Tectonic Evolution and Continental Fragmentation of the Southern West Australian Margin

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Abstract

Continental rocks dredged in 2011 show that the Batavia Knoll and Gulden Draak Knoll, two prominent bathymetric features located ~1600 km offshore Perth, are micro-continents. Plate tectonic modeling reconstructs the pre-rift position of these knolls to the north and south of the Naturaliste Plateau, respectively. The Batavia Knoll was conjugate to part of the northern Naturaliste Plateau, while the Gulden Draak Knoll was conjugate to the western Bruce Rise, Antarctica. Here, we compare basement rocks, patterns of sedimentation, volcanism and structure on the better studied Naturaliste Plateau, Mentelle Basin and Bruce Rise with newly collected data from the knolls. Significant volumes of metamorphic and granitic basement rocks were dredged from both the Batavia and Gulden Draak knolls. Preliminary geochronological and geochemical analyses show that these rocks are continental in nature and include protolith granitoids that were emplaced during the Archaean (~2850 Ma) and the Mesoproterozoic (~1290–1200 Ma) (Gulden Draak Knoll), and during the Early Palaeozoic (~540–530 Ma) (Batavia Knoll). All metamorphic rocks were invariably reworked during the Kuunga Orogeny (~550–500 Ma) during the final assembly of Gondwana. Sediment accumulations are generally relatively thin (up to a few hundred meters) on all the continental fragments, with the exception of NNE to NE oriented rift basins with up to ~2 km of sediments. Sedimentary rocks, predominantly sandstones were dredged from adjacent to the interpreted rift basin locations on both the Batavia and Gulden Draak knolls. Volcanic/intrusive material has been interpreted on the northern flank of the Naturaliste Plateau from seismic profiles, but no basalts were found in either of the Batavia Knoll dredges. Extensive volcanism has also been interpreted on both the Naturaliste Plateau and Bruce Rise. Volcanic material was dredged in one of two sites on the Gulden Draak Knoll, and geophysical data may support the presence of an igneous domain. The structural, volcanic and sedimentary nature of the knolls will be tested in late-2014 with the collection of new magnetic, gravity, seismic reflection and dredge data.

Introduction

The Perth Abyssal Plain, offshore southwest Australia (Fig. 1), formed from about 136 million years ago (Gibbons et al., 2012; Veevers & Li, 1991) when India, Australia and Antarctica separated and drifted apart. Despite forming at the nexus of East Gondwanan breakup, the Perth Abyssal Plain is under-explored and under-studied.

During the Early Cretaceous, the commencement of separation of India from the rest of Eastern Gondwana (Australia and Antarctica), resulted in the formation of two conjugate passive margins, one extending along the western Australian coast and the Antarctic Wilkes Land margin, and the other along the east coast of India (Fig. 2). This separation led to the formation of the Perth Abyssal Plain (Gibbons et al., 2012; Veevers & Li, 1991), de Gonneville Triangle (Munschy, 1998) (Fig. 1) and the Enderby Basin (Gaina et al., 2007) (Fig. 2b).

Many uncertainties still exist within tectonic reconstructions of early India-Australia-Antarctica breakup. A significant problem is that the conjugate continental margin to the Western Australian margin, typically interpreted as comprising Greater India and Argoland, and much of the intervening ocean floor, has now been subducted beneath Eurasia or has been highly tectonised in the India-Eurasia

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collision. Interpretation of the remaining ocean floor offshore Australia, India and Antarctica is problematic for a variety of reasons. Constraining the spreading history in the Perth Abyssal Plain has been hampered by a lack of ship-track data in the western part of the basin. Interpretations of the Enderby Basin (Gaina et al., 2007; Gibbons et al., 2012) have proved elusive due to the difficulties in interpreting magnetic and gravity data that have been severely over-printed by anomalous magmatism related to plume activity in the Enderby Basin, while magnetic anomalies in the Bay of Bengal (Krishna et al., 2009), which formed between India and Antarctica, are obscured beneath a thick sedimentary package. Further hindering accurate reconstructions has been the unclear origin of several major tectonic features across the basin, including the Batavia Knoll, Gulden Draak Knoll and Dirck Hartog Ridge (Fig. 1). Recently, Halpin et al. (2008) used dredge samples collected from a 2005 *RV Southern Surveyor* cruise to confirm that basement rocks from the Naturaliste Plateau (Fig. 1) comprise exhumed continental crust. A recent scientific voyage in 2011 aboard the *RV Southern Surveyor* collected new magnetic, swath and dredge data across the Perth Abyssal Plain to start to address these issues (Williams, 2011).

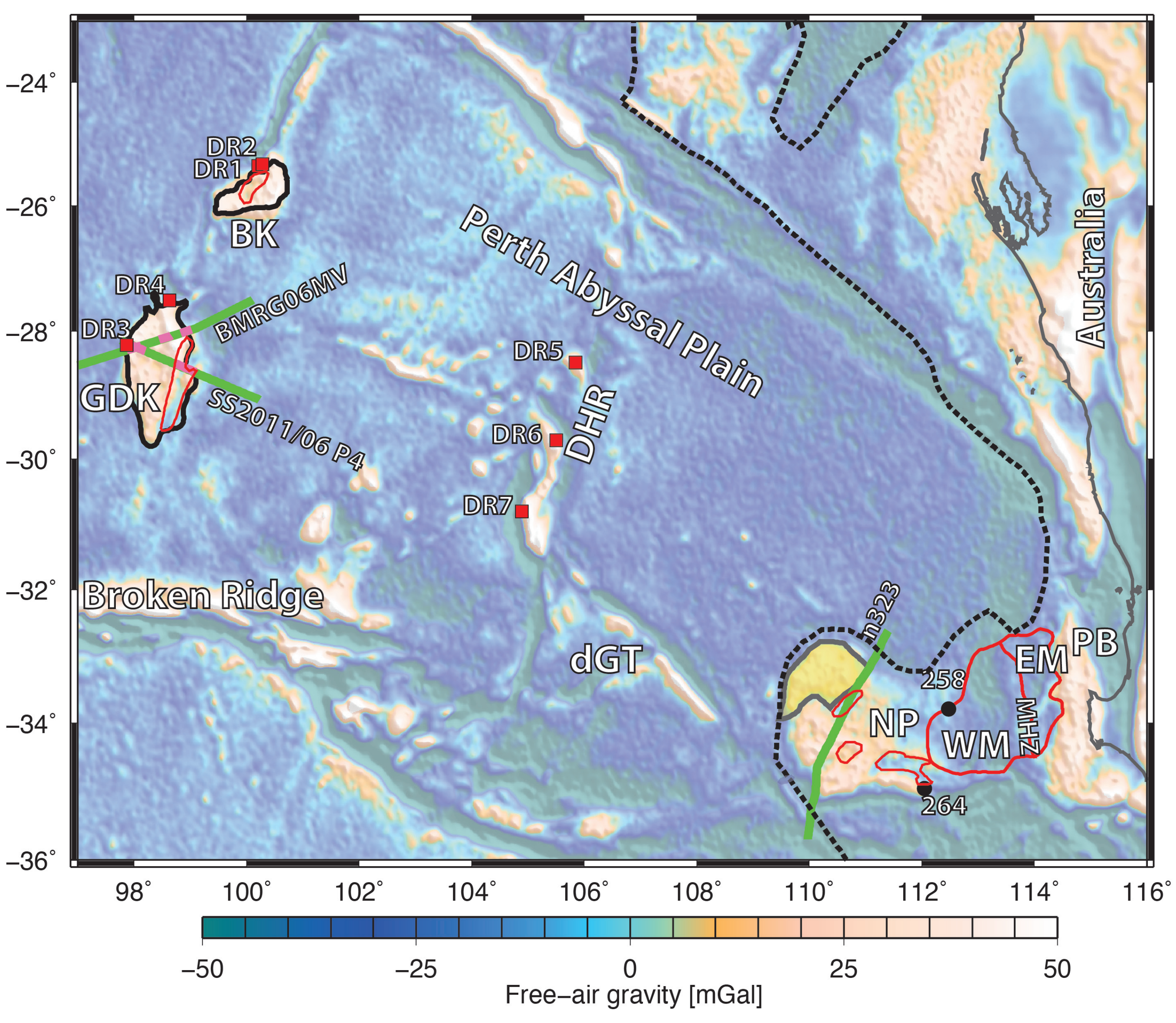

Figure 1. Location map of the Perth Abyssal Plain and key tectonic features. Underlying grid is free-air gravity (Sandwell & Smith, 2009).

Grey line – coastline, red lines – basin outlines; grey outline with yellow shading – volcanics; dashed black line – Australian continent-ocean boundary following Hall et al. (2013); solid black lines – knoll continent-ocean boundaries following the 2500 m bathymetric contour; thick green lines – profile locations (labeled by cruise) shown in Figure 7; pink line segments – predicted basin locations from Williams et al. (2013); red squares – dredge locations from *RV Southern Surveyor* voyage 2011/06; black circles – DSDP Sites; BK – Batavia Knoll; DHR – Dirck Hartog Ridge; EM – East Mentelle Basin; GDK – Gulden Draak Knoll; MHZ – Margaret Hinge Zone; NP – Naturaliste Plateau; PB – Perth Basin; WM – West Mentelle Basin. Naturaliste Plateau basin and volcanics outlines digitized from Borissova et al. (2002).

The Batavia and Gulden Draak knolls now define the western margin of the Perth Abyssal Plain. Together, these bathymetric features cover an area similar to Tasmania, but, prior to the expedition in 2011, very little was known about either feature, with only a handful of shiptrack bathymetric profiles crossing the knolls. They had been previously mapped on navigation charts as seamounts but neither had been directly sampled.

Here, we synthesize new dredge, magnetic and swath bathymetry data collected from the Batavia and Gulden Draak knolls with data from the better-known Naturaliste Plateau, Mentelle Basin and Bruce Rise, Antarctica, which form the conjugate rifted margins to the knolls (Fig. 2). Based on our observations we develop a series of testable hypotheses for the Batavia and Gulden Draak knolls, some of which are currently being investigated based on the 2011 datasets, and others which we aim to test and/or consolidate during a scheduled 5-week scientific voyage (Oct–Nov, 2014) aboard Australia's Marine National Facility, the *RV Investigator*.

Plate Tectonic Reconstruction

A number of different plate tectonic models have been proposed for the Perth Abyssal Plain (Gibbons et al., 2012; Johnson et al., 1976; Markl, 1974, 1978; Mihut, 1997; Powell et al., 1988; Veevers & Li, 1991). The alternative models vary mainly in predicting the age and nature of the crust in the western Perth Abyssal Plain. Some models predict that the crust in the western Perth Abyssal Plain formed entirely within the Cretaceous Normal Superchron (Johnson et al., 1976; Markl, 1974; Mihut, 1997). Other models predict that some Mesozoic spreading anomalies should be observed in the western Perth Abyssal Plain (Gibbons et al., 2012; Powell et al., 1988) and infer that the Batavia and Gulden Draak knolls are micro-continents (Gibbons et al., 2012). However, no evidence has previously been available to support this micro-continent hypothesis.

Magnetic anomaly data collected in 2011 (Williams, 2011), for the first time, confirm that there are Mesozoic anomalies in the western Perth Abyssal Plain that are

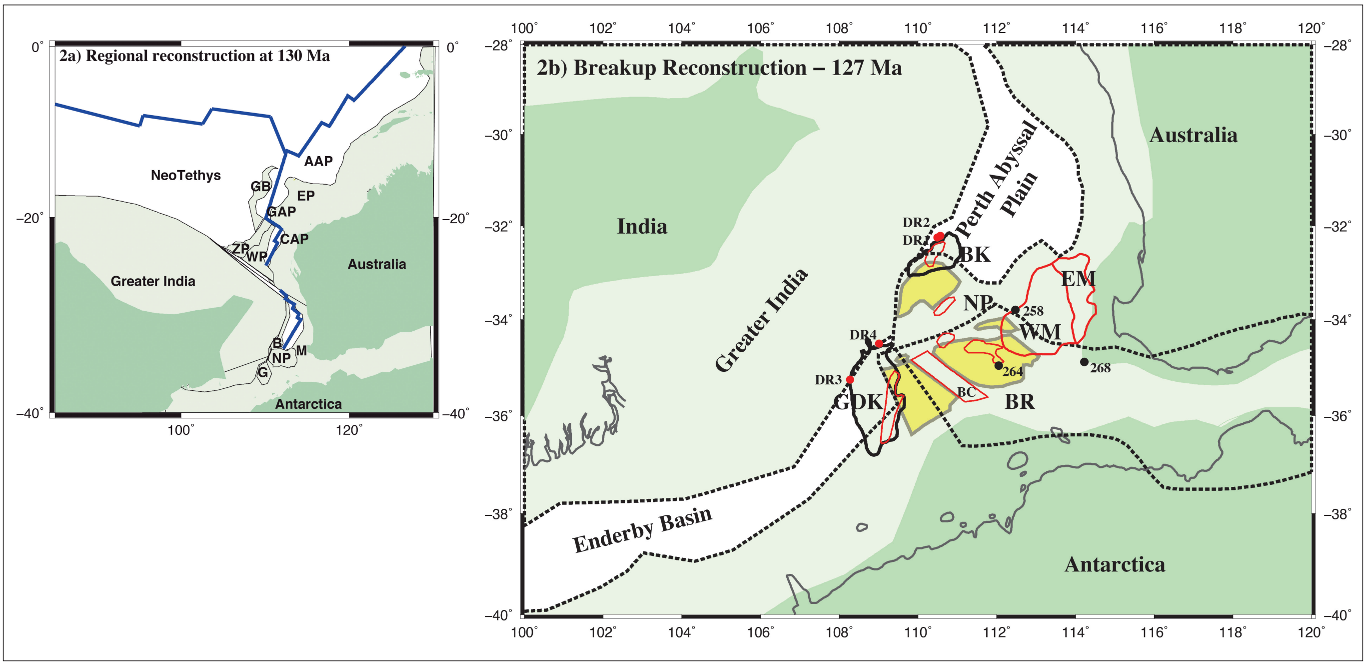

Figure 2. a) Mercator-projected tectonic reconstruction at 130 Ma (Gradstein et al., 1994) with a fixed Australian reference frame. This figure has been adapted from Gibbons et al. (2012, fig. 6c). b) Reconstruction at 127 Ma showing the configuration of Australia, Antarctica and India, and the key continental fragments at the time when the Batavia Knoll and Gulden Draak Knoll rifted from Australia/Antarctica. Fixed Australian reference frame, rotation parameters from Gibbons et al. (2012).

a) Thick blue lines – mid-ocean ridges, dark green shading – present day onshore regions, light green shading represents extent of continental crust, white regions represent oceanic crust. Abbreviations are Argo Abyssal Plain (AAP), Batavia Knoll (B), Cuvier Abyssal Plain (CAP), Exmouth Plateau (EP), Gascoyne Abyssal Plain (GAP), Gascoyne Block (GB), Gulden Draak Knoll (G), Mentelle Basin (M), Naturaliste Plateau (NP), Wallaby Plateau (WP), Zenith Plateau (ZP).

b) Light green shading – extended continental crust, dark green shading – unextended continental crust, white regions – oceanic lithosphere; grey line – coastline, red lines – basin outlines; grey outline with yellow shading – volcanics; dashed black line – Australian continent-ocean boundary following Hall et al. (2013); solid black lines – knoll continent-ocean boundaries following the 2500 m bathymetric contour; red circles – dredge locations from *RV Southern Surveyor* voyage 2011/06; black circles – DSDP Sites; BC – Bruce Canyon; BK – Batavia Knoll; BR – Bruce Rise; DHR – Dirck Hartog Ridge; EM – East Mentelle Basin; GDK – Gulden Draak Knoll; MHZ – Margaret Hinge Zone; NP – Naturaliste Plateau; PB – Perth Basin; WM – West Mentelle Basin. Bruce Rise basin and volcanics outlines digitized from Guseva et al. (2007). Note that the overlap between the Bruce Rise and the Naturaliste Plateau is due to the use of non-deforming plate tectonic outlines.

conjugate to the sequence observed in the eastern Perth Abyssal Plain (Williams et al., 2013a). The locations of these newly interpreted magnetic anomalies are consistent with the hypothesis proposed by Gibbons et al. (2012) that the western Perth Abyssal Plain contains a sequence of Mesozoic anomalies conjugate to those contained in the eastern Perth Abyssal Plain, and that the knolls are micro-continents rifted from Greater India at ~108–100 Ma. The Gibbons et al. (2012) reconstruction is a regional reconstruction for the Indian Ocean that enables the synchronous closure of both the Perth Abyssal Plain and the Enderby Basin. To understand their geological relationships between the Batavia and Gulden Draak knolls, and the Naturaliste Plateau and Bruce Rise, we assess all the blocks in their pre-drift relative positions (Gibbons et al., 2012). Throughout this paper we use the timescale of Gradstein et al. (1994).

Based on these reconstructions (Gibbons et al., 2012), the Batavia and Gulden Draak knolls are juxtaposed to the north and south of the Naturaliste Plateau immediately prior to their final breakup from Australia/Antarctica at ~127 Ma (Fig. 2). At ~136 Ma, Gibbons et al. (2012) reconstructs the Batavia Knoll adjacent to the Mentelle Basin, a Paleozoic to Mesozoic sedimentary basin located off the south-western margin of Australia (Borissova, 2002; Borissova et al., 2010; Bradshaw et al., 2003). Greater India and the Batavia Knoll rifted from the northwestern corner of the Naturaliste Plateau from ~127 Ma, while the Gulden Draak Knoll rifted from the western Bruce Rise around the same time.

Note that the reconstruction at 127 Ma (Fig. 2) shows the relative reconstructed position of the Batavia Knoll, Gulden Draak Knoll, Naturaliste Plateau and Bruce Rise at the very end of continental extension between the knolls and the Naturaliste Plateau and Bruce Rise. Continental rifting between the Naturaliste Plateau (Australian Plate) and the Bruce Rise (Antarctic plate) continued for ~45 million years after Greater India, including the Batavia and Gulden Draak knolls, broke away from Australia. This rifting continued until the onset of seafloor spreading between Australia and Antarctica at ~83 Ma. We have not attempted to deform the continental blocks for times earlier than ~127 Ma to create a realistic rift phase or pre-rift fit. Consequently, there is significant overlap shown in Figure 2 between the Naturaliste Plateau and the Bruce Rise.

Physiography

The Naturaliste Plateau is a relatively flat-topped plateau sitting approximately 2,500 m below sea level (Figs 3b & 4b). The plateau was shaped firstly by the Early Cretaceous (~136 Ma) breakup of India from the co-joined, slowly rifting Australia-Antarctica continent, and then by Late Cretaceous breakup (~83 Ma) between Australia and Antarctica. Figures 3b & 4b show that the western, northwestern, and southern flanks of the Naturaliste Plateau are relatively steep (7–11°), while the eastern portion of the northern flank is more gently sloped (2–4°) (Borissova, 2002). The eastern, western and northern flanks of the Naturaliste Plateau formed during the rifting of India from Australia, while the southern flank formed during rifting between Australia and Antarctica. The Naturaliste Plateau is surrounded by a 30–90 km wide continent-ocean transition in the north and up to 250 km wide continent-ocean transition in the south, where the margin incorporates the Diamantina Fracture Zone (Borissova, 2002).

The Mentelle Basin (Fig. 1) is a 36,400 km^2 basin located just east of the Naturaliste Plateau, on the southwest Australian continental margin. It comprises two distinct sub-basins, the deep water (500–2,000 m) Eastern Mentelle Sub-basin and the ultra-deep water (2,000–4,000 m) Western Mentelle Sub-basin (Borissova et al., 2010; Bradshaw et al., 2003) (Fig. 1). The basin formed as part of the extensional rift system that developed along the western margin of Australia during the Paleozoic to Mesozoic breakup of eastern Gondwana (Borissova et al., 2010) (Fig. 1). Gravity modelling across the basin indicates the presence of very thin continental crust beneath the central parts of the Western Mentelle Sub-basin, suggesting that in the Early Cretaceous continental break-up was nearly reached within this sub-basin (Johnston et al., 2010). Although the continent-ocean transition northwest of the Mentelle Basin is poorly defined, limited available potential field and seismic data suggest that it is over 60 km wide. Crustal stretching factors in the western sub-basin are estimated to be greater than 3, and analogy with the Iberian continental margin suggests simple shear dominated during the final stages of extension (Hall et al., 2013).

The Bruce Rise comprises two morphologically distinct segments separated by the NW-trending Bruce Canyon. The Eastern Bruce Rise is in shallower water (<1,500 m), bounded by steep slopes to the east and north, and the Bruce Canyon to the west (Figs 3c & 4c). The western Bruce Rise is in deeper water (~2,000 m) and the flanks are more gently dipping (Figs 3c and 4c). The western Bruce Rise was likely formed during the Early Cretaceous rifting of India from Australia and Antarctica and so is the possible conjugate to the eastern Gulden Draak Knoll (Fig. 2). The eastern Bruce Rise may have formed during the Late Cretaceous breakup of Australia and Antarctica (Sayers et al., 2001), conjugate to the southern Naturaliste Plateau. The Bruce Rise continent-ocean transition is also well defined on the basis of seismic reflection, sonobuoy, magnetic and gravity data (Leitchenkov et al., 2007; O'Brien & Stagg, 2007).

Both the Batavia and Gulden Draak knolls are relatively smooth-topped, deep-water plateaus, sitting at water depths of ~1,700–2,000 m, and ~1,100 m, respectively (Fig. 3a). The position of the continent–ocean transition around the knolls is unknown but we use the 2,500 m bathymetric contour from the Smith & Sandwell (1997) bathymetry model as a proxy. The Gulden Draak Knoll, at ~1,100 m water depth,

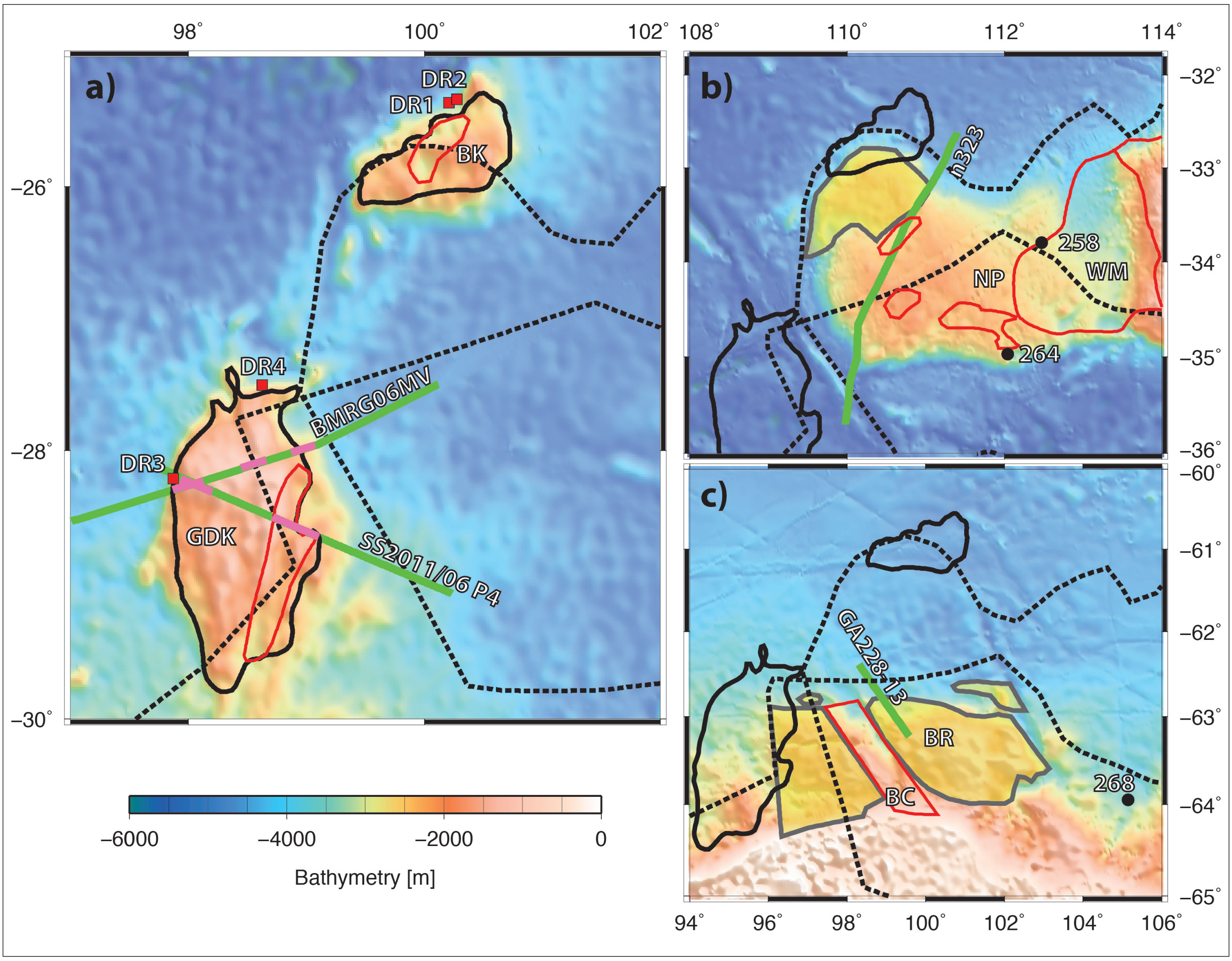

Figure 3. Close-up view of the key continental fragments underlain by version 15.1 of the Smith and Sandwell (1997) bathymetry model, and with the reconstructed position of other fragments at 127 Ma. a) Batavia Knoll and Gulden Draak Knoll. b) Naturaliste Plateau, and c) Bruce Rise. Symbols, lines and labels are as for Figure 2b.

is shallower than the other continental fragments (Batavia Knoll ~1,700–2,000 m, Naturaliste Plateau ~2,500 m and western Bruce Rise ~2,000 m) but has a similar water depth to the eastern Bruce Rise (<1,500 m). The causes of this difference could be related to crustal thickness, mantle-driven dynamic topography, and plume related under-plating. The Gulden Draak Knoll is proximal to Broken Ridge (Fig. 1), a volcanic product of the Kerguelen plume. The free-air gravity expressions of the Gulden Draak Knoll and Broken Ridge are distinct (Fig. 5a), but Williams et al. (2013b) show that a large Bouguer gravity low encompasses both these features and the intervening ocean floor, suggesting a broad area of relatively thick crust.

The eastern and western flanks of both the Batavia and Gulden Draak knolls are morphologically quite different (Fig. 4a). The eastern flanks, conjugates to the northwestern Naturaliste Plateau and the western Bruce Rise, exhibit relatively gently slopes of 4–6° and 2–5°, respectively. In comparison, the western flanks, which were conjugate to Greater India, are much steeper 7–13° (Fig. 4a).

The steep western flanks of the knolls and the steep western flank of the Naturaliste Plateau were all conjugate to Greater India, although breakup occurred at different times; at ~127 Ma for the western Naturaliste Plateau, and at ~108–100 Ma for the knolls. The steep gradient of these western flanks is most likely driven by the composition of the underlying basement and style of rifting. Metamorphic rocks were dredged from the western flanks of both the Batavia (Kobler, 2012) and Gulden Draak knolls (Gardner, 2012), and also from the steeply-dipping southern margin of the Naturaliste Plateau (Beslier et al., 2004; Halpin et al., 2008). The metamorphic rocks of the southern Naturaliste Plateau are thought to represent a middle- to lower-crustal extensional allochthon exhumed during breakup between Australia and Antarctica (Halpin et al., 2008). The Batavia and Gulden Draak knolls also likely represent extended lower continental crust.

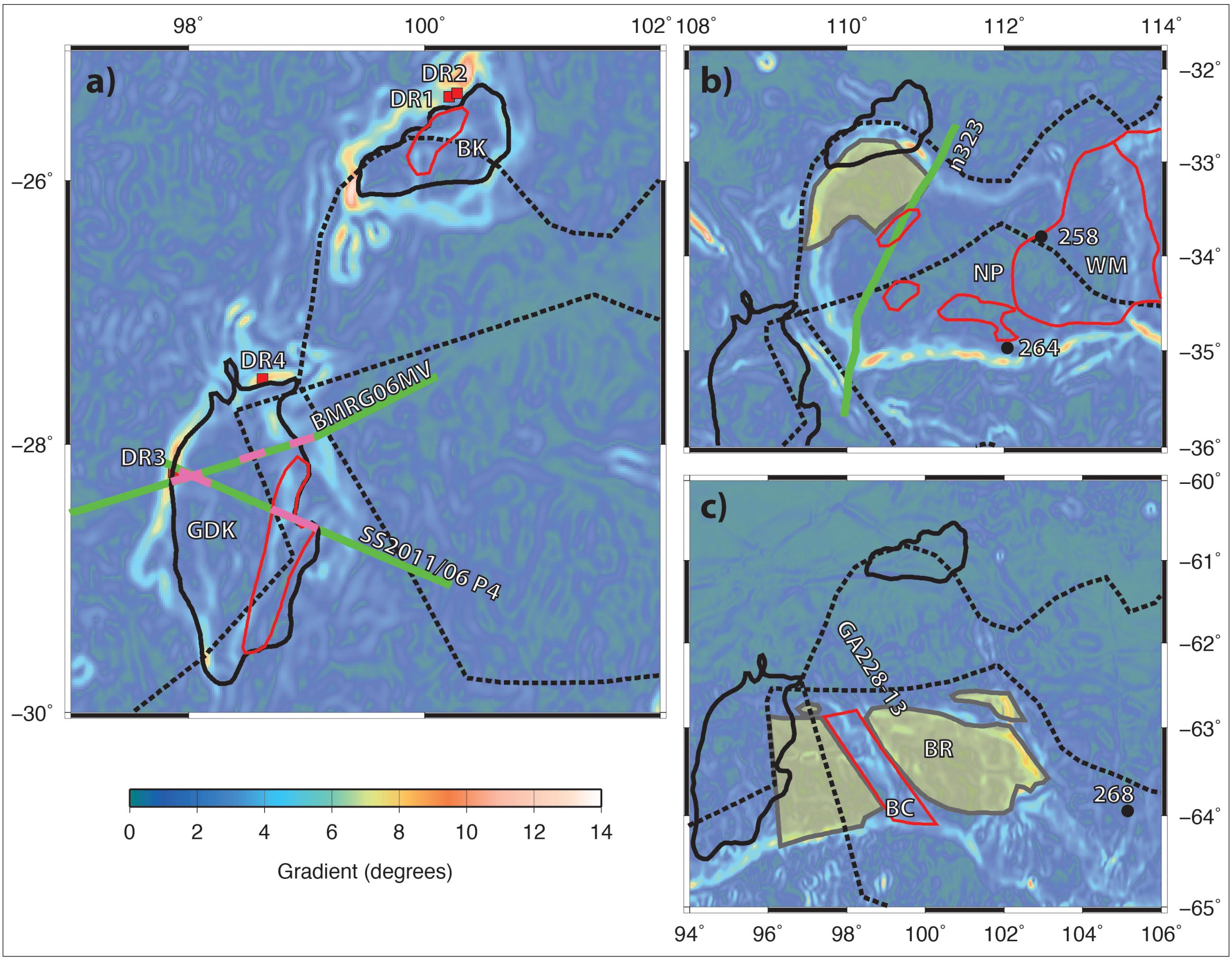

Figure 4. Close-up view of the key continental fragments underlain by bathymetric gradients derived from version 15.1 of the Smith and Sandwell (1997) bathymetry model and with the reconstructed position of the other fragments at 127 Ma. a) Batavia Knoll and Gulden Draak Knoll, b) Naturaliste Plateau and c) Bruce Rise. Symbols, lines and labels are as for Figure 2b.

Basement

Felsic orthogneisses and granites have been dredged from the southern margin of the Naturaliste Plateau (Beslier et al., 2004; Halpin et al., 2008). Halpin et al. (2008) presented U-Pb zircon data from four of these samples that yield minimum emplacement ages of 1230–1190 Ma revealing that the Naturaliste Plateau is floored by Mesoproterozoic continental crust. U-Th-Pb monazite ages for two of these samples cluster at 515 Ma and zircon data from all samples exhibit isotopic disturbance consistent with a high-grade event during the Cambrian (Halpin et al., 2008). This Mesoproterozoic crust is older than the nearest onshore basement inliers of the ~1090–1000 Ma Pinjarra Orogen (Leeuwin, Northampton and Mullingarra complexes) (Bruguier et al., 1999; Ksienzyk et al., 2012; Nelson, 1999) and the relationship with these rocks remains unclear. Based on these geochronological data, the granitoid protoliths show greatest affinity to rocks of the ~1300–1100 Ma Albany-Fraser Orogen in Western Australia and the conjugate Wilkes Orogen in east Antarctica (Halpin et al., 2008). The Albany-Fraser-Wilkes Orogen reflects the site of collision between a combined West Australian–North Australian craton and the South Australian–East Antarctic continent during the assembly of the supercontinent Rodinia (Clark et al., 2000). Evidence for overprinting high-grade metamorphism at 515 Ma in the Naturaliste Plateau basement rocks is coeval with extensive 550–500 Ma tectonic activity in the nearest onshore basement in Western Australia (Leeuwin Complex; Collins, 2003). This late Neoproterozoic–Cambrian orogenesis defines part of the Kuunga Orogen that recorded the Early Palaeozoic collision between the Indo-Antarctic and Australo-Antarctic plates to form East Gondwana (Boger, 2011; Meert, 2003).

Sonobuoy refraction data and gravity modelling suggest that the crust comprising the Bruce Rise is 18–20 km thick,

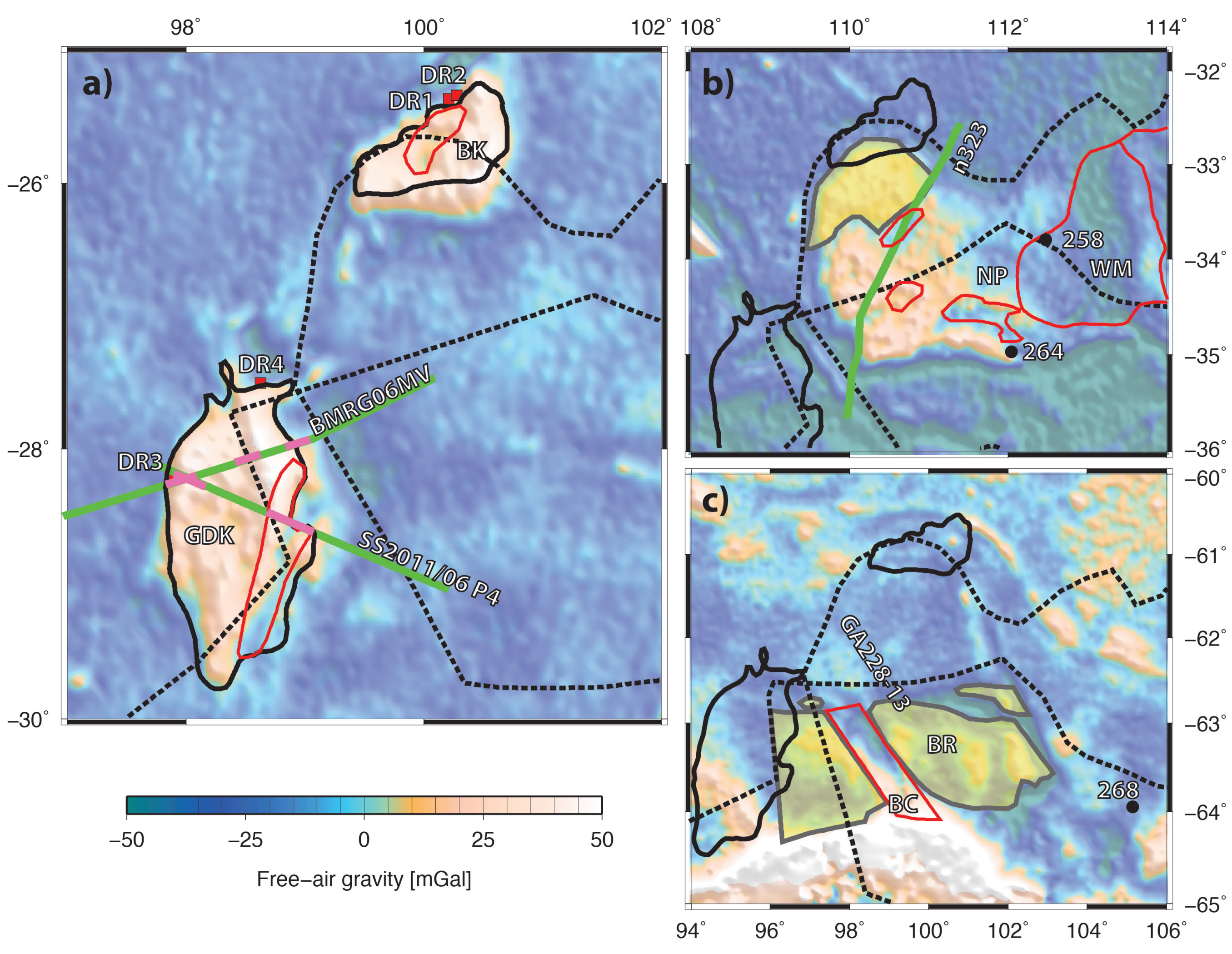

Figure 5. Close-up view of the key continental fragments underlain by free-air gravity (Sandwell and Smith, 2009) with the reconstructed position of the other fragments at 127 Ma. a) Batavia Knoll and Gulden Draak Knoll, b) Naturaliste Plateau and c) Bruce Rise. Symbols, lines and labels are as for Figure 2b.

(Guseva et al., 2007). In seismic reflection data, the basement in the west presents as an acoustically strong surface with an underlying package of seaward-dipping reflectors, while in the east, basement is underlain by sub-parallel, discontinuous and locally contorted reflectors (Guseva et al., 2007; Stagg et al., 2006). This package is ~2 km thick, interpreted as volcanic and is believed to be underlain by thin continental crust (Guseva et al., 2007). Seabed samples dredged from the eastern flank of the Bruce Rise include continental rocks (granites, schists, sandstones, siltstones; Ishihara et al., 1996). These rocks could represent in situ basement and overburden, or be glacially derived (Stagg et al., 2006). No geochronology is currently available for comparison with the other continental plateaus or onshore basement.

Basement rocks dredged from the north-western flank of Batavia Knoll (dredge sites 1 & 2, Figs 1–5) include granites, granite gneisses, intermediate gneisses and schists (Tables 1 & 2, Fig. 6). Zircon grains recovered from two granites and three granite gneisses are affected by complex isotopic disturbance (Pb-loss), however calculated minimum emplacement ages are indistinguishable between ~540–530 Ma (Table 2; Kobler, 2012). These data suggests syn- and post-tectonic felsic magmas intruded during the latest Neoproterozoic and Cambrian (Kobler, 2012).

Basement rocks dredged from the Gulden Draak Knoll (dredge sites 3 & 4, Figs 1–5) include felsic and mafic gneisses, granites and metapelite (Tables 1 & 2, Fig. 6). Geochronological analyses of three felsic orthogneiss samples from the western scarp of the Gulden Draak Knoll indicate that these rocks were originally emplaced during the Archaean (~2850 Ma) and Mesoproterozoic (~1230–1200 Ma), and a metapelitic sample from the same location yields an array of mostly discordant zircon data and suggests deposition of the protolith sediments between 2800–1200 Ma (Gardner, 2012). All these rocks were recrystallised during high-grade metamorphism at ~500 Ma (Gardner, 2012).

Dredge #	Locality	Start Lat (°)	Start Lon (°)	Depth (m)	End Lat (°)	End Long(°)	Depth (m)	Est. Total Weight (kg)	Description (no of samples)
DR1	NW scarp Batavia Knoll	-25.347	100.198	3360	-25.37	100.218	2810	40	granite (29), granite gneiss (6), schist (3), intermediate gneiss (9), fault gauge rock (4)
DR2	NW scarp Batavia Knoll	-25.332	100.285	2870	-25.343	100.298	2730	40	fossiliferous sandstone (yellow-orange, 6), sandstone (yellow-brownish pieces, 2 bags assorted pieces)
DR3	W scarp Gulden Draak Knoll	-28.282	97.868	2880	-28.252	97.851	2695	40	metapelite (1), granite (2), mafic gneiss (2), felsic gneiss (6), cobbles of granite gneiss (3), siltstone (1), sandstone (7), turbidite (2), altered basalt (2)
DR4	N scarp Gulden Draak Knoll	-27.5	98.621	2990	-27.51	98.62	2860	10	basalt (11), trachyte (1)

Table 1. SS11-06 dredge locations and summary dredge hauls from Batavia and Gulden Draak knolls.

Sample #	Lithology	Est. Age (Ma)	Zircon geochronology comments	Reference
DR1-3	Granite	540-530	Pb-loss – minimum emplacement age	Kobler (2012)
DR1-4A	Granite	540-530	Pb-loss – minimum emplacement age	Kobler (2012)
DR1-4B	Biotite schist	—	—	Kobler (2012)
DR1-5	Granite gneiss	540-530	Pb-loss – minimum protolith age	Kobler (2012)
DR1-34	Intermediate gneiss	—	—	Kobler (2012)
DR1-38	Garnet granite gneiss	540-530	Pb-loss – minimum protolith age	Kobler (2012)
DR1-40	Garnet granite gneiss	540	Pb-loss – minimum protolith age	Kobler (2012)
DR1-41	Garnet granite gneiss	—	—	Kobler (2012)
DR3-1	Two feldspar-quartz orthogneiss (cobble)	2850	Pb-loss – minimum protolith age	Gardner (2012)
DR3-2	Quartz-feldspar-biotite orthogneiss	1200	Pb-loss – minimum protolith age	Gardner (2012)
DR3-6	Two feldspar-quartz orthogneiss (cobble)	1290	Pb-loss – minimum protolith age	Gardner (2012)
DR3-15	Garnet-sillimanite-biotite paragneiss	2800-1200	?Deposition age range	Gardner (2012)
DR3-16	Two pyroxene-pargasite orthogneiss	—	—	Gardner (2012)

Table 2. Summary of lithologies and geochronology for samples from Batavia and Gulden Draak knolls from Kobler (2012) and Gardner (2012).

In summary, significant volumes of metamorphic and granitic basement rocks were dredged from both the Batavia and Gulden Draak knolls. Preliminary geochronological and geochemical analyses show that these rocks are continental in nature (Kobler, 2012; Gardner, 2012). The protolith granite to an Archaean gneiss from Gulden Draak Knoll was likely emplaced in either the Yilgarn (Western Australia) or Mawson (east Antarctica) craton at ~2850 Ma (Gardner, 2012). Mesoproterozoic crust from Gulden Draak (1290–1200 Ma) is coeval with that present along the southern margin of the Naturaliste Plateau (1290–1190 Ma); together these rocks likely represent a continuation of the Albany-Fraser-Wilkes Orogen onshore Western Australia and east Antarctica (Halpin et al. 2008; Gardner, 2012). Late Neoproterozoic-

Figure 6. Representative dredge samples retrieved during *RV Southern Surveyor* voyage 2011/06 from (a-d) Batavia Knoll and (e–j) Gulden Draak Knoll. a) Coarse-grained granite, sample DR1-3. b) Granite gneiss, sample DR1-5. c) A representative collection of sandstone samples retrieved from DR2. d) Part of a very large fossiliferous sandstone boulder, sample DR2-6. e) A large (~40cm across) rounded cobble of felsic orthogneiss, sample DR3-1. f) A smaller (~20cm across) rounded cobble of felsic orthogneiss with beveled edge, sample DR3-6. g) Metapelite sample DR3-15, part of a very large (~1m wide) slab. h) Micaceous sandstone, sample DR3-24. g) Volcanic (trachyte) sample, DR4-6. h) Volcanic (amygdaloidal basalt) sample, DR4-12. Australian 50 cent piece used for scale.

Cambrian granite gneisses and granites sampled from Batavia Knoll (540–530 Ma) were emplaced during and soon after collisional tectonism along the Kuunga Orogen (Kobler, 2012). Basement rocks of Gulden Draak and the Naturaliste Plateau also preserve evidence of high-grade reworking during the Early Palaeozoic (Halpin et al. 2008; Gardner, 2012). This close affinity supports the reconstruction (Fig. 2) that shows that the knolls were once contiguous with Australia within Gondwana and now form isolated, offshore micro-continents.

Basins

Seismic reflection data across the western Naturaliste Plateau show three small rift basins, 10–30 km wide, and up to ~120 km long, shown by red outlines in Figures 1–5 (Borissova, 2002). These basins include half grabens and full grabens with ENE-trending normal faults dipping to the NW or SE. The largest basin, consisting of several en-echelon rift segments, is found in the south of the Naturaliste Plateau. Two smaller rift basins are found in the southwestern and northwestern Naturaliste Plateau – a cross-section of the northwestern basin is shown in Figure 7b. The northwest rift separates the northwestern corner of the Naturaliste Plateau from the rest of the plateau. All the rift basins are thought to have formed during the Jurassic–Early Cretaceous as a result of NW-SE extension as India separated from Australia. There is some evidence from seismic reflection data that a Jurassic and older sag basin is present in the centre of the Naturaliste Plateau (Borissova, 2002).

The tectonostratigraphic framework of the Mentelle Basin has been interpreted by Borissova et al. (2010) on the basis of regional seismic data and correlation with the adjacent Perth Basin. The Eastern Mentelle Sub-basin is interpreted to contain up to 8 km of predominantly Permian to Jurassic sediment, similar to the onshore Perth Basin. Its three main depocentres comprise a series of tilted fault blocks that are bounded by E-dipping, NNW to NNE-striking faults (Borissova et al., 2010). The depocentres of the Western Mentelle Sub-basin have been interpreted to contain predominantly Jurassic to Early Cretaceous aged strata based on seismic interpretation (Borissova et al., 2010). Depocentres in the northern and central parts of the sub-basin, are NNE to NE-trending half-graben structures containing between 9 and 11 km of sediment (Borissova et al., 2010). These basins are interpreted to have formed in the Jurassic–Early Cretaceous as a result of NW-SE extension and may be similar in stratigraphy to the Vlaming Sub-basin (Borissova et al., 2010). In the south, several smaller, *en-echelon* half-grabens contain up to 3–5 km of sediment (Borissova et al., 2010). These half-grabens are an eastward continuation of the small rifted basins in the southern part of the Naturaliste Plateau, and their ENE orientation and structural style are consistent with Late Jurassic to Valanginian extension on the southern margin related to early extension between Australia–Antarctica, which formed the third arm of the rift-rift-rift system, with the triple-junction likely located proximal to the Naturaliste Plateau (Borissova, 2002; Borissova et al., 2010; Norvick & Smith, 2001). The Western and Eastern Mentelle sub-basins are separated by the north–south oriented Margaret Hinge Zone, a zone of continental margin collapse which is defined by a series of down-stepping fault blocks that are on-lapped by the Western Mentelle Sub-basin sedimentary succession (Borissova et al., 2010).

The Bruce Rise is similar to the Naturaliste Plateau in that the basement is broken by small, half-grabens. A further major structural feature is the Bruce Canyon (Fig. 2–5), an approximately 1,000 m deep, 40 km wide, fault-bounded basin that separates the eastern and western portions of the rise (Guseva et al., 2007; Stagg et al., 2006) and which is inferred to be a strike-slip zone, albeit with an undetermined sense of motion (Stagg et al., 2006).

For the Batavia and Gulden Draak knolls (Williams et al., 2013b) analysis of new and pre-existing shiptrack magnetic profiles, combined with satellite gravity anomalies, have been used to estimate the variation in basement depth. The Batavia Knoll profile crosses the furthest northeast corner of the plateau and shows that basement is close to the surface in this area. However, a NE-trending gravity low is present in the centre of the Batavia Knoll and we tentatively interpret this feature to be a basin (Fig. 3).

Two magnetic ship-track profiles cross the Gulden Draak Knoll (Williams et al., 2013b) and provide evidence for 25–40 km wide basins containing up to ~2 km of sediment (Williams et al., 2013b). The eastern basin on SS2011/06_P4 is matched by a prominent gravity low that trends NNE (Fig. 5), and we tentatively trace this gravity low to interpret a NNE-striking basin extending along the eastern side of the Gulden Draak Knoll. The other basins are not matched by gravity anomalies, so we are unable to interpret their shape with the available datasets.

When reconstructed (Fig. 2), the interpreted Batavia Knoll and Gulden Draak basins (Fig.1) are proximal to and of similar orientation to the northwest and southwest Naturaliste Plateau basins. They are also similar in orientation to the major Late Jurassic to Early Cretaceous depocentres of the western Mentelle Basin. This is consistent with all four basins forming during the separation of India/Batavia/Gulden Draak from Australia/Antarctica. In detail, the strike of the basins on the knolls are 22–45° different to the ENE orientation of the Naturaliste Plateau basins. This difference may indicate that some rotation of both the Gulden Draak and Batavia knolls has occurred since they rifted from the Naturaliste Plateau and Bruce Rise. Alternatively, the difference may be due to local variations in the trends of basement structures followed by the rift basins. The collection of seismic reflection and refraction data across the knolls, scheduled for October-November 2014, will help resolve the basement structure.

Figure 7 shows a comparison of the basins interpreted using magnetic data on the Gulden Draak Knoll (Williams et al., 2013b) with the basins on the western Naturaliste

Plateau and eastern Bruce Rise. The Gulden Draak basins are similar in width (25 to 40 km) to the northwestern rift on the Naturaliste Plateau. A direct comparison between the depths of the basins on the different continental fragments is difficult to determine because the estimates are in kilometres for the Gulden Draak basins but in two-way time for the Naturaliste Plateau and the Bruce Rise. We have vertically exaggerated the two-way time images so they are roughly comparable to the depth section for the Gulden Draak Knoll by assuming the seismic velocity through water is 1.5 km/s. Hence the bathymetry on each section should be comparable, but the basins in the two-way time sections are probably deeper than they appear. Furthermore, the basement of the Naturaliste Plateau and Bruce Rise has been interpreted from seismic reflection interpretations following the lowermost interpreted horizon, which may not represent the top of crystalline basement.

Sediments

Sediment thicknesses across most of the Naturaliste Plateau and Bruce Rise do not appear to exceed approximately 1 sec two-way time, with thicker accumulations (up to ~2 km) found in the small rift basins. A Valanginian–Hauterivian (Hall et al., 2013) breakup unconformity has been interpreted in all basins of the Naturaliste Plateau, with two syn-rift sequences interpreted below this unconformity in the small rift basins (Borissova, 2002). Based on seismic reflection data Borissova (2002) observed that the seismic character of the central Naturaliste Plateau basement is very different to the metamorphic basement further south, leading Borissova (2002) to propose that Jurassic and older sedimentary sequences (equivalent to those in the south Perth Basin) may be present in the central Naturaliste Plateau.

An interpreted Valanginian to Barremian-aged sequence has been mapped in the north western part of the Naturaliste Plateau and was probably formed in response to regional subsidence that followed breakup in the Perth Abyssal Plain (Borissova, 2002). It is capped by a prominent angular unconformity inferred to be Barremian in age (Borissova 2002). Comparison with the plate reconstructions of Gibbons et al. (2012) suggests that this unconformity may correspond to break-up and the onset of sea-floor spreading between the north-western edge of the Naturaliste Plateau and Greater India at around 127 Ma.

Two DSDP Sites have been drilled on the Naturaliste Plateau, Site 258 in the northeast and Site 264 in the southeast, but neither penetrated close to basement. At Site 264, the oldest unit sampled was altered fossiliferous, volcaniclastic conglomerates that have been interpreted as Cenomanian or older in age (Hayes, 1975). Site 258 sampled 411 m of Cretaceous sedimentary strata. These strata are composed of 11 m of glauconitic detrital sandstone and silty clay overlain by 251 m of mid-Albian to Cenomanian ferruginous detrital clays, and 149 m of Turonian to Santonian nannofossil chalk and siliceous limestone. This is overlain by 114 m of Miocene to recent nannofossil ooze (Davies et al., 1974).

Although data coverage across the Mentelle Basin is sparse, stratigraphic ages have been interpreted by Borissova et al. (2010). Seismic ties to DSDP site 258 provides high resolution data on Mid-Albian to Holocene part of the section, whilst ages and lithologies for older strata are interpreted through indirect correlation with the Vlaming Sub-basin, based stratal relationships and seismic characteristics (Borissova et al., 2010). The age control for the Permo-Triassic section is provided by a seismic tie to two dredges in the Perth Canyon (Heap et al., 2008).

The interpretation of Borissova et al. (2010) shows that the Eastern and Western Mentelle sub-basins differ quite significantly in their tectonic evolution. The Eastern Mentelle Sub-basin has been interpreted to contains up to 7–9 km of sediments, inferred to be predominantly Permian to Jurassic strata, similar in age to the onshore section of the southern Perth Basin. Formation of this sub-basin began in the Early Permian. Rifting resulted in the development of N-S oriented grabens across the sub-basin and was followed by a period of Mid-Permian to Early Jurassic thermal subsidence (Borissova et al., 2010). A second major phase of rifting affected the Mentelle Basin during the Middle Jurassic to Early Cretaceous, however sediments of this age are largely absent over the eastern sub-basin. Instead seismic geometries indicate that the eastern sub-basin underwent significant uplift and erosion during this time.

In contrast, the Western Mentelle Sub-basin comprises predominantly Jurassic to Early Cretaceous aged sediments, more similar in age to the Vlaming and Zeewyck sub-basins of the Perth Basin. Analogy with the Vlaming and Eastern Mentelle sub-basins suggests that Permian to Triassic-aged sediments may also be present beneath these sequences; however the lack of well data and poor seismic quality at depth makes it difficult to directly identify any units of this age (Borissova et al., 2010). Middle Jurassic to Early Cretaceous extension in the Mentelle Basin was focused in the western sub-basin, resulting in the accumulation of about 6–9 km of syn-rift sediments, above which lies a Valanginian to Hauterivian aged syn-breakup supersequence (Mentelle 5) up to 1 km thick (Borissova et al., 2010).

Hauterivian to Cenomanian post-break up thermal subsidence was characterised by deposition of deltaic, deep marine and carbonate-dominated sediments across the entire Mentelle Basin, although these units are thickest in the western sub-basin (Borissova et al., 2010). Subsequent Paleocene to Eocene margin collapse resulted in the development of the Margaret Hinge Zone between the east and west Mentelle sub-basins (Borissova et al., 2010).

Sediment cover across the Bruce Rise generally only reaches a few hundred meters in thickness (Guseva et al., 2007). The Bruce Rise is thought to host probable Cretaceous sediments (Stagg et al., 2006). Two regionally-identified seismic stratigraphic horizons have been interpreted on the western Bruce Rise, marking an Early Eocene unconformity and the onset of glaciation at ~34 Ma (Guseva et al., 2007).

Approximately 40 kg of sedimentary rocks, predominantly sandstones, were dredged from the Batavia Knoll and Gulden Draak Knoll (Table 1 & Fig. 6). These rocks were dredged from the northwest flank of the Batavia Knoll (Dredge 2) and the western scarp of the Gulden Draak Knoll (Dredge 3). Both these locations are adjacent to the locations of sedimentary basins tentatively interpreted based on magnetic (Williams et al., 2013b) and gravity data. Thicker sediment accumulations may be present in the interpreted NNE-trending basin located along the eastern margin of the Gulden Draak Knoll, the basin with no matching free-air gravity signal on the western margin of the Gulden Draak Knoll, and in the more tentatively inferred NE-trending basin in the NE Batavia Knoll. If present, it is likely that these basins contain similar sediments to those dredged from the western margins of the knolls (Table 1). Some basement gneiss dredge samples from dredge 3 from Gulden Draak Knoll include 20–40 cm diameter, rounded cobbles with bevelled edges (Figs 6e & 6f; Table 1), suggestive of a coastal, fluvial or glacial environment.

Based on the depth to magnetic basement results (Williams et al., 2013b), thin sedimentary strata are predicted across the Batavia and Gulden Draak knolls, outside of the interpreted small rift basins. This material is likely to be composed of post-rift deep water oozes.

Volcanics/Intrusives

Both the Naturaliste Plateau and the Bruce Rise are interpreted to exhibit plume-influenced volcanics. A volcanic/igneous province has been interpreted on the northern flank of the Naturaliste Plateau from seismic profiles (Borissova, 2002). Cobbles of conglomerate from *Eltanin* dredge 12 consisting of altered tholeiitic basalt, have been geochemically correlated to the Bunbury Tholeiitic Suite in the Southern Perth Basin (Coleman et al., 1982). They have been interpreted to be the same as material recovered at DSDP Site 264 leading to the somewhat sweeping interpretation that tholeiitic basalt covered large parts of the Naturaliste Plateau during the Cenomanian (Jongsma & Petkovic, 1977). Additionally, Borissova et al. (2002) use magnetic anomalies and seismic reflection data to interpret the NW corner of the Naturaliste Plateau as a volcanic/intrusive complex of an unknown age (grey outline with yellow shading shown in Figs 1–5).

The seismic character of the Bruce Rise acoustic basement, with reflectors that thicken and dip seawards on the Bruce Rise, can be interpreted as sedimentary, but also bear a strong resemblance to interpreted volcanic sequences (Guseva et al., 2007; Hinz et al., 2005) (grey outlines with yellow shading shown on Fig. 2b). Based on multi-channel seismic and sonobuoy data, Guseva et al. (2007) interpreted the thickness of this possible volcanic unit to be ~2 km, and speculated that emplacement occurred synchronously with the Bunbury Basalt extrusion at 132–130 Ma (Coffin et al., 2002).

Within the Western Mentelle Sub-basin, seismic interpretation has identified a syn-breakup supersequence up to 1 km thick, which shows evidence for massive syn-depositional volcanism associated with Valanginian–Hauterivian break-up (Mentelle 5 of Borissova et al., 2010; Johnston et al., 2010). Three main igneous facies have been identified: extrusive flows, cones, sills and dykes, and a strong correlation is observed between the distribution of the thickest volcanic material and regions of greatest crustal thinning (Johnston et al., 2010). This volcanism is interpreted to coincide with breakup-related volcanics in the Perth Basin at around 132 Ma (Borissova et al., 2010; Coffin et al., 2002; Crawford et al., 2006; Crostella & Backhouse, 2000; Johnston et al., 2010). Volcanism is generally restricted to the Western Mentelle Sub-basin and few flows are observed in seismic lines crossing the eastern sub-basin.

No volcanic rocks were dredged from Batavia Knoll. The most likely explanation for this is the sparse sampling, as we feel that it is unlikely that that the Batavia Knoll underwent two rift events (one from Australia at ~130 Ma and one from India at ~108 Ma) without the surface expression of magmatism, particularly because of (i) the Bunbury Basalt-related volcanism on the northern Naturaliste Plateau (Coleman et al., 1982), (ii) the likely presence of igneous provinces on the NW Naturaliste Plateau (Borissova, 2002), and (iii) the relationship between micro-continent formation and mid-ocean ridges jumps towards plumes (Müller et al., 2001) in this case the Kerguelen plume. However, an alternative possibility is that older, Valanginian magmatism was restricted to the central part of the Western Mentelle Sub-basin, east of the Batavia Knoll, in association with the location of greatest crustal thinning, and so did not affect the Batavia Knoll.

Approximately 10 kg of basalts were dredged from the northern tip of the Gulden Draak Knoll (Table 1, Fig. 6). Depth to magnetic basement calculations (Williams et al., 2013b) inferred the presence of two basins in the northwest region of the Gulden Draak Knoll (Fig. 7a), with no matching signature in the free-air gravity. This pattern may support the presence of higher density basaltic material in this region. Alternatively, the absence of a correlation with the free-air gravity may be due to the sediment accumulations being compensated by thin crust, although Bouguer corrected gravity (Williams et al., 2013b) (Fig. 4b) does not exhibit a matching signature.

Conclusions

The Batavia Knoll and Gulden Draak Knoll share many geological traits with their pre-rift conjugates, the Naturaliste Plateau, Mentelle Basin and Bruce Rise. Based on the observed similarities between the knolls and the Naturaliste Plateau and Bruce Rise we have formulated eight hypotheses for the

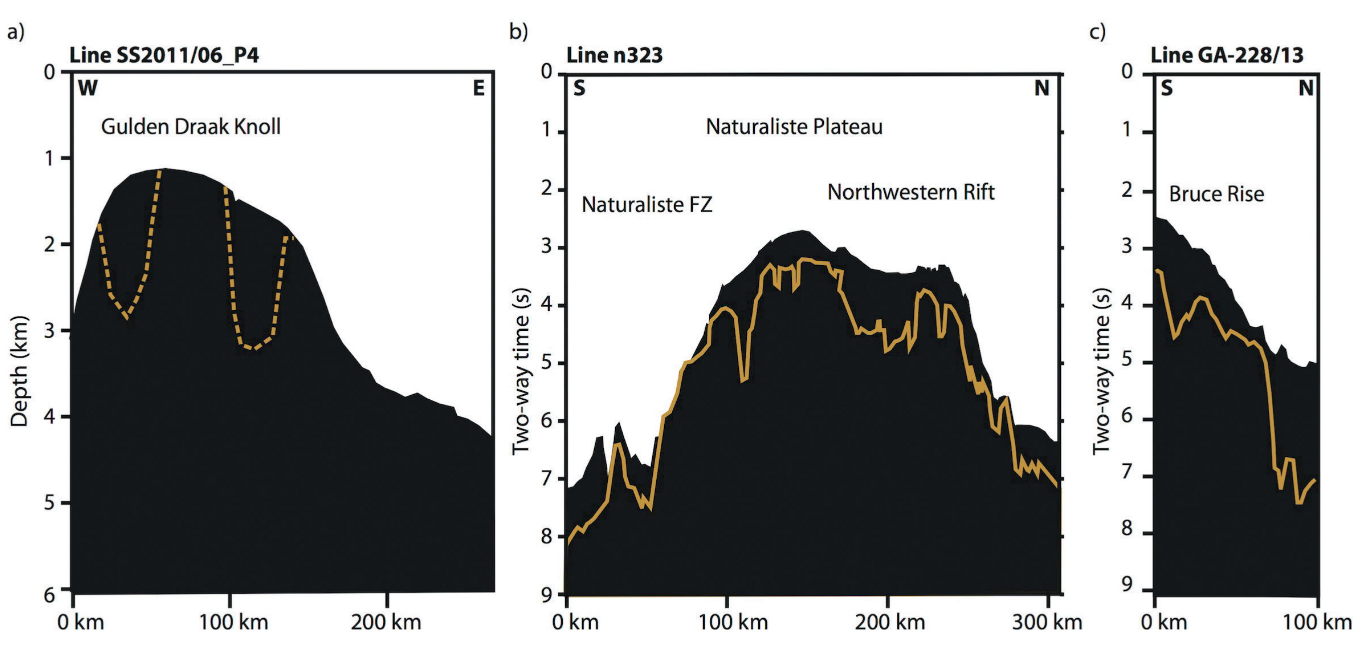

Figure 7. Comparison of the bathymetry (black) and basement depth (orange) of the a) Gulden Draak Knoll – swath bathymetry from voyage SS2011/06 and sediment thicknesses estimated using the magnetic depth to basement method of Williams et al. (this volume), b) Naturaliste Plateau – bathymetry and deepest resolvable sediments from the interpretation of seismic reflection profile n323 presented in Borissova et al. (2002), and c) Bruce Rise – bathymetry and deepest resolvable sediments from the interpretation of seismic reflection profile GA228/13 presented in Stagg et al. (2006). Note that the Gulden Draak Knoll profile is presented in depth, while the Naturaliste Plateau and Bruce Rise profiles are presented in two-way time. We have aligned the images based on assuming a velocity of 1.5 km/s regardless of depth and vertically exaggerated the two-way time images to attain a visual match between the profiles.

morphology, composition and evolution of the Batavia and Gulden Draak knolls, as follows:

Hypothesis 1: The difference in water depth of the Batavia Knoll, Gulden Draak Knoll, Naturaliste Plateau and Bruce Rise is due to a combination of variations in crustal thickness, and plume-related under-plating.

Hypothesis 2: The pattern of relatively steep western flanks and relatively gentle eastern flanks of both the Batavia Knoll and Gulden Draak Knoll is related to broad-scale crustal features, such as low-angle detachment faults, and may point to exhumation from beneath the Australian plate.

Hypothesis 3: The Gulden Draak and Batavia knolls are floored by thinned continental crust previously contiguous with neighbouring continents within East Gondwana. Basement of the Gulden Draak knoll is genetically related to the Naturaliste Plateau and Bruce Rise, and represents part of the Mesoproterozoic Albany-Fraser-Wilkes Orogen previously defined onshore Australia-Antarctica. Basement of the Batavia Knoll is ultimately derived from similar crust, melted and emplaced as granitic plutons during and immediately after collisional orogenesis to form East Gondwana during the late Neoproterozoic-Early Palaeozoic. The pre-breakup location of the Mentelle Basin between the Leeuwin Complex and Batavia Knoll strongly suggests that basement rocks of a similar age and composition also underlie this basin.

Hypothesis 4: The Batavia and Gulden Draak knolls contain small half graben rift basins that formed coevally with the Western Mentelle Sub-Basin and small rift basins on the Naturaliste Plateau during Jurassic to Valanginian continental extension between India, Australia and Antarctica.

Hypothesis 5: The difference in orientation of the basins of the knolls compared with the Naturaliste Plateau basins is due to rotation of the knolls following break-up or to the influence of pre-existing basement fabric.

Hypothesis 6: Fluvial to shallow marine sediments were deposited on the Batavia and Gulden Draak knolls, predominantly in the small rift basins, until the Albian, when the knolls were isolated from India and thermally subsided.

Hypothesis 7: Post-rift deep water oozes comprise the thin sediment cover across the Batavia and Gulden Draak knolls outside the small rift basins.

Hypothesis 8: Extensive, coeval volcanics with Bunbury Basalt affinities occur on the Bruce Rise, Naturaliste Plateau, Batavia Knoll and Gulden Draak Knoll.

Unravelling the tectonic evolution of the Batavia and Gulden Draak knolls is key to understanding the breakup of East Gondwana. We aim to test the hypotheses made in this paper regarding the structural, volcanic and sedimentary nature of the Batavia and Gulden Draak knolls during on-going work on 2011-derived datasets during 2013, and with the collection of new magnetic, gravity, seismic reflection and dredge data aboard the new Australian Marine National Facility scientific research vessel, the *RV Investigator*, during a cruise scheduled for October-November, 2014. The knolls were at the nexus of breakup between the three East Gondwana continents (India, Australia, and Antarctica) and are the only remnants of the Greater Indian margin that was conjugate to the Western Australian margin that have not been lost or substantially altered during India's collision with Eurasia.

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References

BESLIER, M.O., ROYER, J.Y., GIRARDEAU, J., HILL, P.J., BOEUF, E., BUCHANAN, C., CHATIN, F., JACOVETTI, G., MOREAU, A., MUNSCHY, M., PARTOUCHE, C., ROBERT, U. & THOMAS, S., 2004, A wide ocean-continent transition along the south-west Australian margin: first results of the MARGAU/MD110 cruise, *Bulletin De La Societe Geologique De France*, 175, 629–641.

BOGER, S.D., 2011, Antarctica—before and after Gondwana, *Gondwana Research*, 19, 335–371.

BORISSOVA, I., 2002, Geologial framework of the Naturaliste Plateau, Geoscience Australia, Record 2002/20, 78 pp.

BORISSOVA, I., BRADSHAW, B.E., NICHOLSON, C.J., STRUCKMEYER, H.I.M. & PAYNE, D.S., 2010, New exploration opportunities on the southwest Australian margin-deep-water frontier Mentelle Basin, *The APPEA Journal*, 50, 1–13.

BRADSHAW, B.E., ROLLET, N., TOTTERDELL, J. & BORISSOVA., I., 2003, A revised structural framework for frontier basins on the southern and southwestern Australian continental margin, Geoscience Australia, Record 2003/003, 94 pp.

BRUGUIER, O., BOSCH, D., PIDGEON, R.T., BYRNE, D.I. & HARRIS, L.B., 1999, U-Pb chronology of the Northampton Complex, Western Australia-evidence for Grenvillian sedimentation, metamorphism and deformation and geodynamic implications, *Contributions to Mineralogy and Petrology*, 136, 258–272.

CLARK, D.J., HENSEN, B.J. & KINNY, P.D., 2000, Geochronological constraints for a two-stage history of the Albany-Fraser Orogen, Western Australia, *Precambrian Research*, 102, 155–183.

COFFIN, M.F., PRINGLE, M.S., DUNCAN, R.A., GLADCZENKO, T.P., STOREY, M., MÜLLER, R.D. & GAHAGAN, L.M., 2002, Kerguelen Hotspot Magma Output Since 130 Ma, J*ournal of Petrology*, 43, 1121-1139.

COLEMAN, P.J., MICHAEL, P.J. & MUTTER, J.C., 1982, The origin of the Naturaliste Plateau, SE Indian Ocean: implications from dredged basalts, *Journal of Geological Society of Australia*, 29, 457–468.

COLLINS, A.S., 2003, Structure and age of the northern Leeuwin Complex, Western Australia: constraints from field mapping and U–Pb isotopic analysis, *Australian Journal of Earth Science*, 50, 585–599.

CRAWFORD, A.J., DIREEN, N.G., COFFIN, M.F., COHEN, B., PAUL, B. & MITROVIC, L., 2006, Extensive basaltic magmatism on the Naturaliste Plateau, offshore SW Australia, *Geochimica et Cosmochimica Acta*, 18, A116.

CROSTELLA, A. & BACKHOUSE, J., 2000, Geology and petroleum exploration of the central and southern Perth Basin, Western Australia, Geological Survey of Western Australia, Report 57, 85 pp.

DAVIES, T.A., LUYENDYK, B.P., RODOLFO, K.S., KEMPE, D.R.C., MC KELVEY, B.C., LEIDY, R.D., HORVATH, G.J., HYNDMAN, R.D., THIERSTEIN, H.R., HERB, R.C., BOLTOVSKOY, E. & DOYLE, P., 1974, Initial reports of the Deep Sea Drilling Project, Site 258, Volume 26: Washington, US Government Printing Office, 1129 pp.

GAINA, C., MÜLLER, R.D., BROWN, B., ISHIHARA, T. & IVANOV, S., 2007, Breakup and early seafloor spreading between India and Antarctica, *Geophysical Journal International*, 170, 151–169.

GARDNER, R., 2012, Characterising rocks dredged from the Gulden Draak microcontinent, Masters Thesis, Macquarie University, 90 pp, unpublished.

GIBBONS, A., BARCKHAUSEN, U., VAN DEN BOGAARD, P., HOERNLE, K., WERNER, R., WHITTAKER, J.M. & MÜLLER, R.D., 2012, Constraining the Jurassic extent of Greater India: tectonic evolution of the Australian margin, *Geochemistry, Geophyics, Geosystems*, 13, doi: 10.1029/2011GC003919.

GRADSTEIN, F.M., AGTERBERG, F.P., OGG, J.G., HARDENBOL, S., VANVEEN, P., THIERRY, J. & HUANG, Z.H., 1994, A Mesozoic time scale, *Journal of Geophysical Research*, 99, 24051–24074.

GUSEVA, Y.B., LEITCHENKOV, G.L., GANDYUKHIN, V.V. & IVANOV, S.V., 2007, Basement and crustal structure of the Davis Sea region (East Antarctica): implications for tectonic setting and continent to oceanic boundary definition, *U.S. Geological Survey and The National Academies*, Short Research Paper 025, 1047–1051.

HALL, L.S., GIBBONS, A.D., BERNARDEL, G., WHITTAKER, J.M., NICHOLSON, C., ROLLET, N. & MÜLLER, R.D., 2013, Structural Architecture of Australia's Southwest Continental Margin and Implications for Early Cretaceous Basin Evolution, this volume.

HALPIN, J.A., CRAWFORD, A.J., DIREEN, N.G., COFFI, M.F., FORBES, C.J. & BORISSOVA, I., 2008, Naturaliste Plateau, offshore Western Australia: A submarine window into Gondwana assembly and breakup, *Geology*, 36, 807–810.

HAYES, D.E., L.A. FRAKES, P.J. BARRETT, D.A. BURNS, P. CHEN, A.B. FORD, A.G. KANEPS, E.M. KEMP, D.W. MCCOLLOM, D.J.W. PIPER, R.E. WALL AND P.N. WEBB, 1975, Initial Reports of the Deep Sea Drilling Project, 1017 pp.

HEAP, A.D., EDWARDS, J., FOUNTAIN, L., SPINNOCIA, M., HUGHES, M., MATTHEWS, E., GRIFFIN., J., BORISSOVA, I., BLEVIN, J., MITCHELL, C. & KRASSAY, A., 2008, Geomorphology, sedimentology and stratigraphy of submarine canyons on the SW Australian slope, RV Southern Surveyor, September–October 2004, Geoscience Australia Report 2008/16.

HINZ, K., NEBEN, S., GOUSEVA, Y. & KUDRYAVTSEV, G., 2005, A Compilation of Geophysical Data from the Lazarev Sea and the Riiser-Larsen Sea, off Central Dronning Maud Land, East Antarctica, *Geologisches Jahrbuch Reihe B*, 97, 177–196.

ISHIHARA, T., TANAHASHI, M., SATO, M. & OKUDA, Y., 1996, Preliminary report of geophysical and geological surveys of the West Wilkes Land Margin, *Proceedings of the National Institute of Polar Research" Symposium Antarctic Geoscience*, 9, 91–108.

JOHNSON, B.D., POWELL, C.M. & VEEVERS, J.J., 1976, Spreading history of the eastern Indian Ocean and Greater India's northward flight from Antarctica and Australia, *Geological Society of America Bulletin*, 87, 1560–1566.

JOHNSTON, S., HACKNEY, R. & NICHOLSON, C., Distribution of volcanic facies and results from potential field modelling of the Mentelle Basin, southwestern Margin, Australia, in Proceedings *ASEG-PESA 21st Conference and exhibition*, Sydney, 22–26 August, 2010.

JONGSMA, D. & PETKOVIC, P., 1977, The structure of the Naturaliste Plateau and Trough, *The APEA Journal*, 1977, 3–12.

KOBLER, M.E., 2012, Petrographic, geochemical and geochronological characterisation of Batavia Knoll dredge samples, Perth Abyssal Plain: implications for linkage with Gondwana, Honours Thesis, Macquarie University, 110 pp, unpublished.

KRISHNA, K., MICHAEL, L., BHATTACHARYYA, R. & MAJUMDAR, T., 2009, Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin: New constraints on breakup and early spreading history between India and Antarctica, *Journal of Geophysical Research*, 114, B03102_03101-B03102_03121.

KSIENZYK, A.K., JACOBS, J., BOGER, S.D., KOŠLER, J., SIRCOMBE, K.N. & WHITEHOUSE, M.J., 2012, U-Pb ages of metamorphic monazite and detrital zircon from the Northampton Complex: evidence of two orogenic cycles in Western Australia, Precambrian Research, 198–199, 37-50.

LEITCHENKOV, G.L., GANDYUKHIN, V.V., GUSEVA, Y.B. & KAZANKOV, A.Y., 2007, Crustal structure and evolution of the Mawson Sea (western Wilkes Land margin, East Antarctica), in ANDERSON, J., & BARRETT, P., eds., Proceedings of the 10th International Symposium on Antarctic Earth Sciences, U.S. Geological Survey and U.S. National Academy.

MARKL, R.G., 1974, Evidence for the breakup of eastern Gondwanaland by the Early Cretaceous, *Nature*, 251, 196-200.

–, 1978, Further evidence for the Early Cretaceous Breakup of Gondwanaland off southwestern Australia, *Marine Geology*, 26, 41–48.

MEERT, J.G., 2003, A synopsis of events related to the assembly of eastern Gondwana, *Tectonophysics*, 362, 1–40.

MIHUT, D., 1997, Breakup and Mesozoic seafloor spreading between the Australian and Indian plates, Ph.D. thesis, The University of Sydney, 223 pp, unpublished.

MÜLLER, R.D., GAINA, C., ROEST, W. & HANSEN, D.L., 2001, A recipe for microcontinent formation, *Geology*, 29, 203–206.

MUNSCHY, M., 1998, La zone de Diamantine, temoin de la separation de l'Australie et de l'Antarctique: arguments geophysiques, *Comptes Rendus de l'Academie des Sciences – Series IIA – Earth and Planetary Science*, 327, 533–540.

NELSON, D.R., 1999, Compilation of geochronological data, 1998, Geological Survey of Western Australia Record 1999/2.

NORVICK, M.S. & SMITH, M.A., 2001, Mapping the plate tectonic reconstruction of southern and southeastern Australia and implications for petroleum systems, *The APPEA Journal*, 41, 15–35.

O'BRIEN, P.E. & STAGG, H.M.J., 2007, Tectonic elements of the continental margin of East Antarctica, 38-164°E, in COOPER, A. K., (Ed.), Antarctica: a keystone in a changing world – online proceedings of the 10th international symposium on Antarctic earth sciences, USGS Open-File Report 2007.

POWELL, C.M., ROOTS, S.R. & VEEVERS, J.J., 1988, Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean, *Tectonophysics*, 155, 261–283.

SANDWELL, D.T. & SMITH, W.H.F., 2009, Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge segmentation versus spreading rate, *Journal of Geophysical Research*, 114, B01411, doi:10.1029/2008JB006008.

SAYERS, J., SYMONDS, P.A., DIREEN, N.G. & BERNADEL, G., 2001, Nature of the continent-ocean transition on the non-volcanic rifted margin in the central Great Australian Bight, in WILSON, R. C. L., WHITMARSH, R. B., TAYLOR, B., & FROITZHEIM, N., (Eds). Non-volcanic rifting of continental margins: a comparison of evidence from land and sea, Geological Society of London, Special Publication, 187, 51–76.

SMITH, W.H.F. & SANDWELL, D.T., 1997, Global sea floor topography from satellite altimetry and ship depth soundings, *Science*, 277, 1956–1962.

STAGG, H.M.J., COLWELL, J.B., BORISSOVA, I., ISHIHARA, T. & BERNARDEL, G., 2006, The Bruce Rise Area, East Antarctica: Formation of a continental margin near the greater India-Australia-Antarctic triple junction, *Terra Antarctica*, 13, 3–22.

VEEVERS, J. & LI, Z., 1991, Review of seafloor spreading around Australia. II. Marine magnetic anomaly modelling, *Australian Journal of Earth Science*, 38, 391–408.

WESSEL, P. & SMITH, W.H.F., 1991, Free software helps map and display data, EOS Transactions. *American Geophysical Union*, 72, 445–446.

WILLIAMS, S.E., 2011, The Perth Abyssal Plain: Understanding Eastern Gondwana Break-up, RV Southern Surveyor Voyage SS2011_v06 Scientific Highlights, CSIRO, http://www.marine.csiro.au/nationalfacility/voyagedocs/2011/index.htm

WILLIAMS, S.E., WHITTAKER, J.M., GRANOT, R. & MÜLLER, R.D., 2013a, Early India-Australia spreading history revealed by newly detected Mesozoic magnetic anomalies in the Perth Abyssal Plain, *Journal of Geophysical Research*, doi: 10.1002/jgrb.50239.

WILLIAMS, S.E., WHITTAKER, J.M. & MÜLLER, R.D., 2013b, Newly recognised continental fragments rifted from the West Australian margin, this volume.

Biographies

Jo Whittaker joined the Institute for Marine and Antarctic Science (IMAS) at the University of Tasmania in January 2013. Her research interests are predominantly in plate tectonics, marine geophysics and geodynamics. Jo completed a combine science/commerce undergraduate degree with Honours in Geophysics from the University of Sydney in 2003, followed by a Masters in Geophysics from Victoria University, Wellington, New Zealand. She received her PhD, on the tectonic consequences of mid-ocean ridge formation, evolution and subduction, from the University of Sydney in 2008. Following graduation she worked both for industry (GETECH in the UK) and academia (post-doc, University of Sydney).

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Lisa Hall is a senior research scientist in Geoscience Australia's Basin Resources Group. Her current research is focused on unconventional hydrocarbon resource assessments and petroleum systems modelling in a variety of Australian basins. Lisa holds an MSc in Geology and Geophysics from Cambridge University (1999) and a DPhil in structural geology and neotectonics from Oxford University (2003). Member: PESA.

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Madeline Kobler (BSc hons) is an Engineering Geologist at Pells Sullivan Meynink. She graduated from Macquarie University in 2012 with first class honours. Her research focused on petrography, geochronology and geochemical characterisation. Madeline was awarded the Preston Geology Prize (Macquarie University) in 2012 for best performance in 300-level geology units.

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Nathan Daczko (BSc hons, PhD Univ. of Syd.) is an Associate Professor in the Department of Earth and Planetary Sciences at Macquarie University. Fields of research interest include: (i) structural geology and tectonics, (ii) metamorphic petrology and thermobarometry, (iii) evolution of plate boundary zones, (iv) integration of geological and geophysical data, (v) geochronology, and (vi) field mapping. Nathan was awarded the Powell Medal (The Geological Society of Australia, Specialist Group in Tectonics and Structural Geology, for the most outstanding research paper) in 2003, Australian Institute of Political Science NSW/ACT Young Tall Poppy Award in 2006, and E.S. Hills Medal (The Geological Society of Australia, for outstanding contributions to any branch of the geological sciences) in 2010.

Dietmar Müller is Professor of Geophysics at the University of Sydney, Australia. He obtained his PhD in Earth Science from the Scripps Institution of Oceanography in 1993 and his undergraduate degree at the University of Kiel, Germany. After joining the University of Sydney in 1993, he established the University of Sydney Institute for Marine Science and the EarthByte e-research group (www.earthbyte.org), pursuing collaborative development of open-source software and community digital data sets. One of the fundamental aims of his research is geodata and model synthesis through space and time, assimilating the wealth of disparate geological and geophysical data into a four-dimensional Earth model. His achievements have been acknowledged by winning the year 2000 Fresh Science Prize, awarded by the British Council and 'ScienceNow!', followed by the Carey Medal in 2004 for his contributions to the understanding of global tectonics. In 2009 he was awarded a 5-year Australian Laureate Fellowship to build a Virtual Geological Observatory.