Cryptic progeny of craton margins: geochronology and isotope geology of the Albany–Fraser Orogen, with implications for evolution of the Tropicana Zone

by

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Introduction

Craton margins are dynamic, they are locations of exotic terrane transferral, may be the sites of lithospheric attenuation, rifting, and subsequent reattachment, may be active with redistribution of material by subduction, or may simply be passive. Additionally, craton margins are the sites of first-order lithospheric discontinuities that facilitate the transfer of heat and materials (fluids and magmas), and under favorable circumstances can become mineralization corridors. Craton margins have changed over geological time as a result of the transition from high mantle temperatures and low mantle viscosity in the Archean, to relatively low mantle temperatures in the Proterozoic. Such changes may be expected to result in distinctly different craton margin architectures and processes through earth history and to manifest themselves in different mineralization styles. Nonetheless, on a global scale, the most important hydrothermal gold mineralization is associated with late Archean or Paleozoic to Quaternary convergent (subduction) margin settings (Barley et al., 1989).

The Proterozoic margins of Archean cratons are increasingly recognized as key regions where upgrading of ancient mineral endowments to economically viable levels can occur (Lawley et al., 2014). Additionally, other processes along craton margins, such as terrane transfer, may also play important roles in delivering mineral endowment. Distinguishing the nature of craton margin processes (e.g. terrane accretion, reattachment, rifting, stable) has pertinent implications for regional mineral prospectivity.

One such area where a variety of craton margin processes has been in operation is the Albany–Fraser Orogen, a component of the West Australian Craton, located along the southern and southeastern margins of the Archean Yilgarn Craton (Spaggiari et al., 2011). Towards the west, the orogen is truncated by the late Mesoproterozoic to Neoproterozoic Darling Fault Zone and Pinjarra Orogen, whereas the eastern extent of the orogen is overlain by the Bight and Eucla basins. To the northeast, the orogen is overlain by the Officer and Gunbarrel basins. Further northeast, the Proterozoic Musgrave Province has a similar Mesoproterozoic magmatic history, although the basement units have distinctly different Nd- and Hf-isotopic characteristics (Kirkland et al., 2011a,b). The Albany–Fraser Orogen and Musgrave Province may once have been contiguous, but only after 1400 Ma. The crustal evolution of these two regions prior to 1400 Ma is distinctly different. Between c. 1900 and 1400 Ma Hf-isotopic evolution trends contrast apparent crustal reworking for the Musgrave Province, with progressive juvenile input into unradiogenic Archean crust in the Albany–Fraser Orogen (Kirkland et al., 2012a). The eastern margin of the Albany–Fraser Orogen is covered by the Eucla Basin, but is inferred to extend to the Rodona Shear Zone (Spaggiari et al., 2012). On the eastern side of this structure, the orogen is in contact with the Madura Province, which comprises juvenile c. 1410 Ma tonalites and gabbros (e.g. GSWA 192558, Kirkland et al., 2013a) derived from low- to medium-K tholeiitic parental magmas likely produced in an oceanic-arc setting (Loongana Arc; Spaggiari et al., 2014a). Migmatitic gneiss in drillcores of the Madura Province yield a zircon U–Pb date of c. 1480 Ma, interpreted to reflect migmatization, and a range of protolith ages, indicating a component older than the Loongana Arc in the Madura Province, alternatively all these crystallization ages could reflect detritus (Kirkland et al., 2012b). The Albany–Fraser Orogen is interpreted as a component of the Australo–Antarctic, Albany–Fraser–Wilkes Orogen, which was a coherent entity prior to Gondwana breakup (Fitzsimons, 2003).

Prior to the commencement of the Albany–Fraser Orogen project at the Geological Society of Western Australia (GSWA) in 2006, there were comparatively few isotopic datasets for this region (Nelson et al., 1995a; Clark et al., 1999, 2000). Nonetheless, geological understanding of this region's evolution has advanced rapidly with the recent collection and interpretation of large, high-quality geochronology and isotopic datasets. These datasets have enabled the deciphering of the geological history and crustal evolution of this region. Because of the sparse outcrop, coupled with the dominance of granitic gneisses whose ages cannot be distinguished in outcrop, GSWA's geochronology program has been fundamental to understanding the tectonic events that have built this orogen. These data, now coupled with geochemistry (Smithies et al., 2014) have facilitated the interpretation of magnetic and gravity datasets, which in unison, provide important constraints for the interpretation of the deep crustal seismic lines (Spaggiari et al., 2014b).

In the following text we present a brief overview of the U–Pb geochronology collected in various lithotectonic zones of the Albany–Fraser Orogen, before evaluating the isotopic signatures of some of these zones. Within this framework we present the results of recent work in the newly defined Tropicana Zone, that includes the Tropicana gold mine and several prospects to the northeast (Occhipinti et al., 2014). Outcrop is sparse in the Tropicana Zone, but drillcores have provided valuable information on the distinct evolution of this zone. In the northeast, buried under deep regolith, are the Hercules and Atlantis prospects (Plate 1). These contain Archean granites with broadly dioritic compositions, and a very narrow range of low silica values from 58.1 to 63.6 w%, classified as sanukitoids. These Archean granites have been named the Hercules Gneiss. The Tropicana Zone is located along the eastern margin of the Yilgarn Craton, in the Great Victoria Desert. The western boundary of the Tropicana Zone is sharply truncated by the Gunbarrel Fault, and a thick sequence of sedimentary rocks of the Gunbarrel Basin (Plates 1 and 4; Occhipinti et al., 2014).

U–Pb geochronology of the major units of the Albany–Fraser Orogen

Figure 1 presents an overview geological map of the various craton margin lithotectonic elements of the Albany–Fraser Orogen. A summary of the SIMS (SHRIMP) zircon geochronology in these zones is presented in this section.

Northern Foreland (Munglinup Gneiss)

The Northern Foreland reflects the margin of the Yilgarn Craton reworked during the Albany–Fraser Orogeny. Geochronological data have shown that the orthogneisses were derived from late Archean precursors, with at least five phases of granitic magmatism: at c. 2720, 2680, 2670, 2660, and 2620 Ma (e.g. Spaggiari et al., 2011; Fig. 2). These crystallization ages are comparable to those of magmatic events elsewhere in the Yilgarn Craton (Cassidy et al., 2006 and references therein). Such similarity is consistent with the interpretation that the granitic precursors to the Munglinup Gneiss were part of the Yilgarn Craton. Hf-isotopic signatures of the Northern Foreland are similar to many terranes and domains of the Yilgarn Craton, although a unique attribution of the Northern Foreland to a specific component of the Yilgarn Craton is not possible (Kirkland et al., 2011b).

Kepa Kurl Booya Province

The Kepa Kurl Booya Province is the crystalline basement of the Albany–Fraser Orogen (Spaggiari et al., 2009), and lies immediately to both the south and east of the Yilgarn Craton. This zone was affected by Stage I intrusion and metamorphism of the Albany–Fraser Orogeny. The Kepa Kurl Booya Province can be considered as comprising four fault-bounded lithotectonic zones named the Biranup, Fraser, and Nornalup zones, and the newly defined Tropicana Zone. Each of these zones contains rocks with variable protolith ages, but similar timing of overprinting metamorphism or intrusion by younger mafic and felsic magmas.

Biranup Zone

The Biranup Zone comprises largely mid-crustal rocks, including orthogneiss and metagabbro with ages of c. 1810 to 1625 Ma (Spaggiari et al., 2011; Fig. 3). The earliest magmatic pulse in this zone occurred at 1810–1800 Ma and was followed by a second event at 1780–1760 Ma. Deposition of a component of the Barren Basin (see below) was followed rapidly by intrusion of a suite of Biranup Zone granitic magmas at 1686 ± 8 Ma (e.g. GSWA 194701, Kirkland et al., 2011c). Deformation during the Zanthus Event, a compressional component of the 1710–1650 Ma Biranup Orogeny, is constrained by 1676 ± 6 Ma folded migmatitic leucosomes and 1679 ± 6 Ma crosscutting axially planar leucosomes (Kirkland et al., 2011a). A younger suite of granitic and gabbroic rocks, which exhibit distinct mingling and local hybridization textures, is dated at 1665 ± 4 Ma (Eddy Suite; Plate 2). The youngest Biranup Zone magma (excluding Stage I and II granite injections) is a metasyenogranite with a zircon U–Pb crystallization age of 1627 ± 4 Ma (GSWA 194736, Kirkland et al., 2010). Initially, the lack of evidence for a Paleoproterozoic magmatic or tectonothermal event in the southern Yilgarn Craton led to the suggestion that the Biranup Zone was an exotic terrane accreted onto the Yilgarn Craton margin during Stage I of the Albany–Fraser Orogeny (e.g. Nelson et al., 1995a). However, more recent isotopic work has shown that the Biranup Zone was likely to have formed autochthonously along the Yilgarn Craton margin (Kirkland et al., 2011a, 2011b), which is consistent with the presence of fragments of Archean granite isolated within it (Spaggiari et al., 2011). Zircon overgrowths were developed widely during Stage II metamorphism in the Biranup Zone.

Fraser Zone

The Fraser Zone is dominated by the Fraser Range Metamorphics, a sequence of high-grade metasedimentary rocks intruded by sheets of metagabbro and metagranite (Smithies et al., 2013; Clark et al., 2014). Mafic and felsic magmatism in the Fraser Zone were contemporaneous and occurred between c. 1310 and 1283 Ma, soon after deposition of the Arid Basin (see below) (Kirkland et al., 2011a; Spaggiari et al., 2011). Magmatic crystallization of mafic intrusive rocks in the Fraser Zone has been

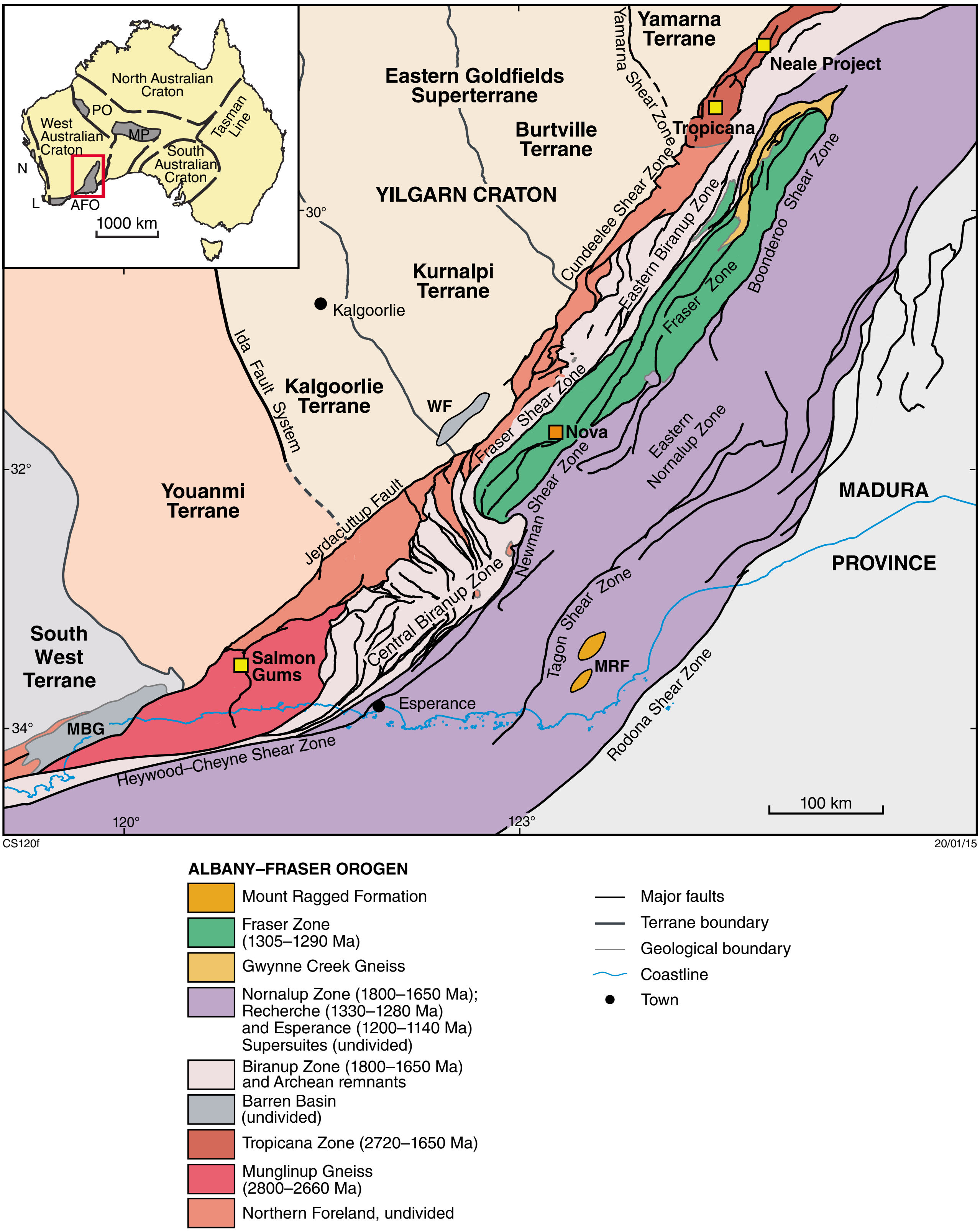
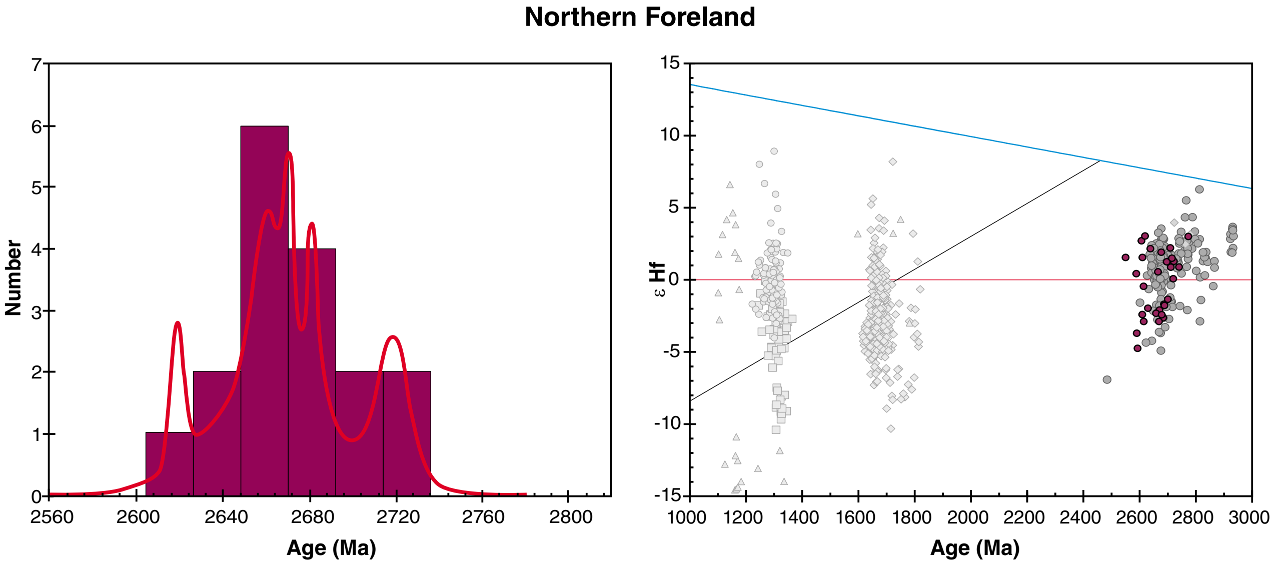


Figure 1. Simplified pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen (modified from Spaggiari et al., 2011) and tectonic subdivisions of the Yilgarn Craton (modified from Geological Survey of Western Australia, 2011; Cassidy et al., 2006; Pawley et al., 2012). Abbreviations used: MBG – Mount Barren Group; WF – Woodline Formation; MRF – Mount Ragged Formation; AFO – Albany–Fraser Orogen; MP – Musgrave Province; PO – Paterson Orogen; L – Leeuwin Province; N – Northhampton Province



Northern Foreland

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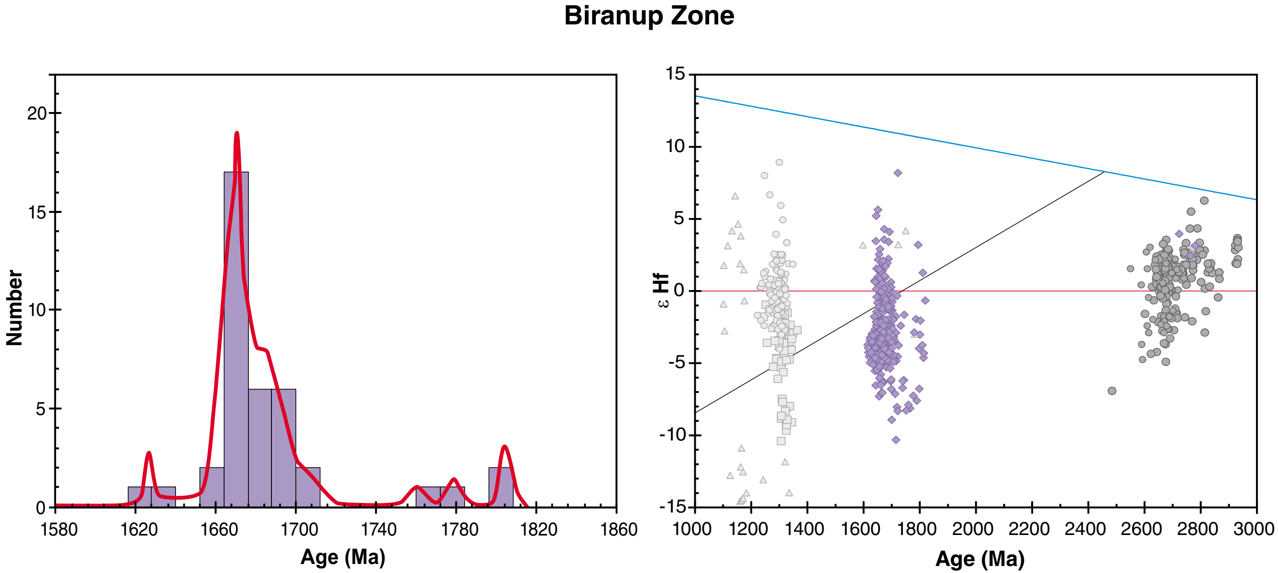
Figure 2. **Left: combined histogram/probability plot of $^{207}Pb^{*}/^{206}Pb^{*}$ crystallization ages of magmatic rocks in the Northern Foreland. Right: εHf evolution plot for the same data (coloured), other data from the Albany–Fraser Orogen in light grey, data from the Yilgarn Craton in dark grey. A reference evolution line corresponding to a $^{176}Lu/^{177}Hf$ ratio of 0.015 is shown in black.**



Biranup Zone

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Figure 3. **Left: combined histogram/probability plot of $^{207}Pb^{*}/^{206}Pb^{*}$ crystallization ages of magmatic rocks in the Biranup Zone. Right: εHf evolution plot for the same data (coloured), other data from the Albany–Fraser Orogen in light grey, data from the Yilgarn Craton in dark grey. A reference evolution line corresponding to a $^{176}Lu/^{177}Hf$ ratio of 0.015 is shown in black.**

dated at 1299 ± 3 Ma (GSWA 194717, Kirkland et al., 2013b), 1299 ± 10 Ma, and 1291 ± 8 Ma (De Waele and Pisarevsky, 2008; Fig. 4). High-grade metamorphism occurred soon after sediment deposition and magmatic intrusion in the Fraser Zone. For example, zircon rims in a psammitic gneiss yield a date of 1292 ± 5 Ma (GSWA 194714, Kirkland et al., 2011d), and metamorphic zircons in a mafic granulite indicate high-grade metamorphism at 1292 ± 6 Ma (GSWA 194718, Kirkland et al., 2011e). Metamorphism has also been constrained at 1304 ± 7 Ma by zircon rim growth within a quartz metasandstone, which indicates a maximum depositional age of 1466 ± 17 Ma (Wingate and Bodorkos, 2007). All isotopic results from the Fraser Zone indicate a very short time interval for sediment deposition, igneous crystallization, and near-coeval granulite-facies metamorphism. The close correspondence between the age of mafic to felsic magmatism and the age of granulite-facies metamorphism implies that magmatism was the thermal impetus for metamorphism. Such similar timing of magmatism and granulite-facies metamorphism implies these rocks were emplaced in the lower-middle to lower crust, consistent with peak metamorphic conditions at c. 1290 Ma of 850°C, at pressures of 7–9 kbars. Peak metamorphism was followed by a period of isobaric cooling at pressures of about 9 kbars (Clark et al., 2014).

Barren Basin

The Barren Basin comprises Paleoproterozoic metasedimentary rocks which overlie the Yilgarn Craton and the Biranup and Nornaup Zones (Spaggiari et al., 2011, 2014a). Detrital zircon grains in sedimentary rocks of the Barren Basin indicate age peaks, in order of significance, at 2634, 1670, 2028, 1792, 1874, and 2248 Ma, defined by 156, 132, 58, 56, 44, 38 analyses, respectively (Fig. 5). Such detrital zircon ages indicate that the major sources of Barren Basin sediments were indigenous West Australian Craton rocks — mainly Proterozoic granites dominant in the Biranup Zone that have magmatic crystallization ages in the range of c. 1800 to 1670 Ma (see also Spaggiari et al., 2014a). A significant Archean c. 2630 Ma detrital zircon age peak in the Barren Basin is strongly similar in age to widespread granitic magmatism at 2640–2620 Ma in the Yilgarn Craton, which was the last major magmatic event to have affected the craton, and was responsible for craton-wide gold mineralization (Kent et al., 1996). Subordinate detrital peaks (e.g. 2030 Ma) are less well constrained but could reflect sediment derivation from the Gascoyne Province (Johnson et al., 2011). The Barren Basin developed during a protracted period of >200 Ma (1815–1600 Ma), with deposition taking place during three phases (before c. 1800 Ma, before c.1700 Ma, and between 1710 and 1600 Ma; Spaggiari et al., 2014a).

Arid Basin

Within the Fraser and Nornalup Zones, metasedimentary rocks that have maximum depositional ages younger than the Biranup Orogeny, but have been intruded by Stage I magmas, are part of the Arid Basin (Spaggiari et al., 2011, 2014a). Detrital zircons from sediments in the Arid Basin indicate age peaks, in order of significance, at 1382, 1672, 1456, 1495, 1557, 1524, and 1789 Ma, defined by 85, 75, 52, 38, 29, 28 and 16 analyses, respectively (Fig. 6).

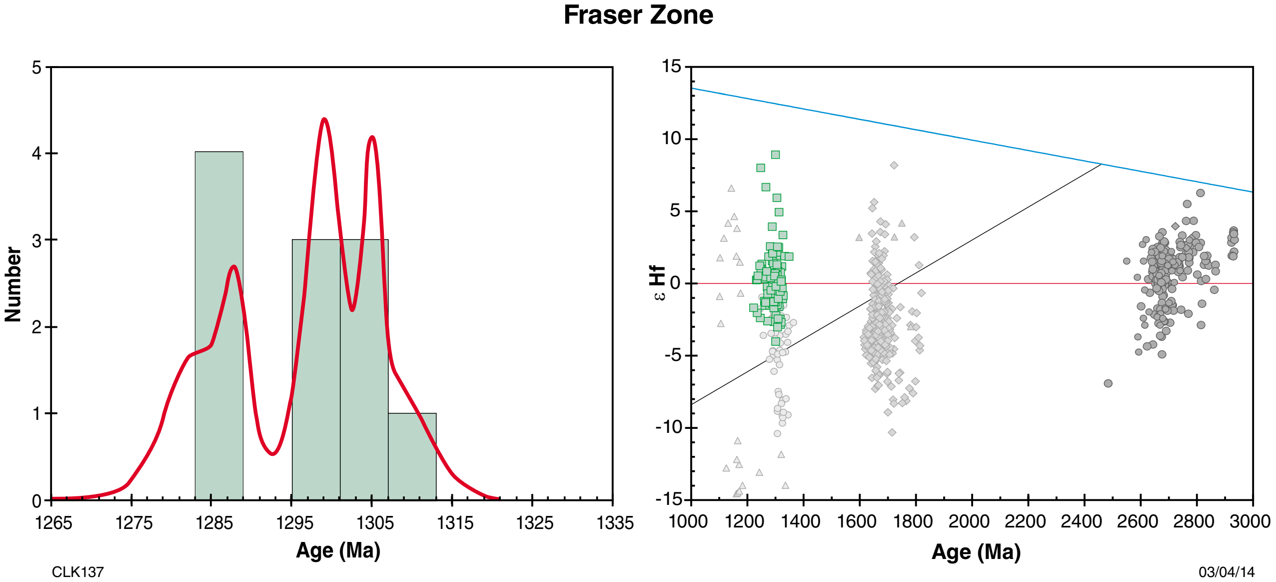

Figure 4. **Left: combined histogram/probability plot of ^{207}Pb*/^{206}Pb* crystallization ages of magmatic rocks in the Fraser Zone. Right: εHf evolution plot for the same data (coloured), other data from the Albany–Fraser Orogen in light grey, data from the Yilgarn Craton in dark grey. A reference evolution line corresponding to a ^{176}Lu/^{177}Hf ratio of 0.015 is shown in black.**

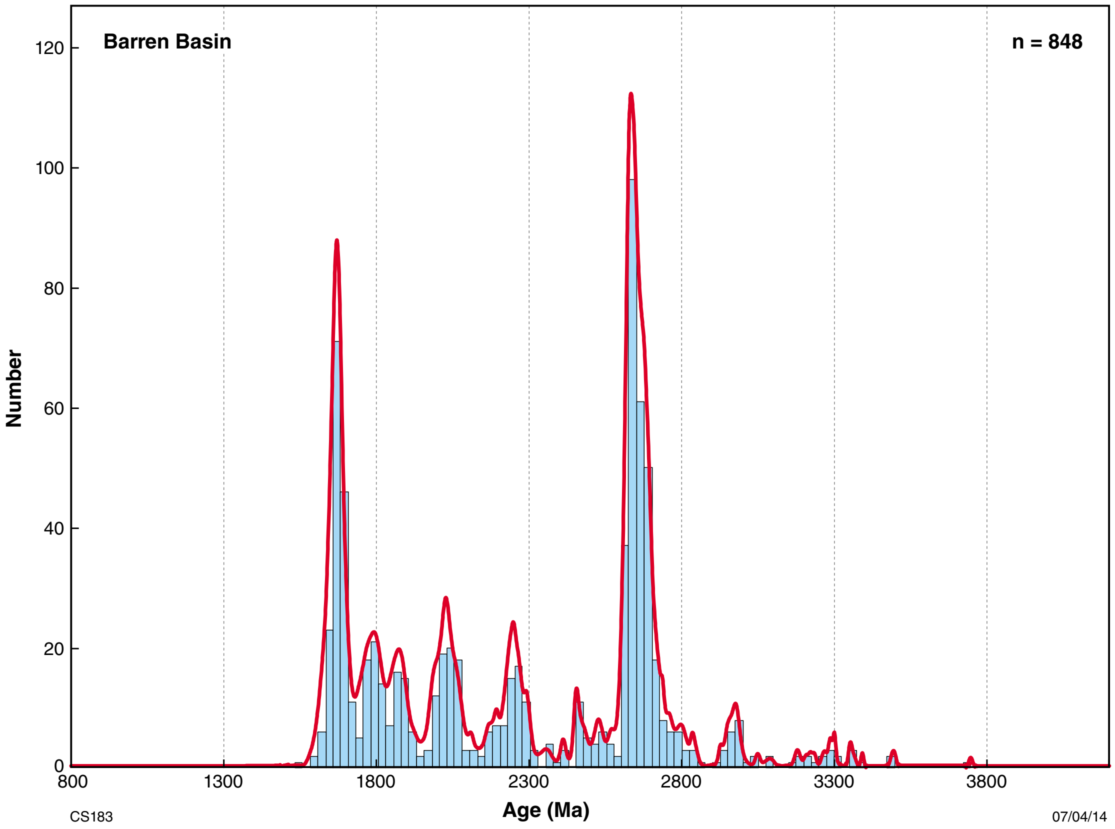

Figure 5. Combined histogram/probability plot of $^{207}Pb^{*}/^{206}Pb^{*}$ crystallization ages of detrital zircons in the Barren Basin (from Spaggiari et al., 2014a)

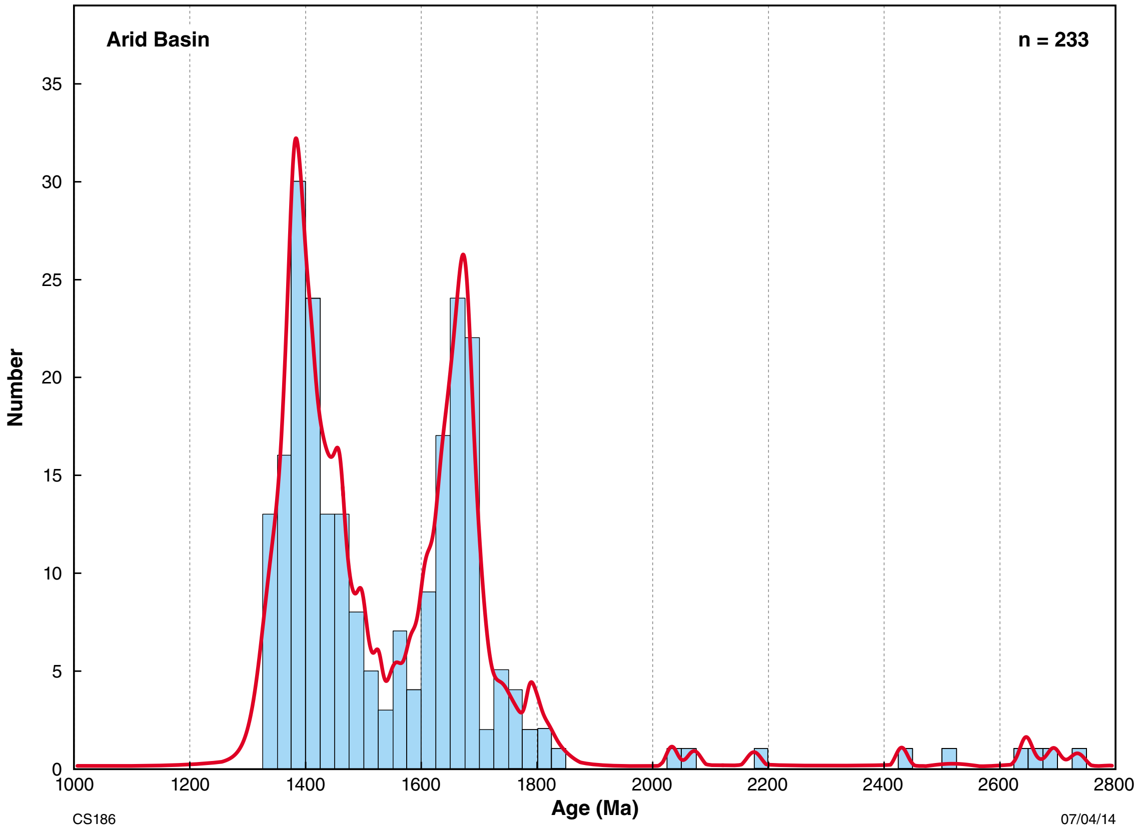

Figure 6. Combined histogram/probability plot of $^{207}Pb^{*}/^{206}Pb^{*}$ crystallization ages of detrital zircons in the Arid Basin (from Spaggiari et al., 2014a)

The 1800–1600 Ma detrital zircon ages are similar to detrital components in the Barren Basin, and suggest either a Biranup and/or Nornalup Zone hinterland for the Arid Basin, or selective reworking of less radiation damaged Proterozoic Barren Basin material (Spaggiari et al., 2014a). However, the detrital population within the Arid Basin also has some unique components not present in the Barren Basin. The dominant detrital component of 1500–1350 Ma is not recognized within the Albany–Fraser Orogen nor the Yilgarn Craton, but was likely derived from the Loongana Arc of the Madura Province to the east of the Albany–Fraser Orogen — a c. 1410 Ma piece of oceanic magmatic arc with a distinct radiogenic Hf-isotopic signature (Spaggiari et al., 2014a).

Recherche and Esperance Supersuites

The southeastern part of the Biranup Zone and the Nornalup Zone contain granitic intrusions of the 1330–1280 Ma Recherche Supersuite and the 1200–1140 Ma Esperance Supersuite (Nelson et al., 1995a; Clark et al., 1999; Smithies et al., 2014).

The Recherche Supersuite is the magmatic expression of Stage I of the Albany–Fraser Orogeny (Fig. 7), during which these rocks were metamorphosed to amphibolite or granulite facies conditions. The Recherche Supersuite contains a variety of granitic rocks including metasyenogranite, metamonzogranite, and metagranodiorite (Smithies et al., 2014). Most of these appear to be mingled with a mafic component, generally present as enclaves of various sizes. The oldest Recherche Supersuite granite presently analysed is a biotite–hornblende monzogranite with calc-silicate boudins from Poison Creek, dated at 1330 ± 14 Ma (GSWA 83662, Nelson, 1995b). Another Recherche Supersuite lithology is peraluminous, garnet-bearing, granodiorite gneiss, from Israelite Bay, dated at 1314 ± 21 Ma (GSWA 83663, Nelson, 1995c). The youngest Recherche Supersuite granite so far dated is a metamonzogranite within the Newman Shear Zone with a zircon crystallization age of 1297 ± 8 Ma (GSWA 194711, Kirkland et al., 2012c)

The Esperance Supersuite is the magmatic response to Stage II of the Albany–Fraser Orogeny (Fig. 8), which caused prolific growth of metamorphic zircon rims within rocks of the Biranup Zone. One of the youngest granites of the Esperance Supersuite is Balladonia Rock, which has a U–Pb zircon crystallization age of c. 1135 Ma (GSWA 83667, Nelson et al., 1995d), whereas the oldest is a biotite monzogranite at Mount Ridley which yielded a U–Pb zircon crystallization age of 1198 ± 11 Ma (GSWA 184374, Kirkland et al., 2012d). The Esperance Supersuite is peraluminous to metaluminous and essentially falls within the field of within plate granite in Ta vs Yb and Nb vs Y tectonic discrimination diagrams.

Hf-isotopic characteristics of the major units of the Albany–Fraser Orogen

The Lu–Hf system can be used as a geochemical tracer, providing information on both the timing of material input into the crust, as well as the process by which this material was added. Coupled with U–Pb geochronology, Hf-isotopic measurements in zircons provide unique, time-integrated information about the relative roles of juvenile mantle input versus reworking of older continental crust. The Hf-isotopic signatures of many units of the Albany–Fraser Orogen have been discussed at length elsewhere (Kirkland et al., 2011a, 2011b; Spaggiari et al., 2014a) and only a brief summary of the salient features is presented here.

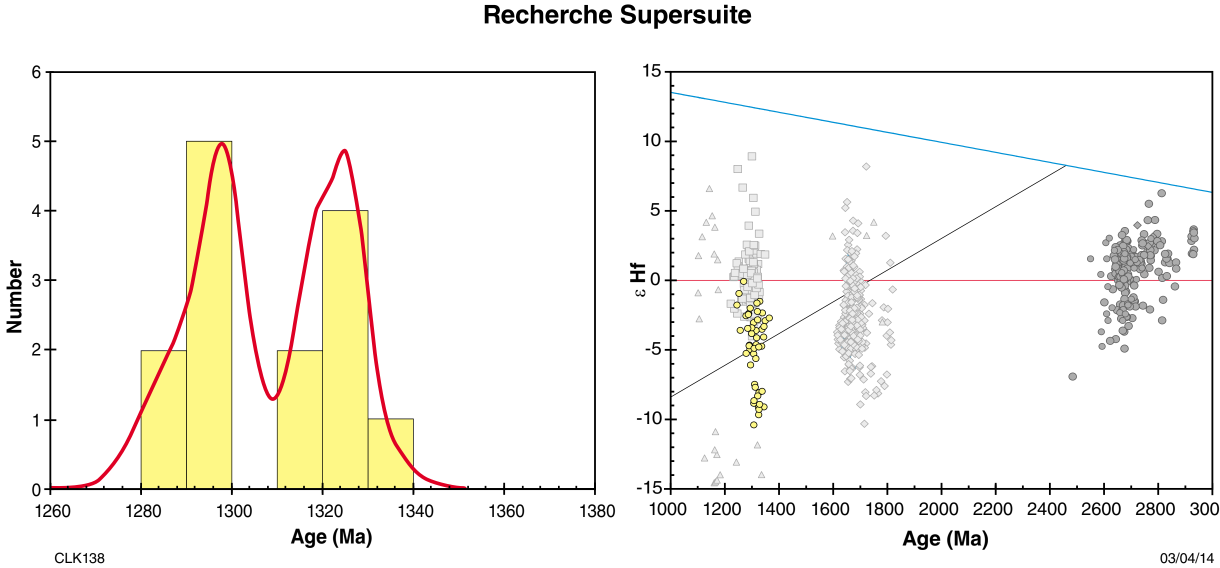
Recherche Supersuite

Figure 7. **Left: combined histogram/probability plot of ^{207}Pb*/^{206}Pb* crystallization ages of magmatic rocks in the Recherche Supersuite. Right: εHf evolution plot for the same data (coloured), other data from the Albany–Fraser Orogen in light grey, data from the Yilgarn Craton in dark grey. A reference evolution line corresponding to a ^{176}Lu/^{177}Hf ratio of 0.015 is shown in black.**

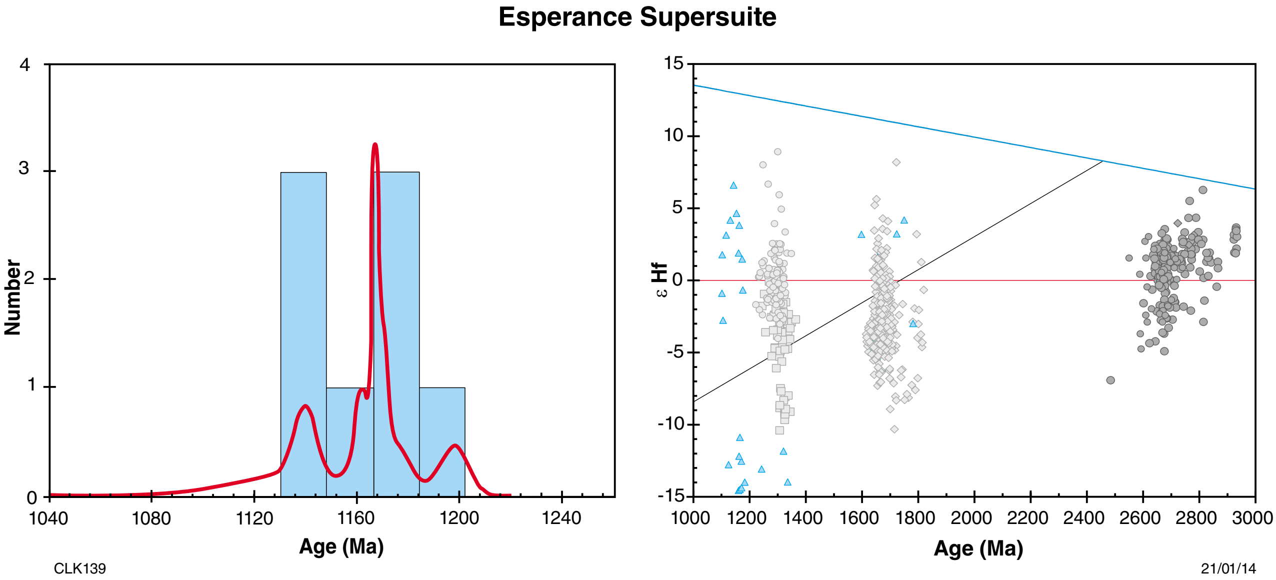

Figure 8. **Left: combined histogram/probability plot of $^{207}Pb^{*}/^{206}Pb^{*}$ crystallization ages of magmatic rocks in the Esperance Supersuite. Right: εHf evolution plot for the same data (coloured), other data from the Albany–Fraser Orogen in light grey, data from the Yilgarn Craton in dark grey. A reference evolution line corresponding to a $^{176}Lu/^{177}Hf$ ratio of 0.015 is shown in black.**

Hf signatures of the Biranup Zone

Biranup Zone magmas show a general trend towards more radiogenic values through time (Fig. 3), although there is significant complexity in this relationship (Kirkland et al., 2011a). There is a step towards more radiogenic values of up to εHf = +6 in magmatic zircons younger than 1700 Ma. The median εHf in zircons younger than 1700 Ma is -2.8 ± 3.0 (1 standard deviation [SD]), whereas in zircons older than 1700 Ma, the median εHf is -3.9 ± 3.0 (1 SD). The most evolved components of the Biranup Zone come from c. 1700 Ma zircons that lie on an andesitic crustal evolution line from the most radiogenic components of the Eastern Goldfields Superterrane of the Yilgarn Craton. The general Hf-isotope signature of the Southern Cross Domain of the Youanmi Terrane is too evolved to have been a source in the Biranup Zone. However, many of the radiogenic components in the Eastern Goldfields Superterrane are viable sources to explain the most evolved Biranup Zone magmas, assuming equilibrium melting of that source and evolution through a normal crustal reservoir. However, if the source was a more mafic residual hornblende- and garnet-bearing component, as indicated for at least some of the magmas by the strong decoupling between Nd and Hf systematics, then a steeper evolution line could explain even more of the isotopic array of the Biranup Zone magmas, with less necessity for significant mantle input. Evolution from an Archean residuum with a $^{176}Lu/^{177}Hf$ ratio of 0.036 is sufficient to evolve to the most radiogenic Biranup Zone Hf isotopic values. The isotopic features of the Biranup Zone indicate that it is not exotic to the margin of the Yilgarn Craton. Rather, it represents either a Paleoproterozoic back-arc or rift on the Yilgarn Craton, which distended and isolated Archean fragments within it (Kirkland et al., 2011a).

Hf signatures of the Arid and Barren Basins

The Hf-isotopic signatures of detritus within the Barren and Arid basins are discussed at length on a sample-by-sample basis in Spaggiari et al. (2014a). Detrital zircons in the Barren Basin have a median εHf of +1 and range from +6 to -18. Two-stage model ages reveal similarities with magmatic rocks of the Biranup Zone and Yilgarn Craton. Detrital zircons in the Arid Basin indicate a median εHf of 0 and range from +12 to -17. Two-stage model ages have similarities with model ages in the Biranup Zone, Yilgarn Craton, and include a 2.0 Ga model-age component (Fig. 9).

Hf signatures of the Fraser Zone and Recherche Supersuite

We consider the mafic to granitic magmatic rocks of the Fraser Zone (Fig. 4) and the Recherche Supersuite (Fig. 7) together, because they are all expressions of Stage I events in the Albany–Fraser Orogen. Five Recherche Supersuite samples yielded igneous zircons that preserve magmatic $^{176}Hf/^{177}Hf$ ratios. The Hf-isotopic compositions fall into two groups (Fig. 7). A radiogenic group comprises most samples and indicates εHf values of 0 to -6 (median εHf = -3.49 ± 1.81 (1SD)). The Hf-isotopic range of this material can be explained by reworking, through a typical crustal reservoir, of Biranup Zone material with moderately radiogenic isotopic compositions (e.g. -3 to + 3). One sample defines a distinctly more evolved signature with εHf values of -8 to -11 (median εHf = -8.93 ± 0.76 [1 SD]). This sample (GSWA 194786, preliminary data) is a metamonzogranite, from east of Boingaring Rocks, with

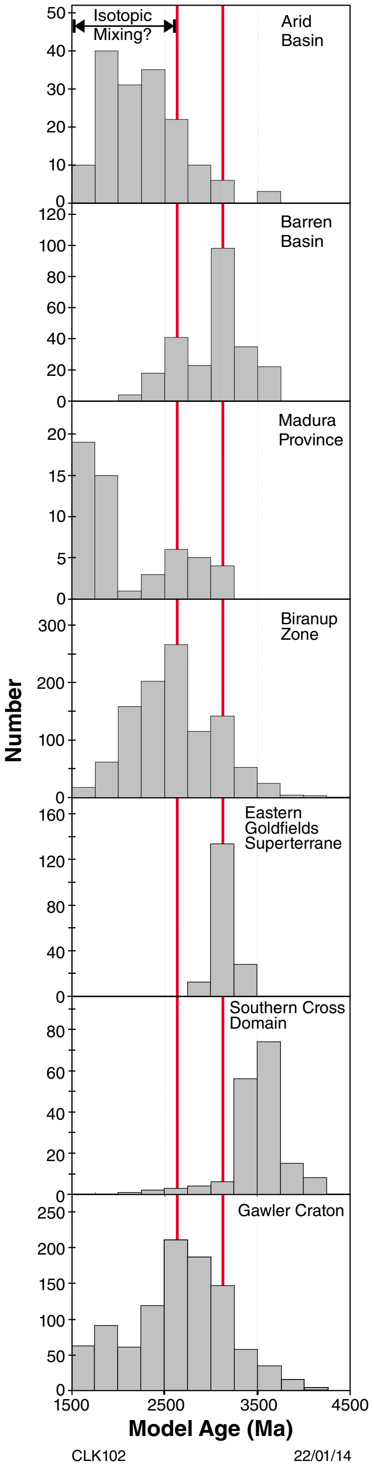

Figure 9. Stacked histograms of model ages from the Barren and Arid Basins in comparison to the Yilgarn Craton, Madura Province, and Gawler Craton. All data (excluding the Gawler Craton) is from <www.dmp.wa.gov.au/geochron/>

a zircon U–Pb crystallization age of 1320 ± 8 Ma. Its isotopic signature suggests greater incorporation of older crustal elements, potentially older Biranup Zone crust.

Ten samples of magmatic rocks in the Fraser Zone yielded igneous zircons that indicate εHf values of +9 to -4 (median εHf = -0.08 ± 2.15 [1SD]) (Fig. 4). The Hf-isotopic range of this material overlaps the more radiogenic members of the Recherche Supersuite granites, but unsurprisingly extends to more depleted values, consistent with the large volume of mafic rocks in the Fraser Zone. The Fraser Zone's isotopic pattern has been interpreted to reflect mantle input into a Biranup Zone source (Kirkland et al., 2011a). Juvenile Biranup Zone magmatic rocks have εHf values (recalculated at 1200 Ma) of c. -8, hence evolution through a normal crustal reservoir (e.g. ^{176}Lu/^{177}Hf = 0.015) could be consistent with the most unradiogenic components of the Fraser Zone directly reworking a Biranup Zone source, which is consistent with the limited inherited zircons in the Fraser Zone magmatic rocks having ages of 1770–1604 Ma.

Geochemical considerations led Smithies et al. (2013) to suggest that the Fraser Zone magmatic rocks were generated by a mantle melt underplated and intraplated at the base of the crust, where it assimilated a <10% component of crust or melt derived from that crust. Chemically, the most likely basement component was regarded as a combination of Archean granite and Munglinup Gneiss, with high La/Yb ratios resulting from extraction from garnet-bearing sources. This conclusion is essentially similar to that from Hf-isotopic and inherited zircon considerations which suggest a Biranup Zone source influenced by mantle melt, because the Biranup magmatic rocks contain a component of reworked Archean crust. In either case, these results indicate that the Yilgarn Craton or its reworked equivalents were present as basement when magmatic rocks of the Fraser Zone were emplaced. This has important implications for the interpretation of seismic line 12GA-AF3, which images Biranup Zone and the Udarra Seismic Province below the Fraser Zone (Plate 4), and indicates that this relationship is not solely due to subsequent thrusting or tectonic displacement (Spaggiari et al., 2014b).

Hf signatures of the Esperance Supersuite

Hf-isotope results are available for two samples of Esperance Supersuite granites (Fig. 8), although one of these (GSWA 194773, Kirkland et al., 2011f) is from the Forrest Zone of the Coompana Province, east of the Madura Province (Spaggiari et al., 2012, 2014c). Sample GSWA 194773, from ditch cuttings of a felsic rock at the bottom of the Alliance Petroleum Eucla No. 1 well, yielded a U–Pb zircon age of 1140 ± 8 Ma, interpreted as the magmatic crystallization age of the felsic protolith. This sample also indicated a median εHf value of +1.9 ± 2.8 (1 SD). In contrast, sample GSWA 182474 (Kirkland et al., 2012f), a granite vein from the Big Red prospect drillcore BRDDH001 (Plate 2), reflects pegmatite intrusion at 1167 ± 2 Ma, and has a considerably more evolved Hf-isotopic signature (median = -15 ± 2.5 [1 SD]). This sample also contains inherited material with ages and isotopic signatures similar to Biranup Zone material. Nd-isotope analyses from other samples of the Esperance Supersuite indicate compositions ($\varepsilon_{Nd\ (1200Ma)}$ = -7 to -5) more radiogenic than can be explained by reworking of Biranup Zone or Archean crust alone and suggests further addition of juvenile mantle material into the orogen. In contrast, GSWA 182474 likely reflects in situ melting of Barren Basin paragneiss.

The Tropicana Zone: a new component of the Kepa Kurl Booya Province

The preceding information has provided the necessary background on the various lithotectonic zones of the Albany–Fraser Orogen and adjacent Yilgarn Craton, to allow discussion of the newly defined Tropicana Zone (Occhipinti et al., 2014), and to evaluate its relationship to the other elements of the orogen. Within the Tropicana Zone, an exploration prospect (Neale Project) has reported up to 23.9 grams per ton Au from rotary core drilling (Watkins, 2012). However, it is not clear if this gold represents the same mineralization as the c. 2500 Ma event at Tropicana (Blenkinsop and Doyle, 2014; Doyle et al., 2014). The tectonic setting for the mineralization event that affected Archean host rocks within the Tropicana Zone is unknown, and the gold could be late Archean, reworked Archean, or Proterozoic.

A suite of drillcore samples from the Hercules Gneiss (Neale Project) within the Tropicana Zone has been investigated to shed light on the mineralization, composition, and evolution of this zone. In the Yilgarn Craton, a class of rare low-Si granites has been referred to as 'mafic granites', and includes a LILE-enriched group of sanukitoids emplaced around 2655 Ma (Champion and Sheraton, 1997). A comparison of the dioritic rocks of the Hercules Gneiss with sanukitoids from the Yilgarn Craton, as well as from other Archean cratons, shows that the Hercules Gneiss has chemical compositions comparable to sanukitoid magmas. Together with the distinctive compositions of sanukitoids, the rarity of these rocks within any Archean craton suggests that the granitic protoliths of the Neale Project area represent a single suite of rocks intruded during a single event.

All samples of the Hercules Gneiss contain a component of near-spherical and/or multifaceted zircons consistent with formation during high-pressure metamorphism. There is considerable debate about the interpretation of U–Pb zircon dates from granulite-facies meta-igneous rocks, reflecting the wide variety of growth and/or alteration processes which may have affected zircons in such rocks. Nonetheless, initiation of granulite-facies metamorphism appears to have been essentially coeval with magmatic crystallization in these sanukitoids. Estimates of the original magmatic crystallization ages of these rocks are hindered by the intense neocrystallization and reworking of zircon during granulite-facies metamorphism. However, all gneisses may have had a magmatic crystallization age of c. 2700 Ma, shortly preceding granulite-facies zircon growth. The best estimate of the age of magmatic crystallization could be reflected in the youngest oscillatory zoned zircon cores, which have textural characteristics of zircons grown within a viscous silicate melt, and which have not been affected by radiogenic-Pb loss. Following this criteria, the date of 2692 ± 16 Ma for zircon cores in sample GSWA 192523 (preliminary data) is the best estimate for the timing of sanukitoid magmatism (Fig. 10).

The age of magmatic protolith components in the Hercules Gneiss is similar to those of many intrusive events within the Yilgarn Craton, although the Burtville Terrane and Southern Cross Domain are the most similar. However, the estimate of c. 2692 Ma for sanukitoid magmatism is distinct from the ages of compositionally similar magmatic rocks elsewhere in the Yilgarn Craton, i.e. 2.76 Ga in the western Yilgarn, and 2.65 Ga in the eastern Yilgarn. Furthermore, prolonged granulite-facies zircon growth at 2718–2554 Ma in the Hercules Gneiss (Fig. 10) is dissimilar to the timing of high-grade events in the rest of the Yilgarn Craton, although its initiation may match some granulite-facies events in the Eastern Goldfields Superterrane (Goscombe et al., 2009). This could indicate that the Tropicana Zone reflects a deeper crustal level, or an unknown component of the Yilgarn Craton, or both. This could be explained by the presence of the Plumridge Detachment, along which the Tropicana Zone has been thrust to the northwest (Plate 4; Occhipinti et al., 2014). The gneissic fabric in the Hercules Gneiss is cut by microgranite veins dated at 1783 ± 3 Ma (GSWA 192550, Kirkland et al., 2014). This indicates that thrusting of the Tropicana Zone onto the Yilgarn Craton was before 1783 Ma, given that similar magmatic events are known from the (para)autochthonous Biranup Zone. The 1783 Ma date is similar to that of the nearby McKay Creek Metasyenogranite dated at 1761 ± 10 Ma (GSWA 182424, Kirkland et al., 2012e), and also to magmatic and volcanic rocks of the Voodoo Child Formation (Plate 1; Occhipinti et al., 2014).

Re–Os analyses of pyrite suggest that gold mineralization occurred at c. 2.1 Ga. Gold and pyrite growth occurred during late alteration processes and brittle fracturing of the sanukitoid host rock. A mineralization event at c. 2.1 Ga does not obviously correlate with major Proterozoic tectonothermal events known elsewhere in the Albany–Fraser Orogen, but may reflect low-grade upgrading of an Archean source. Gold was mobilized prior to the major Proterozoic magmatic and metamorphic events, including the Biranup Orogeny and Stages I and II of the Albany–Fraser Orogeny. Given that sanukitoid magmas are well known for gold fertility, we suggest that they may have been the primary source of gold in the Neale Project area, which was subsequently remobilized and concentrated at c. 2.1 Ga into brittle structures associated with pyrite, quartz, biotite, muscovite, actinolite, clinozoisite–epidote, and chlorite.

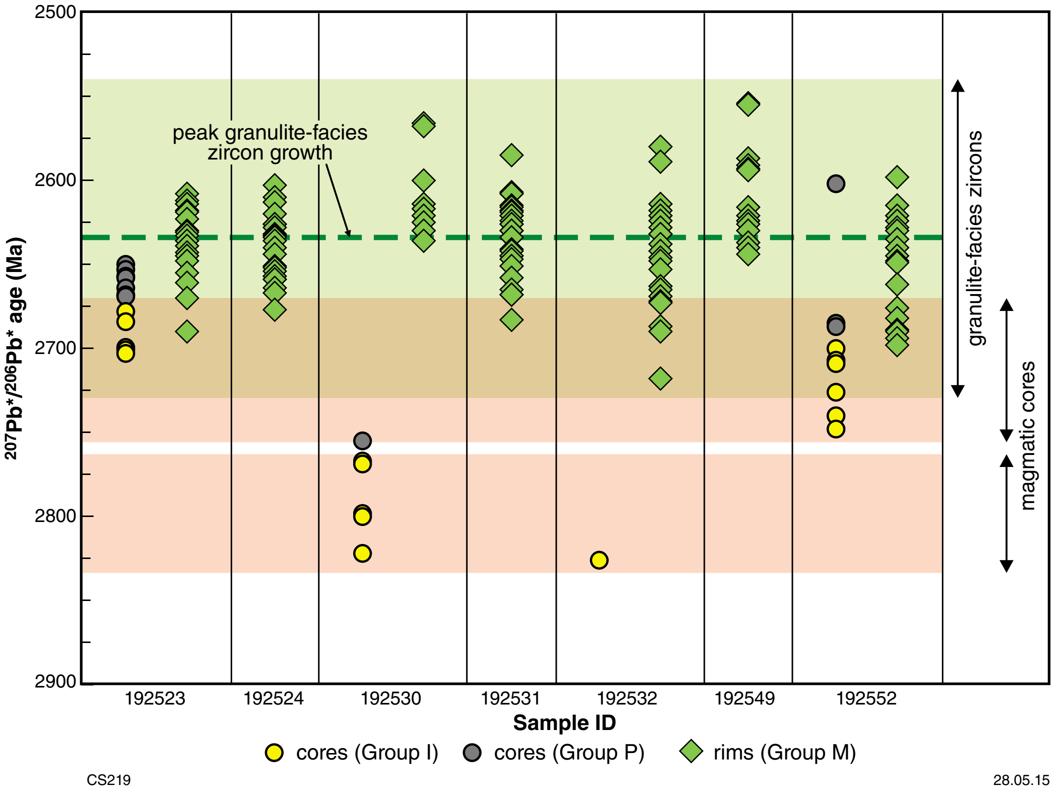

Figure 10. Sample versus age plot illustrating the prolonged granulite-facies zircon growth event within the Hercules Gneiss and the best age estimate for the protolith (sanukitoid magma) estimated to be 2692 ± 16 Ma, based on GSWA 192523 (preliminary data)

Conclusions

U–Pb zircon geochronology, integrated with Lu–Hf isotope measurements on the same dated zircons, has led to new understanding of the evolution of the major components of the Albany–Fraser Orogen:

Northern Foreland

- Crystallization ages of magmatic protoliths are 2722–2619 Ma
- Hf-isotopic signatures are similar to those of Yilgarn Craton rocks
- represents a reworked component of the Yilgarn Craton margin.

Biranup Zone

- Crystallization ages of magmatic protoliths are 1806–1627 Ma
- Hf-isotopic signatures are consistent with juvenile input into an Archean Yilgarn craton source
- numerous distinct magmatic events, including the Biranup Orogeny and prolific Stage II mineral growth
- represents a (para)autochthonous unit.

Fraser Zone

- Crystallization ages of magmatic protoliths are 1310–1283 Ma
- Hf-isotopic signatures are consistent with juvenile input into a Biranup Zone source or a reworked Archean source. Inherited zircons in magmatic rocks are consistent with the former interpretation
- high-grade metamorphism was driven by magmatism
- represents an uplifted (para)autochthonous lower-crustal hot zone.

Barren Basin

- Deposition occurred before c. 1800 Ma, before c. 1700 Ma, and between 1710 and 1600 Ma
- age and Hf-isotopic signatures indicate sediments were derived from the Yilgarn Craton and Biranup Zone.

Arid Basin

- Deposition occurred after the Biranup Orogeny and (just) prior to Stage I events
- detrital zircons were derived from the Biranup Zone, Yilgarn Craton, Loongana Arc, and possibly unknown sources.

Recherche Supersuite

- Crystallization ages of magmatic protoliths are 1330–1283 Ma
- represents the magmatic expression of Stage I of the Albany–Fraser Orogeny
- Hf-isotope signatures are consistent with reworking of a Biranup Zone source.

Esperance Supersuite

- Crystallization ages of magmatic protoliths are 1198–1135 Ma
- represents in situ melting of a range of sources from within the orogen and new radiogenic (mantle) addition into Biranup Zone crust, during Stage II of the Albany–Fraser Orogeny.

Tropicana Zone

- Crystallization age of magmatic (sanukitoid) protoliths estimated to be 2692 ± 16 Ma, but interpretation is hampered by intense granulite-facies overprinting
- the age of 2692 Ma is different to compositionally similar magmatism found elsewhere within the Yilgarn Craton
- prolonged granulite-facies metamorphic zircon growth at 2718–2554 Ma is not similar to the timing of high-grade events in the rest of the Yilgarn Craton
- may represent a deeper crustal level or a different part of the Yilgarn Craton, or both, consistent with the suggestion that it is a piece of the Yilgarn Craton not seen elsewhere, thrust onto the craton margin
- the Tropicana Zone was attached to the craton before c. 1780 Ma, based on 1780 Ma granite veins in the Tropicana Zone and the age of similar magmatism in the (para)autochthonous Biranup Zone
- Re–Os dating of pyrite suggests an age of c. 2.1 Ga for associated gold mineralization; this age is distinct from those of major Proterozoic tectonothermal events elsewhere in the Albany–Fraser Orogen
- sanukitoid magmas may have been the source of gold in the Tropicana Zone.

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