvial environment characterized by channel migration and abandonment evolving to a proximal fluvial environment characterized by rapid periods of sedimentation, producing coarser deposits (Waddell, 2014).

Previously published SHRIMP U–Pb data from the Mount Ragged Formation indicate a maximum depositional age of 1321 ± 24 Ma, but include a single grain dated at 1261 ± 31 Ma (Clark et al., 2000). From this it was difficult to establish whether the Mount Ragged Formation was distinct from other sedimentary rocks of the Arid Basin. The age of 1321 ± 24 Ma was interpreted as consistent with local derivation from the underlying Recherche Supersuite, and the contact was interpreted as an angular unconformity (Clark et al., 2000). Recently acquired geochronology from detrital zircons from the Ragged Range and nearby Diamonds Hill supports the interpretation that the Mount Ragged Formation is younger than the Arid Basin, and indicates that the maximum depositional age could be as young as 1234 ± 32 Ma (based on a single analysis, preliminary data, GSWA 194875). The same sample yielded the youngest conservative estimate for the maximum age of deposition at 1314 ± 19 Ma (based on 14 analyses). Other samples have also yielded younger, single zircon analyses at

1300 ± 28 and 1290 ± 84 Ma (GSWA 194866, Kirkland et al., 2014f; GSWA194874, Kirkland et al., 2014g, respectively). Although sparse, these young single grains appear to occur in all samples, including that of Clark et al. (2000), suggesting deposition took place during the latest part of Stage I of the Albany–Fraser Orogeny, or after it. The significant age component of 1350–1325 Ma is coincident with the early part of Stage I.

Amphibolite-facies metamorphism (4–5 kbars, 550°C) and growth of the 1154 ± 15 Ma rutile, indicate that these rocks were buried and metamorphosed during Stage II (Clark et al., 2000). This is further constrained by the recently dated, undeformed granite intrusion that crops out at Scott Rock, dated at 1175 ± 12 Ma (GSWA 192586, Kirkland et al., 2014e). Aeromagnetic imagery indicates that this granite crosscuts the fold and thrust architecture of the Mount Ragged Formation (Plate 3; Waddell, 2014).

Madura Province

The basement geology of the Madura Province lies completely under cover of the Bight and Eucla Basins, and is interpreted from geophysical interpretations and a small number of exploration and GSWA stratigraphic drillholes (Fig. 3). The province is defined as the area of basement bounded by the Rodona Shear Zone to the west, and the Mundrabilla Shear Zone to the east (Fig. 1; Plates 2 and 3). The Rodona Shear Zone is a wide, northeast-trending, east-dipping, high-strain zone that coincides with the eastern edge of the Albany–Fraser Orogen (Spaggiari et al., 2012, 2014a). Kinematic interpretations from aeromagnetic data indicate a period of west-directed thrusting overprinted by sinistral shearing. The Mundrabilla Shear Zone is a prominent, north–south structure that abruptly loses its magnetic signature to the north under the Officer Basin. It is a wide, straight, shear zone, which suggests it is subvertical, with drag fabrics indicative of a sinistral shear sense, at least during its more recent history. The shear zone is coincident with a surface fault and present-day scarp through the Miocene limestones of the Eucla Basin. Aeromagnetic data indicate a complex structural architecture for the Madura Province, with a dominant northeasterly regional trend (Spaggiari et al., 2012).

The only rock record from within the Rodona Shear Zone is from drillcore from the Hannah 1 prospect (Fig. 3; northeast of Caiguna). This drillhole intersected a coincident magnetic and gravity high, that has a boudin-like geometry. The drillcore contains metadiorite dated at 1170 ± 4 Ma (GSWA 182203, Kirkland et al., 2012c; Spaggiari et al., 2014a). Similar geophysical anomalies occur to the north of this, mainly within the shear zone. The deformed c. 1170 Ma metadiorite from the Hannah 1 drillcore indicates that at least the latest phase of deformation was after c. 1170 Ma.

In the Forrest Zone of the Coompana Province, the Eucla 1 petroleum well intersected a distinct ovoid feature of high magnetic intensity, interpreted as one of a series of northeast-trending granitic intrusions that are dragged into, and cut by, sinistral movement on the Mundrabilla Shear Zone (Fig. 3; Spaggiari et al., 2012). These magnetic intrusions have a similar signature to magnetic intrusions of the Esperance Supersuite in the eastern Nornalup Zone (Spaggiari et al., 2014a). Small rock chips from the base of the well, which are interpreted as derived from a granitic rock, provided a date of 1140 ± 8 Ma, interpreted as the magmatic crystallization age of the granite (GSWA 194773; Kirkland et al., 2011d). A single analysis of an unzoned zircon yielded a date of 1598 ± 14 Ma, interpreted as either the age of an inherited component within the granite, or the age of zircon incorporated from another rock unit (e.g. sedimentary rock) within the drillhole.

Diamond drillcore from the Moodini prospect within the Mundrabilla Shear Zone (about 15 km east of Moodini, Fig. 3), drilled by Venus Metals in March 2011, comprises texturally variable metagranite that is mostly porphyritic, locally with a fine-grained quench texture suggesting rapid cooling (Fig. 4a,b). It is locally cut by coarse pegmatite with large K-feldspars and white mica. The metagranite contains a subhorizontal foliation or linear fabric with a rodded morphology. The fabric is crosscut by localized alteration zones containing quartz, epidote, and possible prehnite in veins. The metagranite has a high magnetic susceptibility, and overlies a discrete north-trending magnetic high in the centre of the Mundrabilla Shear Zone. Zircons from this metagranite have been dated at 1132 ± 9 Ma (hole DDH MORCD 002, 592.83 – 593.39 m depth interval, GSWA 192566, preliminary data), interpreted as the age of magmatic crystallization of the granite. This indicates that sinistral movement on the Mundrabilla Shear Zone either occurred during emplacement of this granite, or after it. The date of the Moodini granite is also within uncertainty of the date from the Eucla 1 granite, and is likely to be part of the same magmatic event.

Madura Province basement rocks

Drilling at the Burkin prospect — which lies east of the Rodona Shear Zone and within the hinge of an interpreted antiformal structure approximately 65 km north of seismic line 12GA-AF3 (Plate 2, Fig. 3) — intersected a complex succession of heterogeneous gneissic rocks, iron-rich layered quartz–chlorite–garnet schist, metamorphosed banded iron-formation, and amphibolite (Benson, 2009; Spaggiari et al., 2012). Core with patches of potentially migmatitic, leucocratic material which crosscut a folded fabric, was sampled for U–Pb zircon geochronology (GSWA 182485, Kirkland et al., 2012d). Three zircon cores (either inherited or detrital) were dated at c. 2408 to 2293 Ma, while four grains provided a possible maximum depositional age of c. 1538 Ma (if the gneiss is interpreted to have a sedimentary protolith). Fourteen analyses of a mix of zircon rims and discrete homogeneous crystals provided a date of 1478 ± 4 Ma, interpreted as high-temperature metamorphism associated with migmatization and production of the leucocratic material (Kirkland et al., 2012b). Alternatively, the 1478 ± 4 Ma date could be a detrital zircon age component of the host rock.

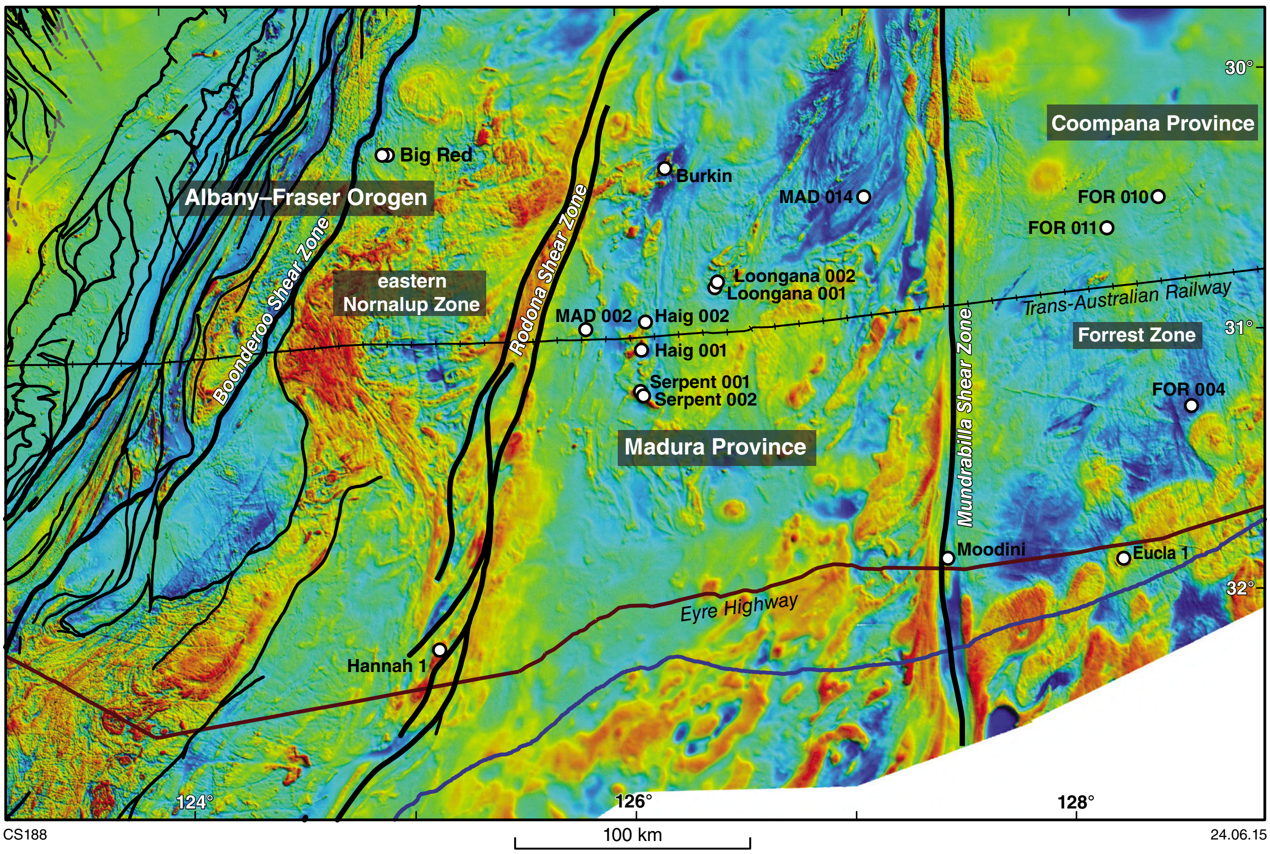

Figure 3. **Reduced-to-pole aeromagnetic image over the east Albany–Fraser Orogen and Eucla Basin, showing major tectonic basement units and simplified structures, and the locations of drillcore sites, including the sites of the 2013 GSWA stratigraphic drilling program.**

In 2013, GSWA drilled two stratigraphic holes in the Madura Province; MAD002 and MAD014 (Fig. 3). MAD002 is located about 4 km north of common depth point (CDP) 20 660 in seismic line 12GA-AF3 (Plate 2), and intersected basement at 389 m. Here, the basement consists of amphibolite schist interlayered with leucogranite veins and pods that are either parallel to the schistosity, or more locally, transgress it (Fig. 4c,d). The drillhole is coincident with a north-northeasterly trending, magnetic fabric of moderate susceptibility. In map view, this magnetic fabric occurs between the westerly dipping Pinto Shear Zone and the westerly dipping Honeymoon Shear Zone, which is interpreted to overlie the gabbroic rocks of the Haig Cave Supersuite (new name, after Haig Cave; seismic line 12GA-AF3; Plates 2 and 4; Spaggiari et al., 2014a).

Haig Cave Supersuite

The Haig Cave Supersuite comprises c. 1410 Ma gabbroic and metagranitic rocks from six diamond drillcores from the Loongana, Haig, and Serpent prospects, which are all from an area of roughly 3500 km^2 located in the central part of the Madura Province (Plate 2; Fig 3). These prospects overlie distinct gravity highs but have variable aeromagnetic signatures.

Weakly layered, medium-grained, mafic cumulate rocks form the basement lithology at the Serpent prospect, and also greatly dominate the Haig prospect, but here are intruded by medium- to coarse-grained trondhjemitic plagiogranite. At both Haig and Serpent geochemically distinct mafic cumulate rocks occur, indicating that distinct intrusive chambers were sampled (Spaggiari et al., 2014b). In Loongana core LNGD001, the upper portion of the basement component is dominated by weakly layered, medium-grained, mafic cumulate rocks, but it also includes an approximately 13 m thick interval of medium-grained, peridotitic cumulate rocks. The lower part of the basement component is dominated by medium- to coarse-grained trondhjemitic plagiogranite, which is also the dominant lithology in LNGD002 (Spaggiari et al., 2014b).

The c. 1410 Ma age of the Haig Cave Supersuite is constrained by dating of the granitic and gabbroic rocks from the Loongana core (see Spaggiari et al., 2012, 2014b, for details and references). Although undated, the Haig and Serpent drillcores are included in the Loongana Supersuite because of lithological and geochemical similarities. Dated zircons from plagiogranite from the Loongana core have juvenile Hf-isotopic compositions (εHf -2.5 to +11.5), with a median εHf of +7.8, and approach mantle-like values, which at 1410 Ma was εHf +12.1 (Spaggiari et al., 2014b). The isotopic and

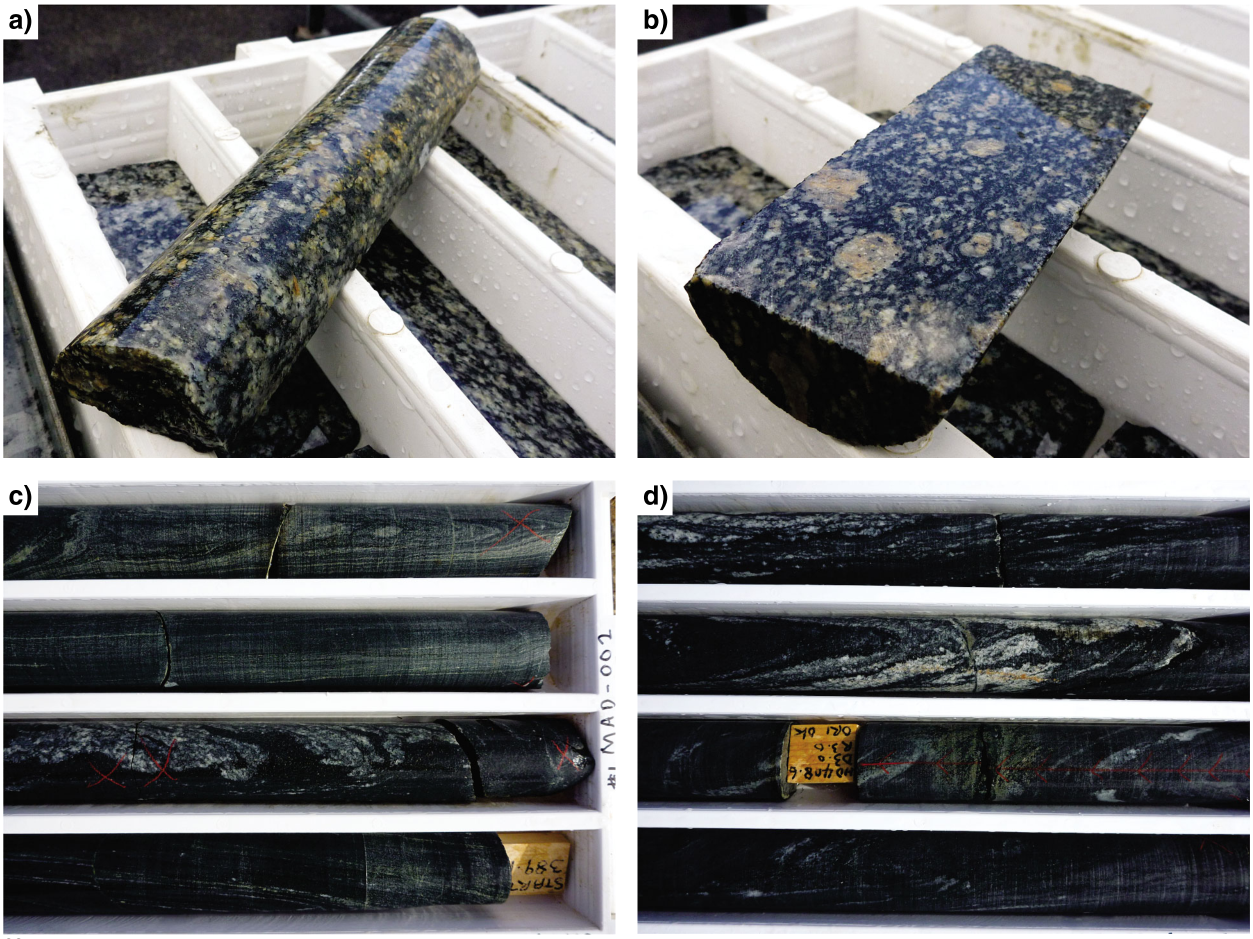

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Figure 4. Photographs of drillcore from the Madura Province: a) quench texture in metagranite from Moodini core; b) foliated porphyritic metagranite from Moodini core; c) laminated amphibolite schist interlayered with leucogranite veins, upper section of basement core at approximately 389 m depth; d) laminated amphibolite schist interlayered with leucogranite veins parallel to the schistosity, approximately 408 m depth

geochemical interpretations suggest that the Haig Cave Supersuite formed in an oceanic-arc setting, with little contribution from continental material (Spaggiari et al., 2014b).

The isotopic values also overlap those found in detrital zircons in the age range 1425–1375 Ma from the Arid Basin, consistent with derivation from the Haig Cave Supersuite. If these zircons were sourced from the Madura Province, they must have been deposited in the Arid Basin by at least c. 1300 Ma, before being intruded by Recherche Supersuite granitic rocks, and the Fraser Zone gabbros.

Salisbury Gneiss

On Salisbury Island (Fig. 1), the Salisbury Gneiss comprises pelitic gneisses and mafic granulite, porphyritic granitic gneiss, and a two-pyroxene metagabbro that is undeformed in its core but deformed and amphibolitic at its margins (Clark, 1999). Outcrops of migmatitic pelitic gneiss record granulite-facies metamorphic conditions of approximately 800°C and >5 MPa (Clark, 1999; Clark et al., 2000). Migmatitic leucosome derived from partial melting of the pelitic gneiss yielded dates of 1214 ± 8 Ma (18 core analyses) and 1182 ± 13 Ma (six rim analyses; Clark et al., 2000). The c. 1214 Ma date provides a minimum age of deposition of the pelitic rocks. This date was interpreted as the age of crystallization of the leucosome, whereas the younger date of 1182 ± 13 Ma was interpreted to reflect zircon growth during decompression from peak metamorphic conditions (Clark et al., 2000). A lack of evidence for Stage I metamorphism led Clark (1999) to interpret deposition of the sediments to have occurred after that event.

Tectonic significance of the Madura Province

Although poorly constrained, all data from the Madura Province collected so far indicate that its geological evolution was different from that of the Albany–Fraser Orogen, until at least 1330 Ma. The presence of the

Loongana oceanic-arc suggests a largely oceanic environment, although it may contain limited older basement components locally (e.g. Burkin prospect). The Rodona Shear Zone is interpreted as a suture between the Albany–Fraser Orogen and Madura Province, which probably formed in the early part of Stage I of the Albany–Fraser Orogeny with accretion of the Loongana oceanic-arc (see below), but has since been modified.

The eastern extent of the Madura Province is ambiguous because it is not clear whether the Mundrabilla Shear Zone also represents a suture, separating the largely oceanic realm of the Madura Province from the Forrest Zone of the Coompana Province. The presence of deformed granites dated at c. 1140 and 1132 Ma indicate that sinistral movement on the Mundrabilla Shear Zone was much later than the accretion of the Loongana oceanic-arc, and was coincident with the later part of Stage II of the Albany–Fraser Orogeny. This movement may have been up to 200 km displacement, and probably pre-dated the Giles Event at c. 1070 Ma in the Musgrave Province (Smithies et al., 2014b). Note that for consistency, we have adopted the naming convention of Korsch et al. (2014), where the Forrest Zone (previously Forrest Province, e.g. Spaggiari et al., 2012), is part of the Coompana Province. These tectonic elements are poorly constrained, but are the subject of ongoing work including GSWA stratigraphic drilling, and interpretation of the recently acquired deep reflection seismic survey, the Eucla–Gawler line.

Tectonic evolution

Proposed models

A summary of tectonic models for the Paleoproterozoic and early part of Stage I of the Albany–Fraser Orogeny are presented below. The models are based on interpretations of the major basin-forming events, and their potential link to magmatism. Full models and details are provided in Spaggiari et al. (2014b).

Barren Basin

The Barren Basin evolved over a period of more than 200 million years (1815–1600 Ma) and is interpreted to have extended at least 1000 km along the southern Yilgarn Craton margin. It is dominated by mature, quartz-rich metasedimentary rocks interpreted to have formed in either a continental rift or a back-arc setting, during which the most dominant source of detritus was shed from the Yilgarn Craton as it underwent extension. This was mixed with locally derived detritus from synmagmatic rocks. If the Barren Basin was formed in a back-arc setting, the subduction zone and magmatic arc must have been a substantial distance outboard of the Yilgarn Craton margin.

Extension of the southern Yilgarn Craton was underway by c. 1805 Ma, resulting in a horst and graben architecture exposing basement highs. Detritus was sourced from the Yilgarn Craton hinterland, the basement highs, and potentially mixed with external sources. These sediments were fed into dominantly fluvial to deltaic, or shallow marine systems, producing the c. 1800 Ma Stirling Range Formation, and potentially even the lowermost unit of the Mount Barren Group, the Steere Formation. Mantle melting produced lower crustal melts and granitic intrusions along middle crustal shear zones, weakening the crust. Extension and magmatism was again prevalent between 1780 and 1760 Ma producing an asymmetric, melt lubricated detachment leading to doming and a core-complex mode of extension (Fig. 5a). This potentially increased the rate of extension and crustal thinning, widening the basin. Although volumetrically minor, gabbroic rocks are typically mingled with the granitic rocks, and indicate an ongoing link to the mantle as the crust thinned. It is likely that volcanism was also prevalent at this time, although the only known example are the dacitic rocks from the Voodoo Child Formation in the Tropicana Zone, which are also associated with mafic–ultramafic rocks (Less, 2013).

During the Biranup Orogeny (1710–1650 Ma), magmatism had increased volumetrically and by 1660 Ma included a greater input of more isotopically juvenile mantle material, forming mingled granitic and gabbroic intrusions such as those defined by the Eddy Suite (Kirkland et al., 2011a,b). The increased magmatism led to thermal subsidence and deepening of the basin, increased sediment load, and formation of deeper depositional centres flanked by topographic highs. Volcanism is again inferred. The compressional c. 1680 Ma Zanthus Event may reflect a brief period of basin inversion, perhaps releasing the first detritus of Biranup Orogeny age into the Barren Basin, feeding units such as the Fly Dam Formation, and to a lesser extent, the Woodline Formation. The Fly Dam Formation, which has a maximum depositional age of c. 1617 Ma, may represent the last stage of basin formation, which may have been due to thermal subsidence following the Biranup Orogeny.

An explanation for the distinct period of quiescence between 1600 and 1455 Ma, shown by the provenance from both the Barren and Arid Basins — and the magmatic history of the Albany–Fraser Orogen — is that the continental rift (or back-arc) described above evolved into a marginal ocean basin, forming an ocean–continent transition and passive margin. If a convergent margin setting is invoked, the quiescent period would indicate substantial retreat of the accompanying subduction zone. This marginal basin marks the initial setting of the Arid Basin.

Arid Basin

By c. 1500 Ma the Arid Basin was a marginal basin that lay outboard of the Yilgarn Craton and Biranup Zone, with the Nornalup Zone as an ocean–continent transition (OCT). These zones define a passive margin that provided the bulk of the detritus to the basin at that time. By c. 1455 Ma the tectonic setting changed to one of convergence, and the marginal basin included an east-dipping ocean–ocean subduction zone and the Loongana oceanic-arc (Fig. 5b). This configuration is based on the interpretation of the c. 1410 Ma Haig Cave Supersuite as an oceanic-arc, which must have been isolated from

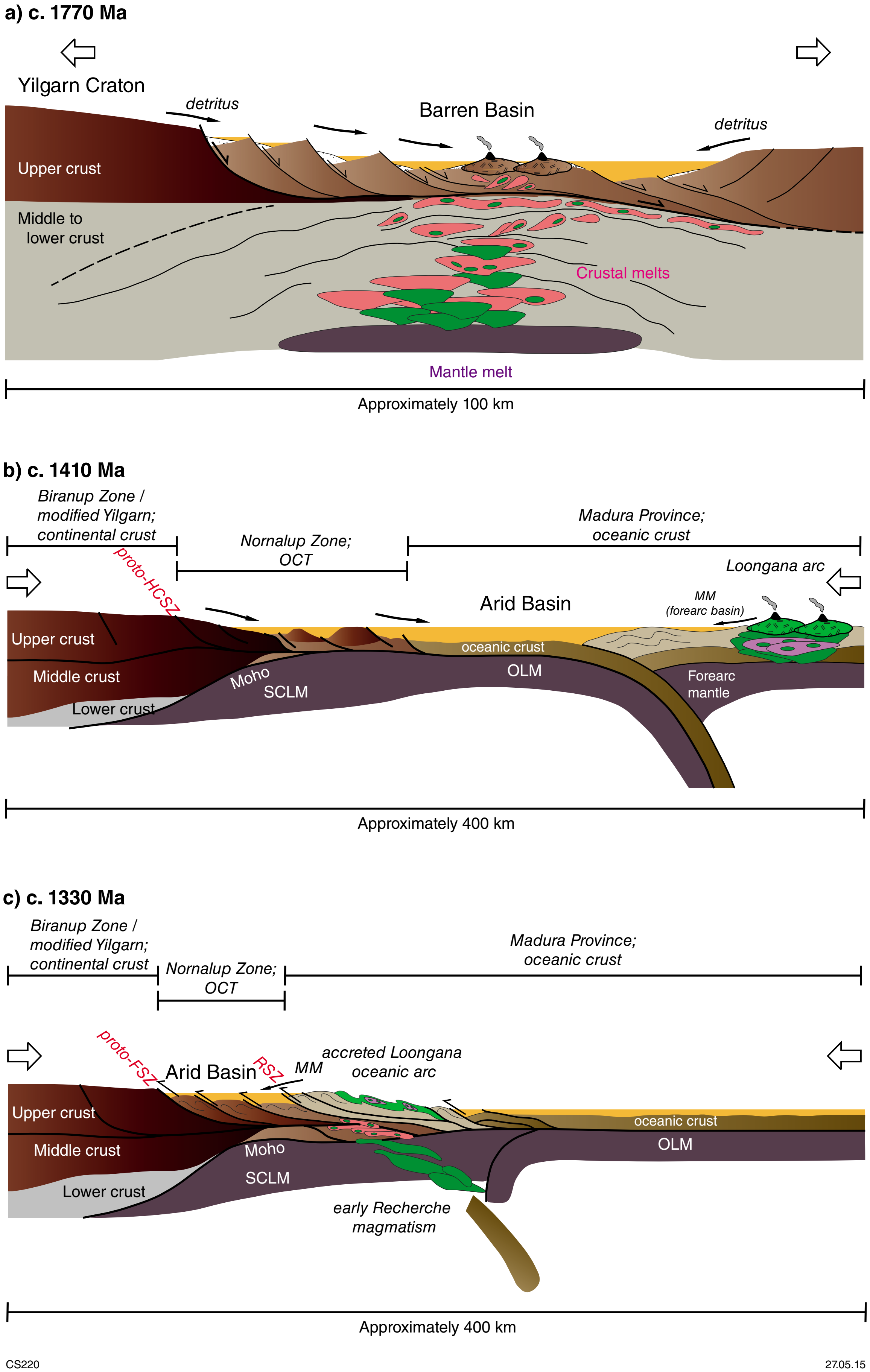
a) c. 1770 Ma
Yilgarn Craton
detritus
Barren Basin
detritus
Upper crust
Middle to
lower crust
Crustal melts
Mantle melt
Approximately 100 km
b) c. 1410 Ma
Biranup Zone /
modified Yilgarn;
continental crust
Nornalup Zone;
OCT
Madura Province;
oceanic crust
Loongana arc
proto-HCSZ
Arid Basin
MM
(forearc basin)
Upper crust
oceanic crust
OLM
Middle crust
Moho
SCLM
Forearc
mantle
Lower crust
Approximately 400 km
c) c. 1330 Ma
Biranup Zone /
modified Yilgarn;
continental crust
Nornalup Zone;
OCT
Madura Province;
oceanic crust
proto-FSZ
Arid Basin
RSZ
MM
accreted Loongana
oceanic arc
Upper crust
oceanic crust
OLM
Middle crust
Moho
SCLM
Lower crust
early Recherche
magmatism
Approximately 400 km
CS220
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Figure 5. (facing) Tectonic evolution of the Barren and Arid Basins: a) extension and magmatism between 1780–1760 Ma produced an asymmetric, melt-lubricated detachment leading to doming and a core-complex mode of extension, and widening of the Barren Basin; b) formation of the Arid Basin as dominantly a marginal basin. Convergent setting and development of the Loongana oceanic-arc at c. 1400 Ma, with the Malcolm Metamorphics interpreted as fore-arc basin sediments; c) closure of the marginal basin, oceanic-arc accretion and slab detachment triggered the onset of Stage I, and early Recherche Supersuite magmatism. Sediments were transferred from the Loongana oceanic-arc and its environs to the Arid Basin via a foreland fold and thrust system. Abbreviations used: SCLM – sub-continental lithospheric mantle; OLM – oceanic lithospheric mantle; OCT– ocean–continent transition; MM – Malcolm Metamorphics; HCSZ – Heywood–Cheyne Shear Zone; FSZ – Fraser Shear Zone; RSZ – Rodona Shear Zone. Green indicates mafic/mantle component; pink indicates crustal melt/granitic component. From Spaggiari et al. (2014b).

any significant mass of continental crust to produce the mafic–ultramafic rocks and low-K plagiogranites present. It is also consistent with the lack of evidence of tectonic activity in the Biranup and Nornalup Zones (the passive margin hinterland) at this time. It is feasible that after c. 1455 Ma the Malcolm Metamorphics were deposited in either a fore-arc or accretionary prism setting onto an oceanic substrate (cf. Adams, 2012), west of the newly formed oceanic-arc.

Sedimentation was continuing well after formation of the Loongana oceanic-arc, until at least c. 1332 Ma (maximum depositional age of the Snowys Dam Formation). Therefore, it is likely that any sediment derived from the oceanic-arc must have either been recycled, or deposited after the oceanic-arc (and subduction) had changed position. The simplest way to explain deposition of the younger Arid Basin sediments onto the Biranup and Nornalup Zone substrate would be to invoke west-directed, oceanic-arc soft collision and accretion onto the passive margin, feeding detritus westwards in a foreland basin system, towards the craton and hinterland (Fig. 5c). The exact timing of this is speculative, but the closure of the marginal ocean basin and termination of east-dipping ocean–ocean subduction in the Madura Province could be viewed as marking the onset of Stage I of the Albany–Fraser Orogeny. If this is correct, the earliest intrusions of the Recherche Supersuite at c. 1330 Ma may have been caused by this event, through initial crustal thickening producing partial melting of the upper crust, with the addition of a mantle component. Oceanic-arc accretion would have produced large-scale compressional structures, forming a suture zone between the Albany–Fraser Orogen (eastern Nornalup Zone) and the Madura Province, marked by the Rodona Shear Zone.

As Stage I of the Albany–Fraser Orogeny progressed, convergence continued and west-dipping subduction was initiated accommodating the continued consumption of the remaining Madura Province oceanic crust, east of the Loongana oceanic-arc. Roll-back of the renewed subduction zone produced an extensional regime, placing the Albany–Fraser Orogen into a back-arc setting that accommodated the main pulse of magmatism which produced the remainder of the Recherche Supersuite and the Fraser Zone gabbros by c. 1300 Ma. By this time, deposition of the Arid Basin had also ceased. West-dipping subduction and roll-back led to the collision or accretion of the South Australian – Mawson Craton, leaving a remnant portion of the oceanic realm that now defines the Madura Province. Therefore, the Madura Province can be broadly interpreted as a suture zone between the Albany–Fraser Orogen and the Coompana Province, with an as yet unidentified major structure marking the western extent of the Coompana Province. That structure most likely lies in the Forrest Zone, beneath the Eucla Basin, and has been intruded by c. 1140 Ma granites, and cut by the Mundrabilla Shear Zone.

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