Newly-recognised Continental Fragments Rifted from the West Australian Margin

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Abstract

The southwest Australian margin formed at the nexus of rifting and breakup between India, Australia and Antarctica in the Early Cretaceous. Studying the basin evolution along this margin has been hampered by a lack of data from the offshore Perth Abyssal Plain (PAP), and from the conjugate Greater Indian margin, which was highly deformed during collision with Eurasia. Here, we present new data (magnetic anomaly profile data, swath bathymetry, and dredge samples) constraining the evolution of the PAP, collected during voyage ss2011/v06 of the *RV Southern Surveyor* in late 2011.

The Batavia Knoll (BK) and Gulden Draak Knoll (GDK) are two prominent, previously unsampled bathymetric features located >1600 km offshore Australia that have been assumed to be igneous features. Successful dredges on the western flanks of both knolls recovered continental basement rocks, revealing that both knolls are microcontinents. We use quantitative analysis of shiptrack magnetic profiles combined with satellite gravity anomalies to estimate the extent and spatial variation in thickness of the continental crust. Sediment thickness estimates are made using depths to magnetic sources for shiptrack profiles.

The geophysical data provide evidence for basin structures within the knolls of a similar scale to those imaged within other fragments of stretched continental crust such as the Naturaliste Plateau. Interpretation of previously unidentified M-series anomalies in the Perth Abyssal Plain, combined with dredge data, support a reconstruction model where the BK and GDKs are microcontinents that initially rifted with Greater India during breakup with Australia at ~130 Ma. As seafloor spreading ceased in the PAP at about 105–100 Ma, a westward ridge jump led to the rifting of the BK and GDK from Greater India.

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Introduction

The Batavia Knoll and Gulden Draak Knoll are submarine plateaus, with a combined area similar to that of Tasmania, lying >1,600 km west of the West Australian continental margin (Fig. 1). Until recently, little has been known about these knolls, and they have received little attention in the scientific literature. Thompson et al. (1978) speculated that the knolls may be a series of volcanic features on a northward trend from Broken Ridge. Though not always stated explicitly, the knolls were implicitly assumed to be igneous features formed on oceanic crust both in interpretations of seafloor spreading anomalies and plate reconstruction models (e.g. Markl, 1974; Johnson et al., 1976; Mihut, 1997).

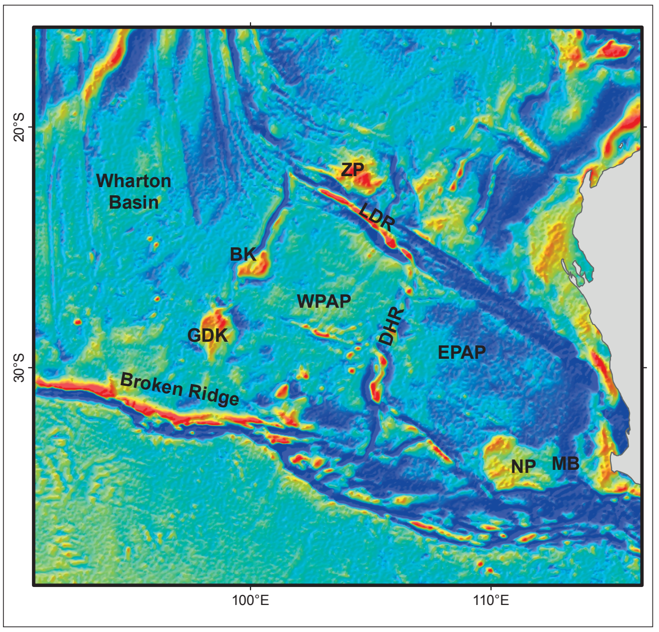

Figure 1. Tectonic features in and around the Perth Abyssal Plain. The underlying image is free-air gravity derived from satellite altimetry (Sandwell & Smith, 2009). The coastline of Western Australia is delineated in grey. Abbreviations: EPAP – East Perth Abyssal Plain; WPAP – West Perth Abyssal Plain; BK – Batavia Knoll; GDK – Gulden Draak Knoll; NP – Naturaliste Plateau; ZP – Zenith Plateau; DHR – Dirck Hartog Ridge; LDR – Lost Dutchman's Ridge.

New data collected in 2011 from the Batavia and Gulden Draak knolls, and from the seafloor between the knolls and the west Australian margin, illustrate that the knolls are in fact continental fragments formed during the Mesozoic breakup of Gondwana. In this paper, we present a synthesis of geophysical data available over the Batavia and Gulden Draak knolls, and discuss the implications of these data for the likely crustal structure of these newly recognized microcontinents. In a companion paper, Whittaker et al. (2013) discuss the tectonic evolution of these continental fragments and compares them to other structural elements formed during Mesozoic breakup between Australia, India and Antarctica, notably the Naturaliste Plateau and the Bruce Rise.

Revised Tectonic History for the Perth Abyssal Plain

The Perth Basin and seafloor within the Perth Abyssal Plain is the only section of crust that directly records the rifting and early spreading history between India and Australia during the Mesozoic breakup of Gondwana. Reconstructing the early spreading history between India and Australia has always been difficult; much of the oceanic crust formed during the Mesozoic has been subsequently subducted beneath Southeast Asia, and where Mesozoic crust is still preserved in the Perth Abyssal Plain, insufficient data have existed to validate tectonic models.

The eastern Perth Abyssal Plain contains a series of linear magnetic anomalies interpreted as M9-M0 (~130 Ma to ~120 Ma) (Markl, 1974; Veevers & Li, 1991). The exact location of the conjugate (Indian plate) Mesozoic section of crust has remained unresolved. Some models predict that the crust in the west PAP formed entirely within the Cretaceous Normal Superchron (Markl, 1974; Johnson et al., 1980; Mihut, 1997). Other models predict that some Mesozoic spreading anomalies should be observed in the west PAP (Powell et al., 1988; Gibbons et al., 2012), but no evidence has been available to support this hypothesis. To date, due to the lack of data, no magnetic interpretation is available for the west PAP.

Recently, we collected new data that further constrain the early seafloor spreading history between India and Australia within the Perth Abyssal Plain. Total-field surface marine magnetic anomaly data collected in October–November 2011 onboard the *R/V Southern Surveyor* reveal previously unrecognized M-series spreading anomalies in the western Perth Abyssal Plain, conjugate to the sequence in the eastern Perth Abyssal Plain, and allow us to reinterpret the youngest anomalies in the eastern part of the basin (Williams et al., 2013). Further evidence for the spreading history comes from dredge samples collected from a series of bathymetric knolls and ridges in the PAP. Samples recovered from the Batavia Knoll comprised granite, granite gneiss and schist and fossiliferous sandstone. Samples from the Gulden Draak Knoll comprised granite, garnet gneiss, sandstones and siltstones, and highly altered basalts. Basement rocks recovered from the Dirck Hartog Ridge were igneous in nature, including gabbros and basalts. A full listing of the samples can be found in Whittaker et al. (2013).

The new observations support a revised tectonic evolution for the breakup history of the western Australian margin (Gibbons et al., 2012). The Batavia and Gulden Draak knolls are microcontinents which rifted away from Australia as part of Greater India during initial breakup at ~130 Ma. The microcontinents then rifted from India when spreading ceased in the PAP during the Cretaceous Normal Superchron, the timing likely shortly before a major change in spreading direction around 105–100 Ma (Veevers, 2000; Matthews et al., 2012). The Batavia Knoll thus represents a fragment of the passive continental margin conjugate to the Perth Basin.

Data

Figure 1 shows the free-air gravity anomaly derived from satellite altimetry (Sandwell & Smith, 2009). Shiptrack geophysical data for the area have been extracted from the National Geophysical Data Center online data repository [http://www.ngdc.noaa.gov/mgg/geodas/]. Two voyages during the 1960's collected data across the Batavia Knoll. Single beam bathymetry and magnetics are available from voyages v1811 and c0909, with marine gravity measurements also available for the former. However, the data for these surveys available within the NGDC database are of limited resolution; the along line spacing between successive magnetic measurements is several kilometres.

The primary source of data in this study are new observations from voyage ss2011/v06 on the Southern Surveyor in October–November 2011. The ocean floor fabric of the PAP was mapped using a Kongsberg EM300 swath mapping system. Water depths in much of the PAP are beyond the manufacturers specifications for this equipment. However, with the exception of some sections of profile 1, the processed data were typically usable and give a ~5 km wide swath along the survey track.

New magnetic anomaly profiles were obtained along profiles traversing the PAP. Data were recorded at a sampling of 1 Hz using a SeaSpy magnetometer towed ~200 m behind the survey vessel. The main field was removed from the data using the 11th generation of the International Geomagnetic Reference Field (Finlay et al., 2010). No diurnal correction has been applied to the data presented in this paper. Base station measurements for three sites in Western Australia were compared to the measurements acquired during the voyage. Two magnetic storms are visible during the duration of the voyage, but neither affected the data presented here.

Further swath data for the PAP come from two recent voyages of the R/V Melville that transited across the PAP (survey IDs bmrg06mv and sojn04mv; data available at http://www.marine-geo.org). These voyages collected swath data using a more powerful swath mapping system, giving swaths ~15 km wide in the abyssal plains. Voyage bmrg06mv also collected magnetic and gravity measurements across the Gulden Draak Knoll.

Morphology of the Knolls

Figures 2 and 3 shows the morphology of the seafloor in the area containing the Batavia and Gulden Draak knolls. The bathymetry map is a composite of different data sets. The bathymetry is well constrained along the recent swath bathymetry profiles. The map is also constrained by sparse single beam shiptrack data, with the remaining areas filled with predictive bathymetry based on sea surface heights from satellite altimetry (Smith & Sandwell, 1997; Becker et al., 2009). The predictive bathymetry estimates provide a useful regional-scale picture of seafloor depth variations, but also show large disparities at short wavelengths compared to the swath profiles, illustrated most clearly in the cross-section comparisons in Figure 5a–c.

A fundamental observation related to both the Batavia and Gulden Draak knolls is that they are broadly asymmetric. Both knolls exhibit relatively steep slopes on the northern and western margins facing the Wharton Basin, and eastern margins dipping more gently towards the PAP. The asymmetry is also illustrated in the cross-sections discussed below.

Where detailed swath data are available around the steeper sections (Fig. 3) they reveal the existence of major, even more steep-sided canyons (slopes typically in excess of 30). Dredging carried out as part of ss2011/v06 targeted these canyon walls. The recovered samples suggest that metamorphic basement rocks, Cretaceous sedimentary units, and basalts are at or near the surface on the upper sections of steep flanks of the knolls. Ages for the various lithologies are currently being determined; preliminary analyses are summarised in Whittaker et al. (2013).

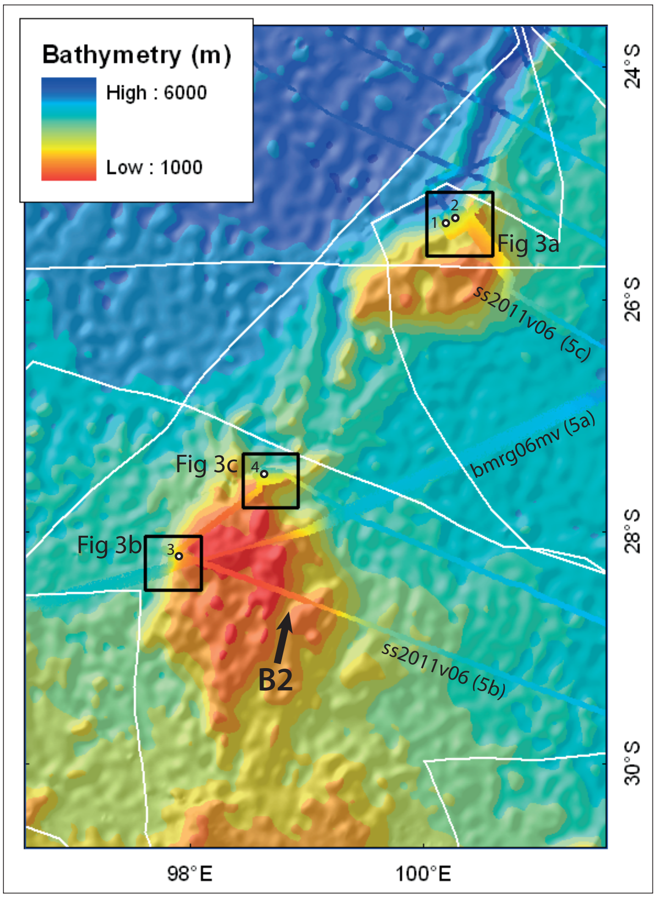

Figure 2. Bathymetry data over the Batavia and Gulden Draak knolls. The brighter coloured bands show bathymetry data for swath profiles from Southern Surveyor voyage ss2011/v06. The NE-SW trending swath profile across the Gulden Draak Knoll is from the R/V Melville (voyage id bmrg06mv). The underlying image is version 15.1 of the Smith & Sandwell (1997) bathymetry model. White lines show where single-beam shiptrack data are available to constrain the Smith and Sandwell (2009) grid. Numbered circles show ss2011/v06 dredge sites. Boxes show locations of areas shown in more detail in Figure 3. B2 denotes gravity low discussed in text.

Gravity Anomalies

The prominent bathymetric expression of the Batavia and Gulden Draak knolls gives rise to clear expression in the map of free-air gravity derived from satellite altimetry (Sandwell & Smith, 2009) (Fig. 4a). The free-air gravity data also exhibit shorter wavelength variations within the knolls, although it is only where reliable bathymetry data are available that we can properly assess whether features at this scale are indicative of bathymetric variations or density variations within the knolls themselves. On the eastern margin of the Gulden Draak Knoll, a N-S trending, ~30 km wide gravity low is crossed by one of our profiles; the swath data indicates a much smoother bathymetry than predicted by satellite altimetry, likely reflecting crustal density variations as discussed below.

From the free-air gravity, we calculate a Bouguer anomaly grid (Fig. 4b). We used the code of Fullea et al. (2008) to calculate the Bouguer correction, with bathymetry taken from version 15.1 of the Smith & Sandwell (2009) grid, and 2.67 g/cc used for the Bouguer reduction density (1.03 g/cc is used for the water density). The bathymetry data used to calculate the Bouguer correction relies heavily on satellite altimetry data, hence we do not use the Bouguer anomaly map to investigate small-scale structures which these bathymetry may not reliably represent. The Bouguer anomaly map is however useful for regional scale interpretation. Both the Batavia and Gulden Draak knolls exhibit Bouguer gravity lows, indicative of a deep crustal root relative to the adjacent oceanic crust in the PAP and Wharton Basin. We also observe that the Bouguer gravity indicates that the Gulden Draak Knoll is much less distinct

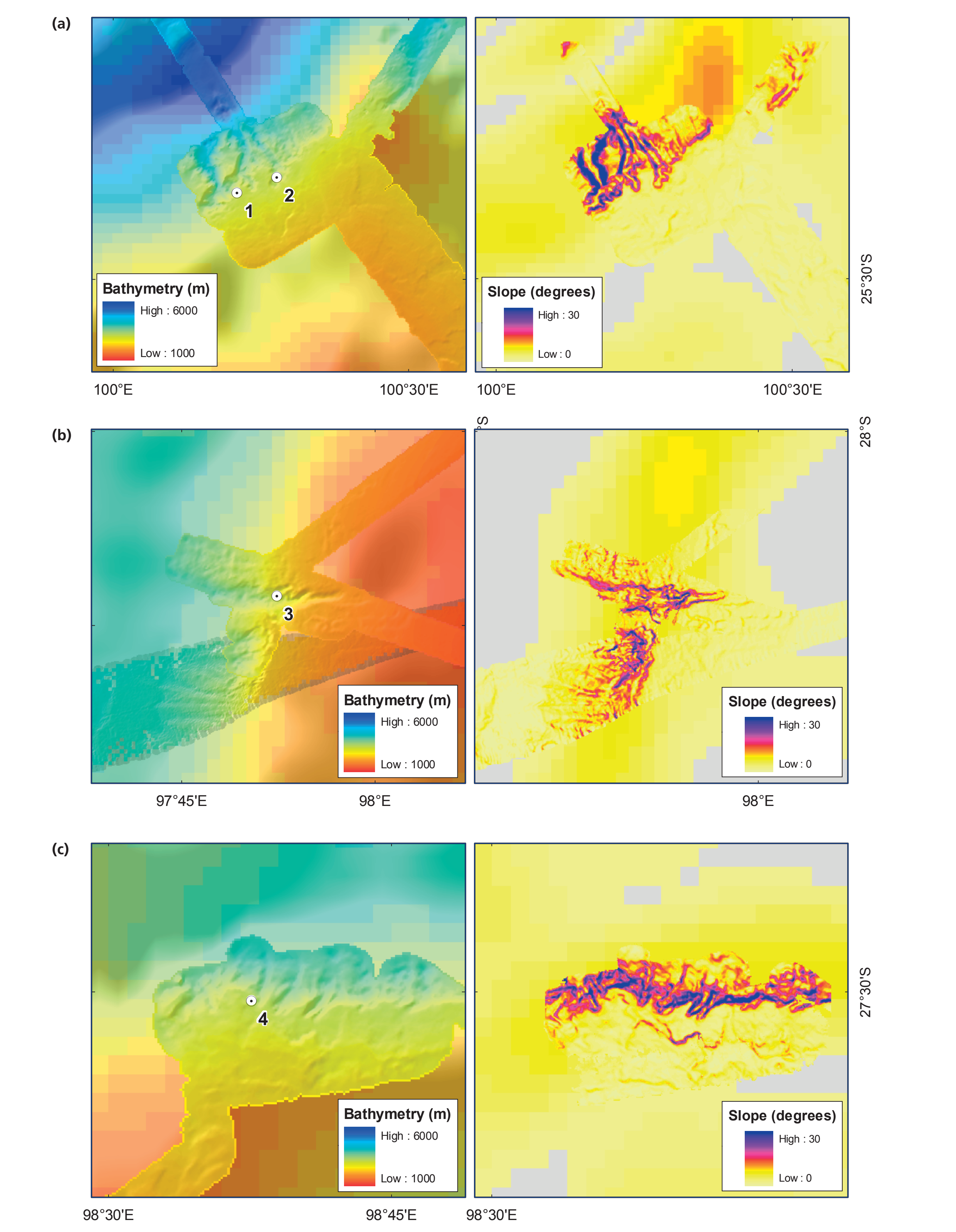

Figure 3. Detailed Swath bathymetry for dredge sites on the Batavia and Gulden Draak Knolls. (a) Batavia Knoll, dredge sites 1 and 2; (b) Gulden Draak Knoll, dredge site 3; (c) Gulden Draak Knoll, dredge site 4.

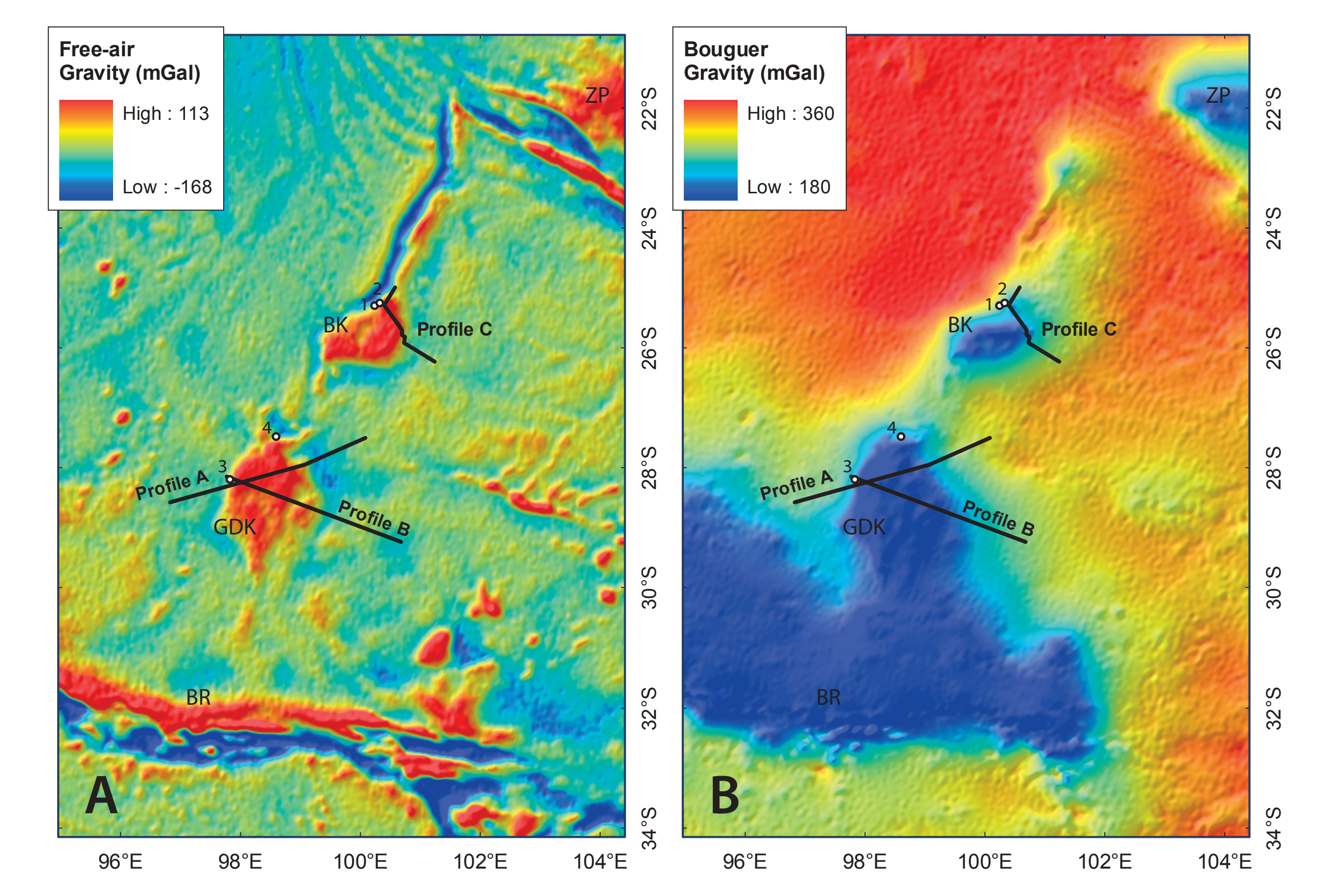

Figure 4. Gravity maps for the Batavia and Gulden Draak knolls. a) Free-air gravity map derived from satellite altimetry (Sandwell & Smith, 2009). b) Bouguer anomaly map, with Bouguer correction calculated using the code of Fullea et al. (2008). Plotted profiles are shown in Figure 5.

from Broken Ridge than the free-air anomaly map would suggest. A major Bouguer gravity low encompasses the Gulden Draak Knoll, Broken Ridge, and much of the area in between.

Geophysical Profiles

We further illustrate the geophysical evidence for the crustal structure of the knolls using a series of profiles. The profile analysis utilizes modern shiptrack data and free-air gravity anomalies extracted from the satellite-derived grid of Sandwell & Smith (2009).

As an additional means to constrain the crustal structure of the knolls, we generate first-order estimates of the depths to magnetic sources. Such an approach is useful for delineating sedimentary basins within continental areas and sediment thickness, under the assumption that sediments have low magnetic susceptibilities and that the major source of the observed anomalies are due to underlying crystalline basement rocks. We estimate magnetic source depths using two automated depth estimation techniques suitable for magnetic anomaly profiles. The first method is a profile-based variant of the Tilt-depth method described by Salem et al. (2007, 2010). The second method is based on the local wavenumber of the magnetic anomaly (Thurston & Smith, 1997).

The Tilt-depth method utilizes the tilt angle of the observed magnetic field (Miller & Singh, 1994; Verduzco et al., 2004). Salem et al. (2007, 2010) showed that the distance between contours of the tilt angle can be related to the depth of a vertical contact source, assuming a reduced to pole (RTP) field. In this case, we adapt the method to profile Total Magnetic Intensity (TMI) data. The grid-based method assumes the magnetic data are RTP, so for the profile case we de-skew the anomalies along each profile using the local inclination of the Earth's field and the profile direction (Blakely, 1996). Assuming that anomaly sources are vertical magnetization boundaries (and for the profile case, assuming the boundaries are 2D structures perpendicular to the profile), the tilt angle is zero over the boundary. The depth to the top of the boundary can be determined from the distance along the profile from the zero point to a given tilt angle value.

Another method to generate magnetic source depth estimates from TMI profiles is to use the local wavenumber (Thurston & Smith, 1997). Maxima in the local wavenumber profile fall over magnetic sources, and the value of the local wavenumber at the maxima is inversely related to the source depth (the exact relationship depending on the source geometry). We plot depth estimates assuming a contact geometry consistent with the tilt-depth estimates. The local wavenumber approach uses second order derivatives of the observed TMI profiles, hence it potentially has a higher resolving power than the tilt-depth but will also be more susceptible to noise within the data. We present results from both methods, and assign greater confidence to the depth estimates in areas where the results from both methods agree.

The TMI profile in Figure 5a is dominated by smooth, long wavelength anomalies within the abyssal plains either side of the knoll where the water depth exceeds 4 km. The dominant spatial wavelength of anomalies clearly decreases over the knoll where the water depth shallows to around 1.5 km. Estimates of the anomaly source depths on the western side of the knoll typically fall close to the seafloor, suggesting crystalline basement rocks near the surface. Groups of source depths >1 km below the seafloor at X = 110–130 km (labeled A1), X = 165–190 km (A2), and more tentatively X = 70–85 km (A3) are regions of possible thicker sediment accumulations. Dredge site 3, where both crystalline basement and sedimentary rocks were recovered (Whittaker et al., 2103), lies on the steep west-dipping bathymetric slope to the west of A3 (at roughly X = 60 km).

This profile is also noteworthy for the availability of shiptrack gravity data. In Figure 5a we plot the free-air gravity anomaly measured with a marine gravity meter against the anomaly extracted along the same profile from the grid of free-air gravity derived from satellite altimetry (Sandwell & Smith, 2009). The comparison shows that the satellite-derived data are fairly robust in this area.

The TMI anomaly in Profile B (Fig. 5b) exhibits two ~400 nT amplitude anomalies towards the western margin of the knoll and a similar amplitude anomaly at the eastern margin (X = 160 km). The TMI anomalies over the knoll are otherwise low amplitude but with short spatial wavelengths, reflected in source depth estimates close to the seafloor for much of the profile. Two areas of the profile exhibit groups of magnetic source depth estimates > 2 km below the bathymetry, from X = 225–250 km (labeled B1) and from X = 130–170 km (B2). The feature labeled B2 broadly corresponds to the feature labeled A3 on profile A. Dredge site 3 falls at the western end of this profile.

The more easterly of these two regions (B2) also corresponds to a major low in the free-air gravity profile extracted from the Sandwell & Smith (2009) grid. This gravity low also gives rise to a coincident 400 m deep local topographic depression in the predictive bathymetry grid (shown by the red line on Fig. 5), but swath data from ss2011/v06 illustrate that in fact bathymetry here dips gently and continuously to the east. Comparison between the satellite-derived gravity data and shipborne data along profile A shows that a gravity low of this scale and amplitude within the satellite-derived data is likely to be robust, and delineates a region of lower density in the shallow subsurface. The gravity anomaly map (Fig. 4) shows that this low extends N-S along the eastern margin of the Gulden Draak Knoll.

The TMI profile along profile C (Fig. 5c) across the northern part of the Batavia Knoll exhibits lower amplitude variations than the profiles across the Gulden Draak Knoll. One contributing factor may be the greater seafloor depth along the profile (depths are > 2 km). The source depth estimates for this profile all lie near the seafloor, with some likely spurious solutions produced within the water column where the profile bends sharply (the vertical yellow lines on Fig. 5c show where the profile bends). The bend in the profile marked at X = 38 km corresponds to the nearest point along the profile to dredge sites 1 and 2, where the recovered lithologies were continental crystalline basement rocks and sandstones respectively (Whittaker et al., 2013).

A further noteworthy aspect of this profile is the large mismatch between swath bathymetry from ss2011/v06 and the v15.1 predictive bathymetry grid (labeled C1). The satellite-derived free air gravity anomaly map shows a distinct peak over the northern corner of the Batavia Knoll, which helps to explain why the predicted bathymetry is shallower here than for the rest of the Batavia Knoll. Another contributing factor is the bathymetry values along a 1960's vintage shiptrack used to constrain the predictive bathymetry grid (Fig. 2). Where this shiptrack crosses the 2011 swath line there is a mismatch of 1 km in the measured depths, which we attribute to errors in the older dataset. The high in the satellite-derived gravity over the northern corner of the Batavia Knoll is nonetheless likely to be real, and may for example indicate a region of higher density basement.

Discussion

Our observations show that the Batavia and Gulden Draak Knolls are fragments of extended continental crust. In a companion paper, Whittaker et al. (2013) show how these fragments can be reconstructed within Gondwana. The Batavia Knoll originally lay adjacent to the Perth Basin and northern margin of the Naturaliste Plateau, while the Gulden Draak Knoll lay adjacent to the southern margin of the Naturaliste Plateau, and the Bruce Rise on the Antarctic margin.

Comparison with the Naturaliste Plateau is particularly relevant, since it also represents a fragment of stretched continental crust formed during Gondwana breakup (Halpin et al., 2008), albeit a fragment that never fully broke away from the Australian continent. Within the western part of the Naturaliste Plateau, three rift basins, 10–30 km wide and 120 km long and containing up to 1.2 seconds (~2 km) thick sediment packages, were identified by Borissova (2002) and Direen et al. (2007) and have been imaged by seismic reflection profiles. These authors, and additionally Borissova et al. (2010) and Bradshaw et al. (2003) have described the

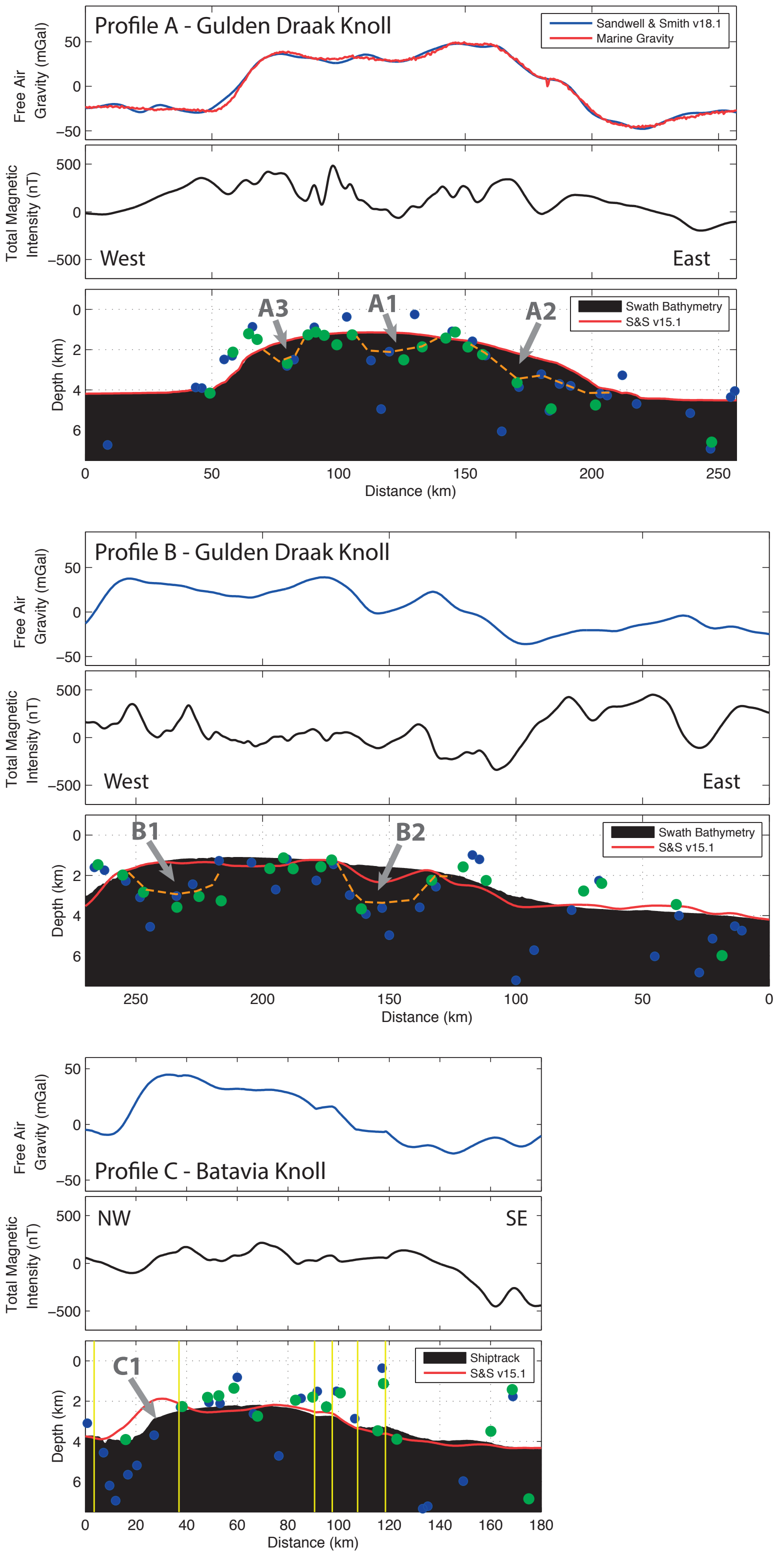

Figure 5. Geophysical profiles across the Batavia and Gulden Draak knolls (locations shown in Fig. 4). For each profile, the top panel shows free-air gravity extracted from version 20.1 of the Sandwell & Smith (2009) grid. For profile A, free-air gravity measured on the survey vessel is also shown. The middle panel shows the Total Magnetic Intensity anomaly. The lower panel shows bathymetry from swath data, with Smith & Sandwell (2009) predictive bathymetry (v15.1) shown for comparison (note that swath data from profile A is already included in the predictive bathymetry grid; swath data from profiles B and C are not). Dots on the lower panel are estimates of magnetic source locations derived from the TMI anomaly profile, generated using the tilt-depth method (green) and local wavenumber (blue) – see text for discussion of the methods and parameters. Dashed orange lines shows possible basin structures.

much larger Mentelle Basin with up to 11 km of sediment in the eastern part of the Naturaliste Plateau. Structures inferred within the Batavia and Gulden Draak knolls from bathymetry and potential field data, are less well constrained. Nonetheless, these simple inferences from these data suggest that basin structures of the same spatial extent and depth as the western rift basins of the Naturaliste Plateau exist in the Gulden Draak Knoll and possibly the Batavia Knoll. Furthermore, they provide testable targets for future seismic experiments planned across the knolls using the new Australian Marine National Facility vessel the *RV Investigator*.

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Biographies

Simon Williams joined the School of Geosciences at the University of Sydney in January 2010. He obtained a PhD in geophysics from the University of Leeds, having completed a degree in geology at Liverpool University. From 2004 to 2009 he worked as a geophysicist at GETECH in the UK, a potential-field geophysics consultancy. Since arriving in Sydney, his research has concentrated on revising the way that plate deformation is described within global plate tectonic reconstructions. He was also chief scientist aboard a 2011 voyage of the CSIRO research vessel Southern Surveyor, which collected new magnetic profiles, swath bathymetry data and dredge samples in the Perth Abyssal Plain, eastern Indian Ocean.

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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