Exposing the Eucla basement: what separates the Albany–Fraser Orogen and the Gawler Craton?

by

CV Spaggiari, RH Smithies, MTD Wingate, CL Kirkland[1], and RN England[2]

The Eucla basement of southern Western Australia and South Australia represents a vast area of Precambrian crust entirely covered by younger basins forming one of the world's largest karst plains — the Nullarbor Plain. An understanding of the age, character, and evolution of this Precambrian crust is fundamental to geodynamic models of the amalgamation of the West (WAC) and South Australian Cratons (SAC), but our ability to test such models has been hampered due to a lack of information. The Eucla basement stratigraphic drilling program, funded through the Exploration Incentive Scheme (EIS), was established to address this knowledge gap and provide critical information to assist in the determination of regional mineral prospectivity, by providing high-quality diamond drillcores from the Madura Province and the Western Australian component of the Coompana Province (Fig. 1), which separate the Albany–Fraser Orogen (WAC) from the Gawler Craton (SAC). This abstract provides a synthesis of the first results and interpretations that were presented at a workshop in Perth in September 2015 (Spaggiari and Smithies, 2015).

Regional setting

The eastern edge of the Albany–Fraser Orogen is marked by the Rodona Shear Zone — a broad network of shear zones with a dominant, moderate-to-steep easterly dip (Spaggiari et al., 2014a). Kinematic indicators interpreted from aeromagnetic data suggest craton-vergent thrusting followed by sinistral strike-slip movement. This major shear zone is interpreted as a suture zone between an accreted oceanic island arc and associated rocks (Madura Province) and the Paleo- to Mesoproterozoic Albany–Fraser Orogen, which represents reworked Archean Yilgarn Craton crust (Spaggiari et al., 2015; Kirkland et al., 2015; Smithies et al., 2015). To the east, the Madura Province is truncated by the Mundrabilla Shear Zone — a wide, distinctly straight, north-trending, subvertical shear zone with well-defined sinistral kinematics (Fig. 1).

Not much is known about the Coompana Province, which is defined as the Precambrian basement east of the Mundrabilla Shear Zone and west of the west-dipping Jindargna Shear Zone, along which the eastern edge of the Coompana Province lies structurally above the western edge of the Gawler Craton in South Australia (Dutch et al., 2015). The western component of the Coompana Province is loosely defined as the Forrest Zone (Fig. 1).

Both the Madura and Coompana Provinces are extensively intruded by ferrogabbroic to granitic rocks of the 1192–1125 Ma Moodini Supersuite. This supersuite is similar in composition and age to the Pitjantjatjara Supersuite of the Musgrave Province and the Esperance Supersuite of the Albany–Fraser Orogen — with the latter supersuite additionally preserving an isotopic and geochemical heritage of reworked Archean crust of the Yilgarn Craton.

Madura Province

Prior to the Geological Survey of Western Australia (GSWA) stratigraphic drilling program, a total of 10 diamond cores existed in the Madura Province, drilled as exploration targets into either magnetic or gravity highs, or both. In contrast, the three new stratigraphic holes are located over regional magnetic and gravity domains to aid in regional interpretation of the basement geology (Fig. 1). Our current understanding of the evolution of the Madura Province and its prospectivity is summarized below. Of note is the existence of a large tract (>65 000 km^2, which includes widespread intrusions of the younger Moodini Supersuite) of oceanic and oceanic-arc crust of variable age and character, the non-reworked components of which are considered to be a well-preserved Proterozoic ophiolite. The western edge of this ophiolite was accreted to the passive continental margin of the Albany–Fraser Orogen (WAC) by c. 1330 Ma.

Geochemical and isotopic data from the Madura Province, and also from the Forrest Zone of the Coompana Province, point to a common, extensive, juvenile crustal basement (Fig. 2). A primitive zircon Hf isotope array, anchored at depleted-mantle-like compositions at 2.0 – 1.9 Ga, is interpreted to reflect a complex mix of new and progressively reworked oceanic-plate magmatic rocks, which also form the basement to the Musgrave Province (Kirkland et al., 2015). This array contrasts markedly with isotope arrays that reflect the evolution of the WAC and the SAC.

1 Centre for Exploration Targeting, Curtin Node, Department of Applied Geology, Curtin University, Bentley WA 6845

2 Petrology Services, Duncraig,WA 6023

E-MORB basalts, adakites, and the Loongana Arc

Metabasalt from drillcores MAD002 (the Pinto Basalt, named after Pinto Bore) and NSD (EIS co-funded core drilled by Teck Australia) have E-MORB/OIB signatures and are interpreted to record the formation of proto-oceanic crust in the Madura Province associated with lithospheric extension on the southeastern WAC continent edge. This extension is constrained to have occurred between c. 1950 and 1450 Ma, but probably between c. 1600 and 1500 Ma, during formation of an ocean–continent transition (OCT; Spaggiari et al., 2015). High Ti/Yb ratios in the most primitive basalts from MAD002 suggest melting of a deep (>2.8 GPa = >100 km) garnet-bearing mantle source and associated asthenospheric upwelling.

The MAD002 drillcore comprises two main units: 1) fine-grained, variably coloured, distinctly laminated to layered, schistose metabasalt (Pinto Basalt), and 2) medium-grained, generally pale grey to white, thin leucogranite veins (metamorphosed plagiogranite). Distinct layering in the metabasalt comprises assemblages of blue-green hornblende–plagioclase–titanite, typically with variable quantities of epidote, biotite, and quartz, and locally with ilmenite, rutile, and magnetite. The basalt schist is interpreted as lower amphibolite facies, with very minor indication of retrogression. Variably pyritized pyrrhotite and chalcopyrite are disseminated in the metabasalt, and stringers include pyrite, chalcopyrite and magnetite, with up to 2146 ppm Cu (GSWA 206770, 458.29 – 458.46 m). The plagiogranite is composed of plagioclase–quartz–biotite, locally with hornblende and magnetite, and minor chlorite and sulfides, and intrudes the metabasalt. It has an emplacement age of 1389 ± 7 Ma, and has the composition of adakite.

Steeply northeasterly to vertically plunging, tight chevron and typically Z- or S-folds are observed in both the metabasalt and the plagiogranite (adakite). These folds are interpreted as part of a regional-scale, open, west-northwest trending F_2 fold. Small-scale refolded folds imply an earlier phase of F_1 folding, consistent with interpretations of aeromagnetic data. Thin plagiogranite veins transgress the folds, which suggests the plagiogranite intruded either pre- or syn-folding, or both, with late injections or remobilization of the felsic material as the folds formed.

The adakitic plagiogranite in MAD002 is part of the 1415–1389 Ma Haig Cave Supersuite, which comprises a series of medium-grained, gabbroic cumulate rocks, locally with peridotitic cumulate, intruded by trondhjemitic plagiogranite. The Haig Cave Supersuite is found in drillcores from the Loongana, Haig, and Serpent prospects, and is interpreted as the accreted portion of an oceanic island arc (Loongana Arc; Spaggiari et al., 2015). The adakitic plagiogranite is interpreted to have originated as a partial melt of subducting oceanic lithosphere, but geochemistry and Nd-isotope data indicate this was not related to the E-MORB/OIB basaltic crust it intrudes. The present position and structural relationship of MAD002, west of the Loongana Arc, suggests that the adakitic plagiogranite intruded the Pinto Basalt close to, or within, the fore-arc. The MAD002 adakitic plagiogranite is interpreted to have been emplaced at a high crustal level, most likely during folding and lower amphibolite facies metamorphism, but was sourced from melting at much greater depths of around 52 km.

N-MORB basalts and the Loongana Arc

Basalts from the MAD011 drillcore, the Burkin prospect, and from outcrops at Point Malcolm, have weakly enriched N-MORB-like compositions interpreted as having been derived from a weakly subduction-enriched back- or fore-arc mantle source most likely associated with the Loongana Arc. In drillcore MAD011 the basalt occurs as rafts and xenoliths in c. 1140 Ma medium- to coarse-grained monzogabbro that is compositionally and isotopically unrelated (i.e. not co-genetic).

Prospectivity

The E-MORB/OIB basaltic crust and potential associated sedimentary rocks are considered prospective for VMS-style mineralization or exhalative deposits. The disseminated sulfide minerals (variably pyritized pyrrhotite and chalcopyrite) and high Cu values in the MAD002 metabasalt support this inference. N-MORB basalt from the Burkin prospect is associated with metasedimentary rocks that contain fine-grained layers of plagioclase–chlorite–hornblende–epidote and magnetite, and are interpreted to be metamorphosed mafic sedimentary or volcano-sedimentary rocks. The magnetite layers contain up to 8.6 wt% MnO, and previous geochemical data identified several horizons of anomalous copper (up to ~1000 ppm; Harley, 2010). These features indicate the potential for exhalative or VMS-style deposits, perhaps in a fore-arc setting during the early stages of formation of the c. 1400 Ma Loongana Arc. This arc may also be prospective for subduction-related mineralization, including platinum group elements (PGE) and nickel.

Forrest Zone, Coompana Province

The GSWA EIS stratigraphic drilling program provided the first diamond drillcores from the Forrest Zone (Fig. 1). Here we summarize our current understanding of the evolution and prospectivity of the Forrest Zone.

Toolgana Supersuite

The oldest rocks identified so far in the Coompana Province are granitic to dioritic gneisses of the c. 1610 Ma Toolgana Supersuite from the Forrest Zone (Fig. 2). These rocks are magnesian, calc-alkalic, high-K intrusions interpreted to have been derived from a subduction-modified (enriched) mantle source, compatible with a primitive arc setting. The gneisses occur in drillcores FOR008 and FOR004, in the southeastern portion of the Forrest Zone, with possible remnants in the northwest in drillcores FOR011 and FOR010 (Fig. 1). Although located a considerable distance away, the c. 1610 Ma Toolgana Supersuite has similar geochemical characteristics and age as rocks of the St Peter Suite of the Nuyts Domain in the Gawler Craton, which are interpreted as juvenile, magmatic arc-related intrusions (Swain et al., 2008).

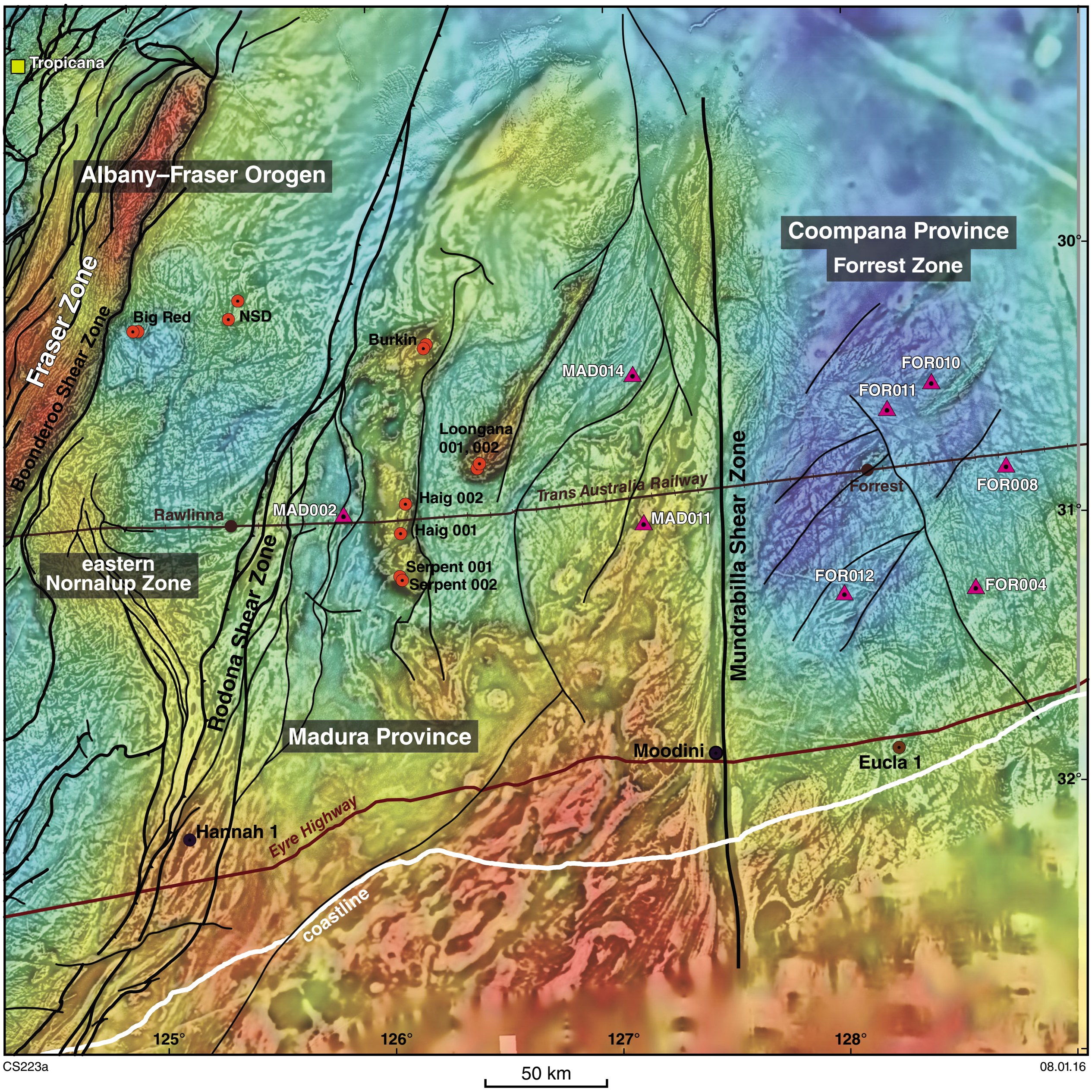
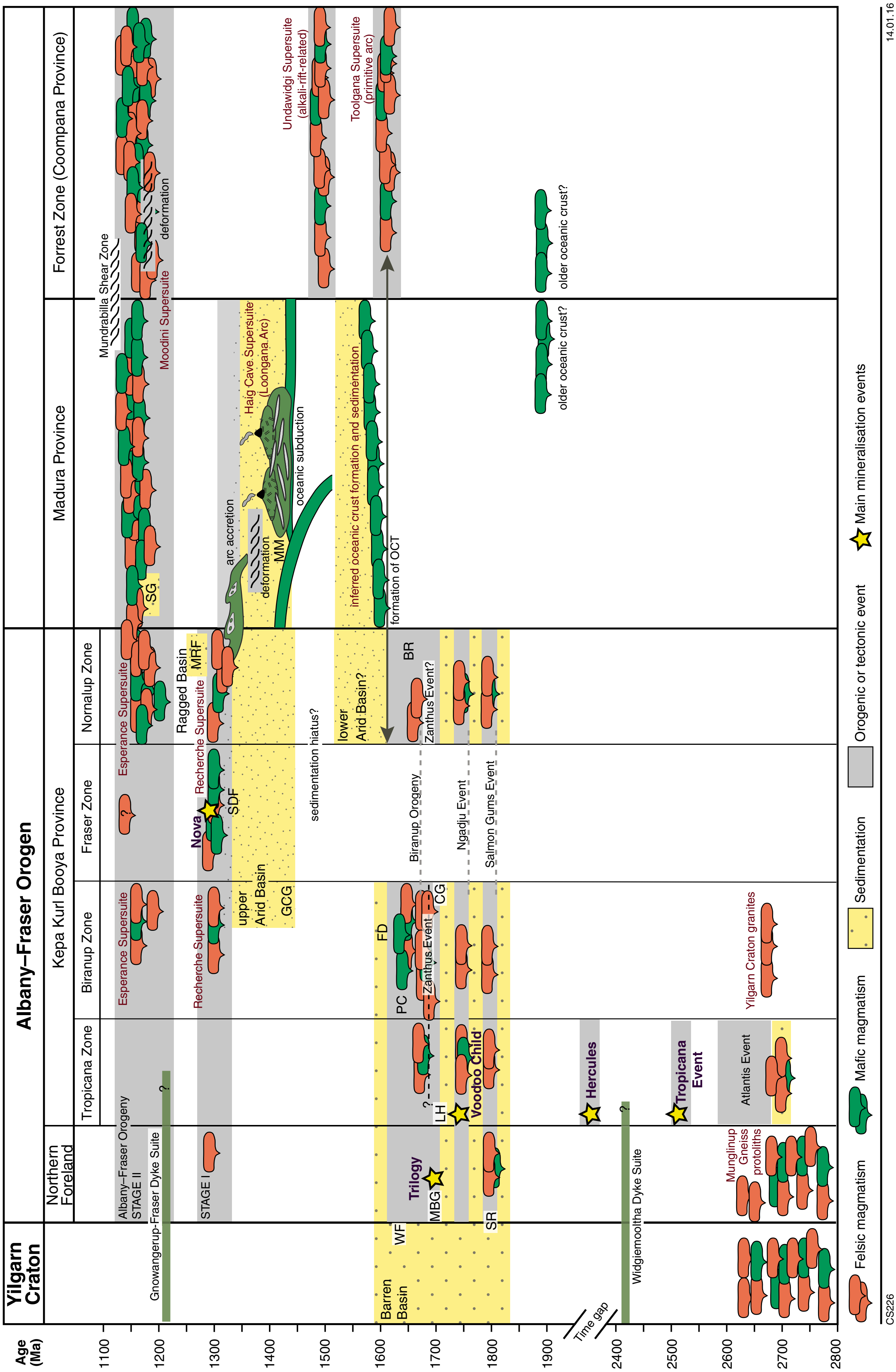


Figure 1. Simplified structures and drillsite locations plotted on a drape image of gravity (colour) and reduced-to-pole, first vertical derivative aeromagnetic data (greyscale). The stratigraphic drillsites are shown with pink triangles, EIS co-funded drillsites with orange dots, donated core sites with purple dots, and the Eucla 1 petroleum well with a brown dot.

Figure 2. (opposite) Time–space diagram of the Albany–Fraser Orogen, Madura Province and Forrest Zone. Abbreviations used: BR – Big Red paragneiss; CG – Coramup Gneiss; FD – Fly Dam Formation; GCG – Gwynne Creek Gneiss; LH – Lindsay Hill Formation; MM – Malcolm Metamorphics; MBG – Mount Barren Group; MRF – Mount Ragged Formation; PC – Ponton Creek Gneiss; SG – Salisbury Gneiss; SDF – Snowys Dam Formation; SR – Stirling Range Formation; WF – Woodline Formation. Modified from Spaggiari et al. (2014b).


Age (Ma)
Yilgarn Craton
Albany–Fraser Orogen
Northern Foreland
Kepa Kurl Booya Province
Tropicana Zone
Biranup Zone
Fraser Zone
Nornalup Zone
Madura Province
Forrest Zone (Coompana Province)
Barren Basin
WF
Gnowangerup-Fraser Dyke Suite
Albany–Fraser Orogeny STAGE II
STAGE I
Trilogy
MBG
SR
Munglinup Gneiss protoliths
Widgiemooltha Dyke Suite
Time gap
Hercules
Tropicana Event
Atlantis Event
LH
Voodoo Child
Esperance Supersuite
Recherche Supersuite
upper Arid Basin
GCG
PC
FD
Zanthus Event
CG
Yilgarn Craton granites
Nova
SDF
Biranup Orogeny
Ngadju Event
Salmon Gums Event
sedimentation hiatus?
Ragged Basin
MRF
lower Arid Basin?
BR
Zanthus Event?
SG
arc accretion
deformation
MM
oceanic subduction
Haig Cave Supersuite (Loongana Arc)
inferred oceanic crust formation and sedimentation
formation of OCT
Moodini Supersuite
Mundrabilla Shear Zone
older oceanic crust?
Undawidgi Supersuite (alkali-rift-related)
Toolgana Supersuite (primitive arc)
Felsic magmatism
Mafic magmatism
Sedimentation
Orogenic or tectonic event
Main mineralisation events
CS226
14.01.16

Granitic gneisses in FOR008 have a well-developed gneissosity that has a dominantly shallow dip, and is locally folded into flat-lying, small-scale folds. Kinematic and folding relationships indicate a history of top- to-the-west or northwest transport (prior to or during migmatization), localized folding and probable thickening, closely followed by partial melting at c. 1150 Ma. The gneissic foliation in the upper part of FOR004 generally dips west to southwest, which suggests that these gneisses occur within a large, gently west-plunging fold nose. This is consistent with the presence of gently inclined folds with gentle plunges, mostly around 20º towards 280. In the lower part of the core, mesocratic rocks contain small-scale refolded folds, with second generation (F_2) west-plunging folds similar to those described above.

Both cores contain minor amounts of sulfides and some Cu (up to 1154 ppm Cu in FOR008 in altered gneiss). FOR008 has zones of chlorite–epidote–hematite greenschist facies alteration, chalcopyrite veinlets, stockwork veins and carbonate veins. FOR004 locally shows retrograde alteration with biotite altered to chlorite and locally sericite, plagioclase overgrown by sericite, and sparse chalcopyrite. Thin chlorite–epidote–quartz veins cut the foliation.

Undawidgi Supersuite

The c. 1490 Ma Undawidgi Supersuite occurs in the northwestern part of the Forrest Zone, in drillcores FOR012, FOR011 and FOR010 (Fig. 1). The Undawidgi Supersuite includes metamorphosed syenogranite, monzogranite, tonalite, monzodiorite, syenite, mafic schist and probable felsic volcanic rocks. In FOR012 the upper part of the core comprises mylonitic to ultramylonitic, fine- to medium-grained metagranite and the lower part comprises intensely foliated to mylonitic, fine-grained, upper greenschist facies, grey to dark grey felsic schist, interpreted as a metarhyolite. This felsic schist contains minor disseminated pyrite and chalcopyrite, with up to 1172 ppm Cu (GSWA 206795). Structural observations in FOR012 indicate large-scale, gently inclined to subhorizontal folding with an upper limb dipping predominantly to the northwest (upper part of the core), a lower limb dipping to the southeast, and a fold closure to the northwest. This geometry may be indicative of the overall shape of a northeasterly trending wedge that is visible in aeromagnetic data.

The Undawidgi Supersuite is interpreted to have formed in a rift setting through partial melting of lower mafic crust with the introduction of a mantle component. The supersuite is temporally, geochemically and isotopically comparable to c. 1500 Ma granodiorite gneiss in the Mallabie 1 drillcore from southwestern South Australia (Wade et al., 2007), and its geochemistry suggests recycling of c. 1610 Ma arc crust of the Toolgana Supersuite. This event could be interpreted as widespread, c. 1500 to 1488 Ma lithospheric extension of the oceanic basement, including extension of the c. 1610 Ma subduction-related magmatic arcs (Toolgana Supersuite, and possibly the St Peter Suite), to produce a suite of high-K, rift-related intrusions and volcanic rocks.

The presence of Cu in these rocks (up to 1172 ppm in FOR012; GSWA 206795), and significant alteration including chlorite–epidote–sericite, could indicate a potential for VMS deposits. These alkali-rich, magnetite-bearing, and probable high-level intrusive or volcanic rocks that formed from melting of alkali-metasomatized, subduction-related mafic crust also indicate a potential for IOCG-type mineralization in the region. The presence in drillcore FOR011 of syenites, most likely of c. 1488 Ma crystallization age, with near peralkaline compositions, also suggests the possibility for Nb, Ta, REE mineralization in rift-related alkaline magmatic settings.

Metagranitic rocks in drillcore FOR011 exhibit subparallel layering and a well-developed foliation folded into gently northeasterly plunging folds. Similar relationships are observed in drillcore FOR010, with a calculated fold axis of 20° to 061. The metagranitic rocks in FOR010 are intruded by c. 1175 Ma hornblende–biotite metagranite (Bottle Corner Shoshonite), which shows similar structural features. However, the presence of crosscutting veins of Bottle Corner Shoshonite suggest that the deformation took place during pulses of shoshonite intrusion (recorded in both FOR010 and FOR011).

Spatially, there appears to be a division between the dominance of c. 1490 Ma Undawidgi Supersuite to the northwest, and c. 1610 Ma Toolgana Supersuite to the southeast, possibly separated by a major, northeasterly trending shear zone between the mylonitic rocks in FOR012, which are interpreted as part of a large wedge-shaped fold closing to the northwest, and the subhorizontally folded granite gneiss in FOR008. Although speculative, the structure could be an inverted, c. 1500 Ma rift-related feature that extended arc rocks of the Toolgana Supersuite.

The Maralinga Event and formation of the high-KFe and high-KMg (shoshonite) series Moodini Supersuite

The 1200–1120 Ma Maralinga Event is predominantly characterized by the emplacement of the voluminous magmas of the Moodini Supersuite. These include the high-temperature, high-KFe series of mafic to A-type felsic intrusions that form a voluminous component of the Madura Province, and the high-KMg series intrusions of the Bottle Corner Shoshonite, which appear to be restricted to the Forrest Zone of the Coompana Province.

In the Madura Province, the high-KFe series of the Moodini Supersuite occurs in drillcores MAD011 (ferro-monzogabbro; Kestral Cavern Gabbro), MAD014 (high-Th granodiorite to monzogranite), and the Moodini prospect (Fig. 1). The Moodini Supersuite appears to be particularly voluminous in the southeastern part of the province, where it forms high-intensity magnetic and strong gravity anomalies that are drawn into the Mundrabilla Shear Zone with sinistral shear sense. In the southeastern part of the Forrest Zone, the Moodini Supersuite is interpreted as a series of northeasterly trending plutons of high magnetic intensity, intersected by the Eucla 1 petroleum well (Fig. 1).

The high-KMg series intrusions of the Bottle Corner Shoshonite occur in the northwestern part of the Forrest Zone in drillcores FOR010 and FOR011. Here, both primitive, mafic shoshonite and high silica derivatives form intrusions that make up to 25% of the crust sampled in these cores. Their compositions reflect deep melting of wet, oxidized, subduction-modified mantle lithosphere and so their presence indicates that the Forrest Zone retained a thick lithosphere typical of accreted arc terrains prior to and during the Maralinga Event. This contrasts strongly with the Madura Province (and Musgrave Province), where crustal melting components and asthenospheric mantle additions strongly suggest highly extended, dry and reduced crust with little or no remaining lithosphere. Importantly, the Bottle Corner Shoshonite shows many of the compositional attributes considered indicative of magmas potentially prospective for Cu and Cu–Au mineralization, including high Sr/Y and evidence for extensive amphibole fractionation.

High-KFe series magmas synchronous with, and compositionally equivalent to, those of the Maralinga Event were also produced in the contiguous regions of the Albany–Fraser Orogen (Esperance Supersuite) and the Musgrave Province (Pitjantjatjara Supersuite) during Stage II of the Albany–Fraser Orogeny (1225–1140 Ma) and the Musgrave Orogeny (1220–1150 Ma), respectively. Together, these define a geographically continuous northeast-trending belt of geochemically specialized magmas at least 1500 km long and up to 500 km wide. These magmas reflect hybridization of asthenospheric melts by lower crustal material that partially melted at low pressures and at temperatures up to 1000ºC. This high-KFe magmatic belt defines the massive regional extent of crust that remained relatively thin and isotopically much less evolved compared to the neighbouring cratonic regions (WAC and SAC) and to the reworked arc terrains of the Forrest Zone of the Coompana Province. Thus, the Maralinga Event can be interpreted to relate to melting of old oceanic crust that was previously not substantially modified during convergence of the WAC and the SAC. In fact, it appears that at least in southern and western parts of central Australia, the WAC and SAC never actually collided. Instead, the two cratons remain separated by the Madura and Coompana Provinces, representing the variably reworked remnants of the oceanic crust that separated them.

References

Dutch, RA, Doublier, MP, Pawley, MJ, Wise, TW, Reid, AJ, Clark, D, Kennett, BLN, Fraser, G, Thiel, S and Van der Weilen, S 2015, Geological and geodynamic implications of the western Gawler Craton section of seismic line 13GA-EG1, *in* What lies beneath the Western Gawler Craton? 13GA-EG1 Seismic and Magnetotelluric Workshop 2015 *compiled by* RA Dutch, MJ Pawley and TW Wise: Report Book 2015/00029, Department of State Development, South Australia, Adelaide, p. 59–80.

Harley, DN 2010, Terminal Report, Burkin Project, Western Australia, EL 69/1972, a085906 Part a, Gunson Resources, 4p.

Kirkland, CL, Smithies, RH and Spaggiari, CV 2015, Foreign contemporaries – Uravelling disparate isotopic signatures from Mesoproterozoic Central and Western Australia: Precambrian Research special issue, v. 265, p. 218–231.

Smithies, RH, Spaggiari, CV and Kirkland, CL 2015, Building the crust of the Albany–Fraser Orogen; constraints from granite geochemistry: Geological Survey of Western Australia, Report 150, 49p.

Spaggiari, CV, Kirkland, CL, Smithies, RH, Wingate, MTD, and Belousova, EA 2015, Transformation of an Archean craton margin during Proterozoic basin formation and magmatism: The Albany–Fraser Orogen, Western Australia: Precambrian Research, v. 266, p. 440–466.

Spaggiari, CV, Occhipinti, SA, Korsch, RJ, Doublier, MP, Clark, DJ, Dentith, MC, Gessner, K, Doyle, MG, Tyler, IM, Kennett, BLN, Costelloe, RD, Fomin, T and Holzschuh, J 2014a, Interpretation of Albany–Fraser seismic lines 12GA-AF1, 12GA-AF2 and 12GA-AF3: implications for crustal architecture, *in* Albany-Fraser Orogen seismic and magnetotelluric (MT) workshop 2014: extended abstracts *compiled by* CV Spaggiari and IM Tyler, Geological Survey of Western Australia, Record 2014/6, p. 28–51.

Spaggiari, CV, Kirkland, CL, Smithies, RH, Occhipinti, SA and Wingate, MTD 2014b, Geological framework of the Albany–Fraser Orogen, *in* Albany–Fraser Orogen seismic and magnetotelluric (MT) workshop 2014: extended abstracts *compiled by* CV Spaggiari and IM Tyler: Geological Survey of Western Australia, Record 2014/6, p. 12–27.

Spaggiari, CV and Smithies, RH (compilers) 2015, Eucla basement stratigraphic drilling results release workshop: extended abstracts: Geological Survey of Western Australia, Record 2015/10, 70p.

Swain, G, Barovich, K, Hand, M, Ferris, G and Schwartz, M 2008, Petrogenesis of the St Peter Suite, southern Australia: Arc magmatism and Proterozoic crustal growth of the South Australian Craton: Precambrian Research, v. 166, p. 283–296.

Wade, BP, Payne, JL, Hand, M and Barovich, KM 2007, Petrogenesis of ca 1.50 Ga granitic gneiss of the Coompana Block: filling the ‘magmatic gap’ of Mesoproterozoic Australia: Australian Journal of Earth Sciences, v. 54, p. 1089–1102.